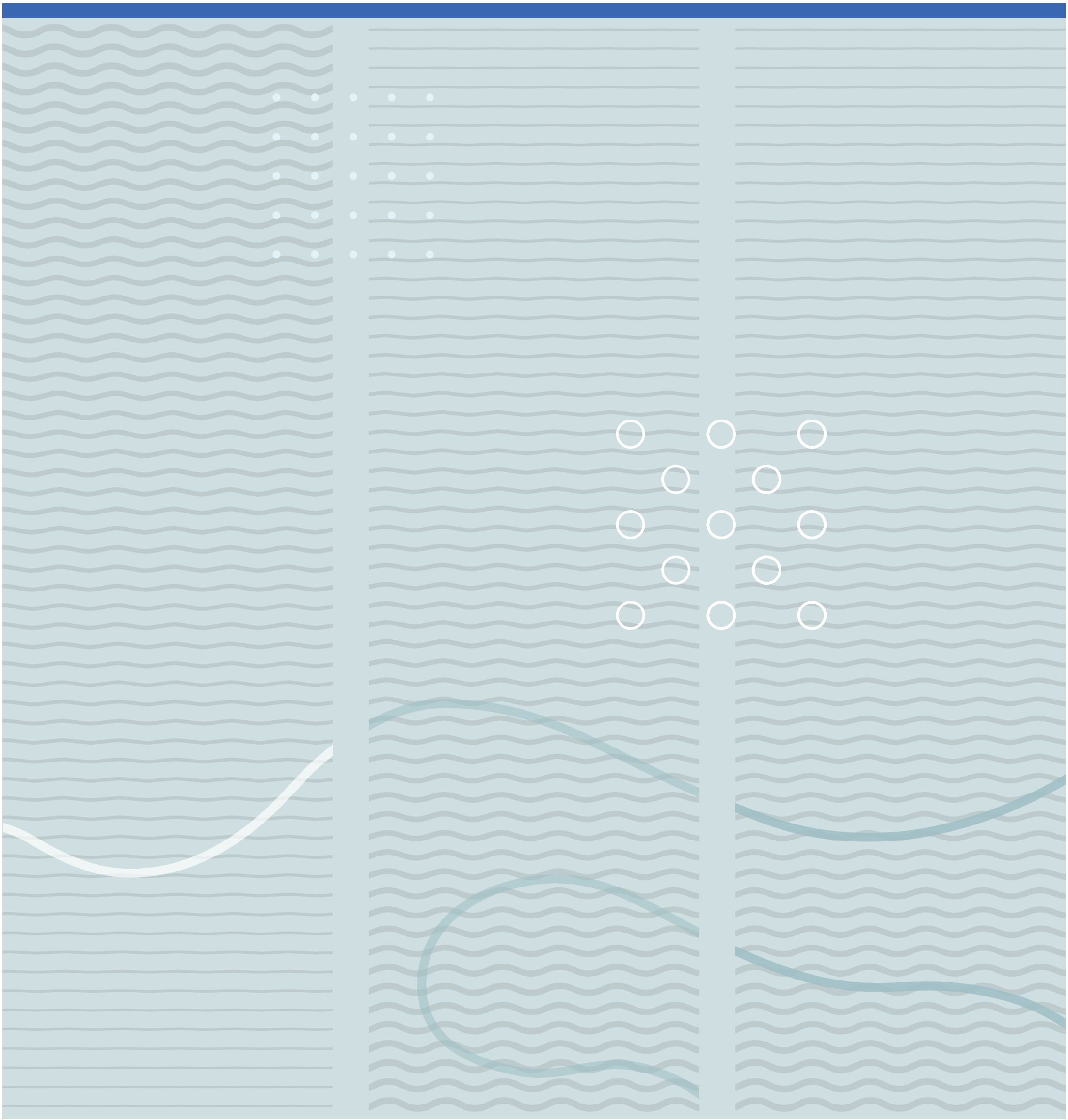
University of South-Eastern Norway
Faculty of Health and Social Sciences
—
Doctoral dissertation no. 137
2022

Sigbjørn Litleskare

Virtual green exercise - developing a new concept for health promotion



Sigbjørn Litleskare

Virtual green exercise - developing a new concept for health promotion

Dissertation submitted to the Faculty of Health and
Social Sciences, University of South-Eastern Norway,
in partial fulfillment of the requirements for the
degree of dr.philos. (doctor philosophiae).

Faculty of Health and Social Sciences
University of South-Eastern Norway
Drammen, 2022

Doctoral dissertations at the University of South-Eastern Norway no. 137

ISSN: 2535-5244(print)
ISSN: 2535-5252 (online)

ISBN: 978-82-7206-695-5 (print)
ISBN: 978-82-7206-696-2 (online)

Print: University of South-Eastern Norway

Table of contents

Acknowledgements

This thesis is based on experimental work carried out in the Sport Physiology Laboratory of Inland Norway University of Applied Sciences, Campus Elverum. The final publication of this thesis (Paper IV) received funding from the Regional Research Fond – Innlandet, Norway (grant n. 292761).

It would not be possible for me to complete the work required for this thesis without the support from my colleagues and the institution. Most importantly, thanks to you Giovanna. You were the spark that initiated this project, and you have been an inspiration and a door opener for me throughout this process. Thanks for all the feedback, support, and motivation you have provided during our years working on this project.

I would also like to thank all the co-authors of the individual papers. You have provided important contributions to this work, and to my development as a future scientist. It has been a joy working with such a diverse group of people, ranging from master students and programmers to environmental psychologists and public health researchers.

Thanks to all my friends and co-workers that has willingly participated in pilot testing of the early iterations of our virtual reality creations. I would also like to thank all my colleagues that has found the time to engage in discussions of research methods, statistics and scientific conduct. In this regard, I would like to give a special thanks to the late Arild Vaktskjold for his contributions to my statistical understanding, and Svein Barene for our discussions of how to write scientific texts.

I would also like to thank the Inland Norway University of Applied Sciences for providing me with additional research time. It can be challenging as a lecturer to find the time to conduct research. The additional research time enabled me to complete this thesis.

List of abbreviations

VR	Virtual reality
HMD	Head-mounted display
MET	Metabolic equivalent of task
SD	Standard deviation
IQR	Interquartile range

Summary

Introduction

Recent advances in virtual reality (VR) technology have been followed by extensive interest within research and health promotion, including the field of green exercise. Green exercise refers to any physical activity in natural environments. This type of exercise has been associated with additional psychophysiological health benefits compared to indoor and urban exercise, such as stress reduction and improved mental well-being. Virtual green exercise seeks to apply VR technology to extend the benefits of green exercise to people who are unable to engage in active visits to real nature and to improve methodological rigor in studies investigating the potential benefits of green exercise by allowing lab-based experiments that simulate outdoor environments. Unfortunately, VR technology may also cause negative side effects in the form of cybersickness, leading to negative reactions such as dizziness, nausea and general discomfort. This thesis aims to understand how the potential health benefits of virtual green exercise can be maximized while simultaneously minimizing undesirable side effects such as cybersickness. The thesis summarizes five studies that applied VR technology to develop and optimize a protocol for virtual green exercise.

Methods

Four experimental studies with different study designs (Studies 1, 2, 3 and 5) and one narrative review (Study 4) were conducted with a primary focus on assessing the acute effects of virtual green exercise. Either quantitative- or mixed-methods were implemented in the respective studies. This research was designed as a continuous process, which means that each study guided the design and procedures of the following study. In total, 136 people volunteered and participated in the experimental studies. The gender distribution was balanced with 68 males and 68 females. The majority of participants were young, healthy, and active individuals.

Results

Study 1 compared virtual green exercise, in the form of 360° videos, to both real green exercise and a sedentary exposure to virtual nature. The results showed that the concept had potential, but also that cybersickness had a profound impact on experiences in virtual green exercise. This malaise was negatively associated with indicators of psychophysiological health, leading to negative affective responses and low levels of enjoyment. Study 2 compared two 360˚ videos with different levels of scene stability to assess whether improved stability could reduce the severity of cybersickness. The results revealed that improved stability in 360˚ videos significantly reduced issues related to cybersickness and negative affective outcomes. Study 3 expanded on these results and found that postural instability is both a potential cause and objective measure of cybersickness, but also that the relation between postural instability and cybersickness is highly individual. Study 4 comprised a review of literature that was conducted (1) to identify common issues with modern VR technology, (2) to identify the most likely areas of application for virtual green exercise, and (3) to describe best practice for virtual green exercise research. Study 5 implemented the techniques and procedures identified in Study 4, comparing two different techniques for creating virtual natural environments (i.e. 360˚ video and 3D model) and a control condition comprising indoor exercise. The results showed minimal impact of cybersickness in the two virtual conditions. The level of enjoyment, a key factor for exercise participation, was higher after virtual green exercise compared to indoor exercise. All three experimental conditions in Study 5 improved affect and reduced indicators of stress, with no significant differences between conditions.

Conclusion

These results demonstrate that adopting virtual green exercise within health promotion and research requires the use of appropriate techniques to create and deliver enjoyable experiences without causing cybersickness. Scene stability emerged as a major factor contributing to cybersickness and negative affective responses. When scene stability was improved and appropriate techniques were implemented, the results support the use of virtual green exercise within physical activity promotion in particular, as the levels of enjoyment were higher after virtual green exercise compared to indoor exercise in Study 5. The results also highlight the challenges of reproducing the range of psychophysiological health benefits associated with real green exercise.

List of papers

I. Calogiuri, G., Litleskare, S., Fagerheim, K. A., Rydgren, T. L., Brambilla, E., & Thurston, M. (2018). Experiencing Nature through Immersive Virtual Environments: Environmental Perceptions, Physical Engagement, and Affective Responses during a Simulated Nature Walk. Frontiers in Psychology, 8. https://doi.org/Artn 2321 10.3389/Fpsyg.2017.02321

II. Litleskare, S., & Calogiuri, G. (2019). Camera Stabilization in 360 degrees Videos and Its Impact on Cyber Sickness, Environmental Perceptions, and Psychophysiological Responses to a Simulated Nature Walk: A Single-Blinded Randomized Trial. *Frontiers in Psychology*, *10*, 2436. https://doi.org/10.3389/fpsyg.2019.02436

III. Litleskare, S. (2021). The relationship between postural stability and cybersickness: It's complicated – An experimental trial assessing practical implications of cybersickness etiology. *Physiology & Behavior*, *236*, 113422. https://doi.org/10.1016/j.physbeh.2021.113422

IV. Litleskare, S., MacIntyre, T. E., & Calogiuri, G. (2020). Enable, Reconnect and Augment: A New ERA of Virtual Nature Research and Application. *Int J Environ Res Public Health*, *17*(5). https://doi.org/10.3390/ijerph17051738

V. Litleskare, S., Fröhlich, F., Flaten, O. E., Haile, A., Johnsen, S. Å. K., & Calogiuri, G. Taking real steps in virtual nature: A randomized blinded trial. *Virtual Reality*. https://doi.org/10.1007/s10055-022-00670-2

1. Introduction

Physical activity is known to promote a range of benefits to human health and well-being (Garber et al., 2011; Warburton et al., 2006). In recent years, it has also become apparent that one's exercise environment impacts the beneficial effects of exercise. Some environments may have a detrimental effect on human health, such as certain urban environments (Krefis et al., 2018; Pinchoff et al., 2020), while natural environments are associated with a range of psychophysiological health benefits including stress reduction and mental well-being (Calogiuri & Chroni, 2014; Corazon et al., 2019; Frumkin et al., 2017; Moeller et al., 2018; White et al., 2018, 2019, 2021). These two behaviors, nature exposure and physical activity, merge in a concept known as "green exercise"—that is, *any physical activity in the presence of nature* (Pretty et al., 2003). By performing green exercise, it is believed that one may achieve the benefits of nature exposure while also achieving the health benefits of physical activity (Gladwell et al., 2013; Rogerson et al., 2019). In a recent review of literature, Lahart et al. (2019) did indeed find evidence of greater improvements in affective state, enjoyment and perceived exertion after green exercise when compared to indoor exercise. Unfortunately, for some people, it is challenging or not feasible to engage in green exercise. The most commonly reported barriers to participation include poor health, lack of time, perceived safety and accessibility (Calogiuri et al., 2016; Calogiuri & Chroni, 2014; Gladwell et al., 2013; Scott & Jackson, 1996; Selby et al., 2019). There is also evidence of high risk of bias and low quality of evidence in green exercise research (Lahart et al., 2019), which signify the need for robust and rigorously designed studies.

Recent advances within virtual reality (VR) have been proposed as a potential solution to the issues of low experimental rigor and barriers to engage in green exercise (Frumkin et al., 2017). Virtual reality is a medium composed of interactive computer simulations that senses the participant's position and actions and replaces or augments the feedback to one or more senses (Sherman & Craig, 2003, *p.*13). This technology may be used to create virtual experiences of natural environments and allow people to engage in virtual green exercise. The usefulness of virtual green exercise relies on in its ability to replicate the previously mentioned psychophysiological health benefits associated with real green exercise. Thus, a potential concern regarding the application of virtual green exercise is that VR technology is known to cause negative side effects in the form of cybersickness (Kennedy et al., 2010). This malaise may limit the ability to replicate the benefits of real nature. Cybersickness is considered a specific type of visually induced motion sickness that causes symptoms such as dizziness, nausea and general discomfort (Kennedy et al., 1993, 2010). Research within virtual green exercise must aim to reduce the impact of cybersickness whilst maximizing the positive effects. In order to succeed, this work should be based on the strengths and weaknesses of VR technology, the mechanisms for beneficial effects of nature exposure and physical exercise, and the success and failures of previous research within virtual green exercise.

1.1 Potential benefits and limitations of VR

VR technology has been accessible for several decades, but despite its great potential, it has not yet made its way into the everyday life of the general population. The fact that VR lacks mass-appeal probably relates to the many known limitations of the technology. To tap into the full potential of VR and create beneficial experiences with virtual green exercise, it will be necessary to overcome these limitations and identify strategies to maximize its potential.

1.1.1 Definitions and brief history of VR

VR can be defined as “A medium composed of interactive computer simulations that senses the participant’s position and actions and replaces or augments the feedback to one or more senses, giving the feeling of being mentally immersed or present in the simulation” (Sherman & Craig, 2003, *p*.13). The basic principle of VR technology is that the sensory information from the display (e.g. the virtual natural environment) completely replaces the sensory information from the actual surroundings (e.g. the lab environment; Slater et al., 1995). The term “VR” is used to refer to a wide range of different technologies and devices, including head mounted displays (HMD) and curved screens (Anthes et al., 2016; Smith, 2015). For the purpose of this thesis, the term will be limited to HMDs that are able to track the movement of a person’s head, allowing 360˚ vision of the virtual environment (Figure 1). Less immersive technology, such as TV screens and projections, will be referred to as “digital technology”.

Figure 1: Examples of head-mounted displays (HMDs) in a sedentary exposure to virtual nature (left) and virtual green exercise (right).

VR technology was first conceptualized more than 50 years ago, and the idea sparked interest from both manufacturers and researchers (Anthes et al., 2016; Cummings & Bailenson, 2016). In turn, this interest led to the development of the first HMD in the 1960s (Anthes et al., 2016). The first HMDs that were developed came with major limitations of hardware and software, which caused issues such as high latencies and low image resolution (Anthes et al., 2016). More issues became apparent as VR technology continued to develop; some of the more well-known issues include visible flickering of the display, the "screen door effect" where gaps between pixels become visible, and high rendering requirements that leads to a forced reduction of the complexity of images (Anthes et al., 2016; Chang et al., 2020). Many of these issues are also known to cause cybersickness as summarized by Chang et al. (2020). After about 20 years of continuous theorizing and development to solve these issues and optimize experiences, the term "virtual reality" was coined in 1989, ushering in a wave of publicity and commercially available VR devices such as Nintendo's Virtual Boy (Anthes et al., 2016; "Virtual Boy," 2021). Despite the initial hype and substantial resources invested in VR at the time, this wave of VR ultimately failed. The failure of VR is illustrated by the Virtual Boy, which became the lowest selling console in Nintendo's history ("Virtual Boy," 2021). The downfall of the first wave of VR was largely attributed to the many unresolved issues with the technology.

Despite the initial failure of VR, a Kickstarter campaign in 2012 for the Occulus Rift initiated a new wave of VR devices followed by the inevitable hype. Some have estimated that the industry will reach 500 million headsets sold by 2025, with sales of VR content generating 5.4

billion USD (Gene et al., n.d.). The newer generation of VR technology had also improved in light of the significant leaps in computer technology, leading to improved image resolution, lighter HMDs, and increased processing power. The technology continued to improve in subsequent years, as stated by Anthes et al. (2016) in their review of VR technology: “When you read this publication, it will most likely be out of date. Current development in Virtual Reality (VR) technology is happening at unprecedented speed.” However, some of the limitations from the previous wave of VR technology remained. The screen door effect and visible flickering was still present, and the content was still limited to rather poor image quality and low levels of complexity, due to issues with computing power (Anthes et al., 2016). Some studies have also shown that these newer displays with higher fidelity may increase the risk of cybersickness (Chang et al., 2020; Sharples et al., 2008; Yildirim, 2020). Thus, encouraged by the potential of the technology, researchers and manufacturers are still looking to optimize VR experiences; but in order to succeed, it will also be necessary to understand its limitations.

1.1.2 Key concepts of VR

Content in VR is generally created using one of two different approaches: recording 360˚ videos or creating 3D models (Joseph et al., 2020). 360˚ videos are considered the least time consuming and allow realistic representations of natural environments to be used in studies of virtual green exercise. The main drawback of these videos is limited interactivity (Joseph et al., 2020). 3D models, on the other hand, allow high levels of interactivity. These models are created using specialized computer programs and game engines. 3D models can achieve high levels of realism, but are time consuming to create and require high-end hardware (Joseph et al., 2020). Regardless of the technique used to create VR content, the keys to unlocking the potential of VR technology are found in the concepts of immersion, presence and cybersickness.

1.1.2.1 Immersion

Immersion is defined as the extent to which a computer-generated environment is “capable of delivering an inclusive, extensive, surrounding, and vivid illusion of reality to the senses of a human participant” (Slater & Wilbur, 1997). Immersion is solely related to technical aspects such as frame rate, field of view and image resolution (Bowman & McMahan, 2007; Cummings & Bailenson, 2016; Slater & Wilbur, 1997), and it is theoretically possible to objectively assess a systems level of immersion. To achieve high levels of immersion, it is generally deemed necessary to enclose the user within the virtual environment and shut out the “real world,” replacing the sensory input from the real surroundings with sensory input from the virtual environment (Slater et al., 1995). This objective is partly achievable by modern HMDs by occupying the user’s full field of view and replacing the vision of the surrounding environment with visual stimuli from the virtual environment. HMDs also replace auditory input from the surrounding environment with soundscapes from the virtual environment. This procedure effectively replaces visual and auditory real-world input with inputs from the virtual environment, but it does not replace input from other senses such as olfactory and proprioceptive inputs. In the context of virtual green exercise, the technology allows for visual representations of natural environments with the associated ambient sound, but not any of the other sensory experiences associated with nature exposure. Despite of these limitations, modern HMDs are highly immersive according to the framework proposed in the meta-analysis by Cummings and Bailenson (2016). In their meta-analysis, the authors highlight the ability to track movements, stereoscopic visuals and a large field of view as key aspects contributing to immersion, all of which are features of high fidelity HMDs.

1.1.2.2 Presence

One of the reasons immersion is considered important is its relationship to *presence* (Cummings & Bailenson, 2016; Figure 2), which is defined as the subjective feeling of “being in the virtual environment” (Slater & Wilbur, 1997). This concept describes the psychological feeling of being mentally transported from the physical location and to the virtual location, ideally to such a degree that the virtual environment feels more real than the actual surroundings. It is believed that higher levels of immersion will increase the likelihood of inducing feelings of presence (Cummings & Bailenson, 2016; Figure 2). This is an important objective of VR technology, as presence relates to the effectiveness of the virtual environment and ultimately the virtual environments ability to fulfill its purpose (Botella et al., 2017; Bowman & McMahan, 2007; Grassini et al., 2020; Slater & Wilbur, 1997; Steuer, 1992; Triberti et al., 2014). Within the field of virtual green exercise, this translates into the ability of the virtual natural environment to elicit the previously mentioned psychophysiological benefits associated with exposure to real nature. However, as presence is a subjective psychological feeling, it logically depends on personality traits (Kober & Neuper, 2013), which complicates the relationship between immersion and presence. In other words, two different people can watch the same virtual environment, using the same technology with a pre-set level of immersion, but still experience different degrees of presence (Sacau et al., 2008; Weech et al., 2019). Thus, the effectiveness of a specific virtual environment, presented with a specific type of technology, may vary from person to person.

1.1.2.3 Cybersickness

The effectiveness of virtual environments does not only rely on increasing positive aspects such as immersion and presence, but also on reducing the impact of negative aspects such as cybersickness. Cybersickness is considered a specific type of visually induced motion sickness (Kennedy et al., 2010) and causes symptoms including dizziness, nausea, fatigue, sweating and general discomfort (Smith, 2015). This malaise has been reported to occur in as many as 100% of research participants depending on the technology used, the duration of immersion and the contents of the virtual environment (Allen et al., 2016; Merhi et al., 2007; Murata, 2004). The discomfort caused by cybersickness will naturally influence the user's experience of a virtual environment (Somrak et al., 2019). Furthermore, previous research reports that cybersickness and presence are inversely related, which suggests that cybersickness may have a negative impact on presence in virtual environments (Weech et al., 2019; Figure 2). The negative impact of cybersickness on virtual experiences is unfortunate, and this issue may become even more prevalent in the coming years as research has shown that visual displays that are considered more immersive are more prone to induce cybersickness (Chang et al., 2020; Guna et al., 2019; LaViola, 2000; Sharples et al., 2008; Yildirim, 2020). This creates a paradox whereby the most immersive displays may provide higher degrees of immersion and presence, even though they may at the same time increase the prevalence and severity of cybersickness. Thus, the challenge of creating effective virtual environments depends on the ability to make use of highly immersive technologies to create content that elicits high levels of presence, while avoiding the issue of cybersickness. Although some have successfully identified strategies to reduce the symptoms of the malaise (Duzmanska et al., 2018; Gavgani et al., 2017; LaViola, 2000), the elusive origin of cyber sickness is still unclear and a final solution does not seem imminent. Improved understanding of cybersickness etiology is an important step towards a final solution; or at the very least, a step towards identifying additional strategies for reducing its impact on virtual experiences and virtual green exercise in particular.

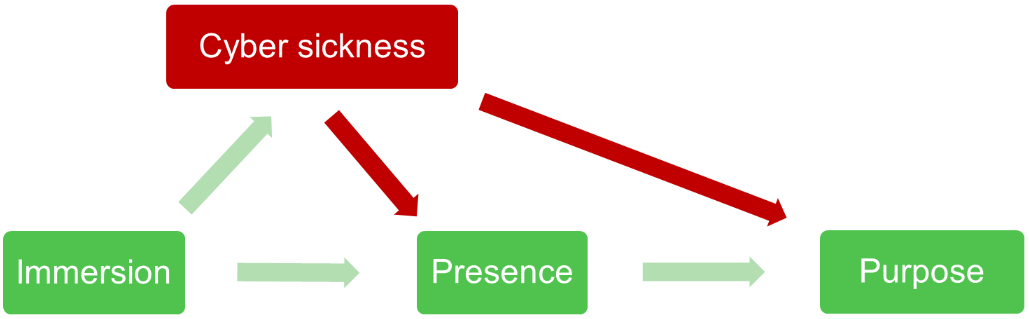


Figure 2: Model depicting how the interaction between immersion, presence, and cybersickness influence the effectiveness of VR. Green boxes indicate desirable effects of VR exposure, while red boxes indicate negative effects of VR exposure. Green arrows indicate an amplifying effect, while red arrows indicate a deteriorating effect.

The etiology of cyber sickness is closely related to the etiology of general motion sickness; however, despite several decades of research, the cause of cybersickness is still unknown. Several theories have been proposed (LaViola, 2000), but two theories are currently dominant in the literature: the sensory conflict theory and the postural instability theory. The sensory conflict theory posits that cyber sickness is caused by a conflict between two or more sensory systems and between experienced and expected stimuli based on past experiences (Oman, 1990; Reason, 1978; Reason & Brand, 1975). In the context of VR, this translates into a mismatch between visual input from the HMD and the input from the real surroundings provided by vestibular and proprioceptive systems. According to the sensory conflict theory, this sensory mismatch causes an increase in cybersickness symptoms. This theory is supported by the fact that patients with a dysfunctional vestibular system are particularly susceptible to cybersickness, due to increased conflict between vestibular and visual input; however, patients with a complete loss of vestibular functioning experience less cybersickness compared to healthy individuals due to a complete lack of conflict between vestibular and visual input (A. C. Paillard et al., 2013). In contrast, the postural instability theory proposes that postural instability is the cause of cybersickness rather than sensory conflict. The theory states that situations leading to motion sickness are characterized by a period where neural patterns of movement control are reorganized to adapt to an unfamiliar stimulus. During this reorganization period, it is suggested that movement control is less efficient, and that postural instability occurs as a result (i.e., reduced ability to maintain a stable upright position). The theory proposes that this instability is a prerequisite for the development of cybersickness, and postulate that cybersickness will only occur in people who experience postural instability

(Riccio & Stoffregen, 1991; Stoffregen et al., 2010). In support of this theory, studies have shown that individuals who exhibit low levels of postural stability are more prone to motion sickness and that manipulation of stance width reduces both postural instability and motion sickness (Stoffregen et al., 2010; Stoffregen & Smart, 1998). The negative impact of sensory conflict and/or postural instability is a concern in all types of VR content, but it is particularly concerning in studies of virtual green exercise as increased sensory conflict and/or postural instability may lead to issues with maintaining upright balance during exercise. There has been considerable research seeking to the identify the specific cause of the malaise based on these theories (Arcioni et al., 2019; Bonato et al., 2009; Chardonnet et al., 2017; Fulvio et al., 2019; Kennedy et al., 2010; Lackner, 2014; LaViola, 2000; Lo & So, 2001; McCauley & Sharkey, 1992; Nishiike et al., 2013; Palmisano et al., 2018; Rebenitsch & Owen, 2016; Riccio & Stoffregen, 1991; Risi & Palmisano, 2019; Weech et al., 2018). The research has produced some interesting and useful results, but the etiology of cybersickness is still unclear.

Even though the cause of cybersickness is debated, researchers have successfully identified several factors that increase or decrease the incidence and severity of the malaise. For example, research regarding personal factors that may influence cybersickness has revealed that people with high anxiety scores are at higher risk of cybersickness (Mittelstaedt, 2020), while an affinity for adrenaline sports (Guna et al., 2019) and habituation to a specific VR experience reduces cybersickness (Gavgani et al., 2017). Content factors also influence cybersickness, and it has been shown that increased exposure duration (Duzmanska et al., 2018), improved visual realism and graphical quality (Pouke et al., 2018), moving dynamic content (Chang et al., 2020), and 360˚ videos when compared to 3D models (Saredakis et al., 2020) all increase and the risk of cybersickness. Hardware is the final category of factors that influence cybersickness, and research within this field report that increased movement lag, latencies, and field of view increase cybersickness (Chang et al., 2020). Saredakis et al. (2020) also confirmed that the fidelity of displays might increase the incidence and severity of cybersickness. In this regard, Chang et al. (2020) have recently proposed their multimodal fidelity hypothesis, which postulates that increased fidelity of displays actually can reduce symptoms of cybersickness if an accompanying range of synchronous multimodal sensory information is provided to the user. In other words, immersive displays may increase cybersickness if they only provide high-fidelity visual input, while cybersickness symptoms may be reduced if the visual stimuli are accompanied by high fidelity input to other senses as well (e.g., auditory and proprioceptive). In support of this idea, Saredakis et al. (2020)

reported lower levels of cybersickness in dynamic VR content when it is combined with actual walking. Nevertheless, despite of the substantial research in the field, both the etiology of cybersickness and the optimal strategy for reducing its impact remain unknown. This complicates the process of developing a virtual green exercise protocol that maximizes the potential of VR technology. Still, the current research provides a solid starting point for further experimentation.

1.2 Health benefits of exercise, nature, and real green exercise

To understand how to optimize the potential health benefits of virtual green exercise, one should look to previous research concerning real nature and exercise to understand why and how these concepts are considered beneficial. The characteristics of both the natural environment and the exercise performed may influence the psychophysiological health benefits.

1.2.1 Health benefits and mechanisms of exercise

As the positive effects of exercise are well known and have been extensively researched (Garber et al., 2011; Warburton et al., 2006), these will only be mentioned briefly in this thesis. Regular exercise is associated with a reduction of mortality risk and prevention of a wide range of associated diseases such as diabetes, cancer and cardiac disease (Garber et al., 2011; Warburton et al., 2006). The health benefits of exercise are mainly associated with a multitude of biological changes that occur during physical activity; this in turn leads to measurable changes in indicators of psychophysiological health such as reduction of stress levels and blood pressure and improvements of affect and well-being (Garber et al., 2011; Warburton et al., 2006). Previous research also shows that many of these effects can occur acutely after a single bout of exercise; for example, blood pressure can be reduced after acute bouts of exercise (Thompson et al., 2001). Interestingly, the intensity required to measure acute changes in beneficial effects of exercise is as little as 40% of maximal oxygen consumption (Thompson et al., 2001), which translates into a brisk walk for the fitness levels of the general population (Ghadieh & Saab, 2015). The American College of Sports Medicine further highlights that the health benefits of exercise can be accumulated in bouts as short as 10 minutes (Garber et al., 2011). These findings suggest that some health benefits of exercise are measurable after a brief bout of low to moderate intensity exercise, such as a 10-minute walk (see e.g. Ekkekakis et al., 2000; Mach et al., 2005). In regard to developing a protocol for virtual green exercise, this means that a 10-minute walk in VR should be sufficient to detect measurable changes in the indicators of psychophysiological benefits of exercise. This is important due to the previously mentioned issues with prolonged VR exposure and cybersickness (Duzmanska et al., 2018).

1.2.2 Health benefits and mechanisms of nature exposure

Many of the beneficial effects of nature exposure are the same as those obtained by exercise. However, the primary pathways that trigger these effects are believed to be different. As with exercise, nature exposure may improve blood pressure, stress levels, affect and well-being (Bowler et al., 2010; Corazon et al., 2019; Frumkin et al., 2017; Haluza et al., 2014; Hunter et al., 2019; McMahan & Estes, 2015; Rogerson et al., 2020; Twohig-Bennett & Jones, 2018). For example, living in neighborhoods with close proximity to natural environments is associated with higher levels of well-being (White et al., 2021); and achieving 120 minutes of weekly nature exposure is associated with improvements of health and well-being similar in scale to achieving the recommended levels of physical activity (White et al., 2019). The precise mechanisms that would explain these positive effects of nature exposure are not fully understood. Research has proposed several pathways, including enhanced immune function, better air quality, increased levels of physical activity, greater social cohesion, and psychological recovery and restoration (Frumkin et al., 2017). In relation to acute bouts of virtual green exercise, most of these pathways can be excluded (e.g. better air quality), and it is likely that any psychophysiological health benefits are caused by psychological recovery and restoration.

The most commonly cited psychological pathways in relation to nature exposure are stress reduction and attention restoration (Frumkin et al., 2017). Ulrich et al. (1991) proposed the stress reduction theory based on the idea that humans have an innate predisposition towards natural environments. Natural environments exhibit qualities that have been essential to human survival, such as trees for shelter and food and water for nourishment. According to Ulrich et al. (1991), humans respond positively with feelings of pleasantness and calm to environments that exhibit these qualities. In turn, this leads to reduced stress levels and improved mood. In accordance with this theory, several studies have shown beneficial effects of nature exposure on stress levels and mood, and it is suggested that these effects occur through activation of the parasympathetic nervous system (Corazon et al., 2019; McMahan & Estes, 2015; Twohig-Bennett & Jones, 2018). The attention restoration theory proposes a slightly different pathway for the beneficial effects of nature exposure (R. Kaplan, 1989; S. Kaplan, 1995). This theory defines two types of attention—directed and involuntary. According to this theory, the directed attention required to perform most tasks of modern life can become depleted, which is a condition known as attention fatigue (Bowler et al., 2010). The theory further posits that attention restoration may occur when humans are exposed to environments that capture our effortless, involuntary, and spontaneous attention. This restoration process is believed to be linked with affect, and when restoration occurs it should be followed by a positive change in affect. Natural environments exhibit four qualities that are considered essential for restoration and replenishment of attention fatigue: fascination, being away, extent and compatibility. Fascination occurs when a person finds the environment intrinsically interesting. Such environments are believed to capture the involuntary attention of a person, thus allowing replenishment of directed attention. Being away refers to the environment's ability to provide a feeling of being psychologically distant from everyday demands and concerns that require directed attention. Extent relates to the elements in an environment and whether they are organized coherently, whether the environment allows exploration, and whether it is large enough to maintain involuntary attention for more than a brief moment. Lastly, compatibility describes whether the environment is compatible with the person's inclinations and interests. These four qualities can occur in all types of environments, but natural environments are believed to possess fascinating qualities that are especially advantageous (Hartig et al., 1991; 2003) such as the clouds moving in the sky and leaves waving in the breeze. In accordance with this theory, previous research has shown that natural environments trigger feelings of restoration and elicit improved performance on attention tasks (Berto, 2005; Hartig et al., 1991). Both the stress reduction theory and the attention restoration theory are psychological in origin, but some have also suggested additional acute benefits of nature exposure through a chemical link between nature and human health (Kuo, 2015). Many plants release biological and chemical agents into the air that are believed to have a positive effect on the human immune system, blood pressure and activity of the autonomic nervous system (Kuo, 2015). It is not feasible to replicate these effects in experiences of virtual nature, thus limiting the potential of virtual green exercise. However, this also makes virtual nature experiences a great tool for studying the psychological mechanism underlying the connection between nature and health, such as stress reduction and attention restoration, without the interfering effects of biological and chemical agents.

1.2.2.1 Optimal qualities of natural environments

Based on the stress reduction theory and the attention restoration theory, many researchers have made assumptions regarding the optimal qualities of a natural environment for inducing psychophysiological benefits, such as trees for shelter or fascinating elements that capture the viewers effortless attention. In this regard, Shanahan et al. (2015) have proposed a framework to estimate the optimal dose of nature exposure. Similar to exercise dose, this framework is based on the principles of intensity and duration. Intensity of nature exposure relates to both the quantity and quality of the nature elements present in a natural environment (Shanahan et al., 2015). Quantity can be understood as the amount of greenery present in the environment. Interestingly, research has shown that there is an upper limit for the optimal amount of greenery and vegetation (Gatersleben & Andrews, 2013; Lindquist et al., 2020; Schebella et al., 2020; Wang et al., 2019). Gatersleben and Andrews (2013) have demonstrated this concept by showing that natural environments with high levels of prospect (i.e., clear field of vision) were indeed restorative, while environments with dense vegetation and high levels of refuge (i.e., places to hide) were not. These reports suggest that there is a u-shaped relationship between the amount of greenery and optimal psychophysiological response to a natural environment. Quality, on the other hand, relates to the type and structure of natural elements in an environment. Research suggests that the type and structure of natural elements may moderate the impact on psychophysiological outcomes. Jiang et al. (2020) showed, in a virtual driving simulator, that trees and shrubs placed at regular intervals along a road had a more positive impact on the drivers metal status compared to irregular placement of greenery (Jiang et al., 2020). Research has also proposed that a feeling of awe or amazement in natural environments may be more beneficial than environments that do not evoke a sense of awe (Frumkin et al., 2017), and that the inclusion of some water elements may be beneficial (Browning et al., 2020a; Wang et al., 2019). Recent research also reports the somewhat paradoxical finding that natural environments should include some built elements, at least for optimal stress reduction (Wang et al., 2019).

Duration of nature exposure is easier to quantify as it describes the time spent in natural environments. Shanahan et al. (2015) highlight that the duration of nature exposure should be measured in a time scale that is relevant for the health response of interest. This thesis is primarily interested in the acute psychophysiological responses to a virtual nature walk. Some studies suggest that these acute effects are measurable after as little as six minutes of nature exposure (Browning et al., 2019), while a recent review of literature suggests a minimum of

10 minutes of exposure may be required (Meredith et al., 2020). Interestingly, 10 minutes should also be sufficient to elicit some of the positive effects of exercise, as previously mentioned.

1.2.3 The green exercise concept

Any type of physical activity performed within, or in proximity to, a natural environment can be considered green exercise (Pretty et al., 2003). This includes a walk in the park, skiing in the mountains and children playing in the forest. Research within this field has demonstrated that green exercise can provide health benefits beyond physical activity indoors and in urban environments. Individual studies have shown that, compared to indoor and urban exercise, green exercise can elicit greater effects in the following areas: (1) indicators of psychophysiological health, including positive affective outcomes (Calogiuri et al., 2015; Focht, 2009; Hartig et al., 2003; Lacharité-Lemieux et al., 2015), enjoyment (Focht, 2009), blood pressure (Pretty et al., 2005), cortisol levels (Harte & Eifert, 1995), depression (Lacharité-Lemieux et al., 2015), and perceived restoration (Kajosaari & Pasanen, 2021); (2) physical engagement including perceived effort (Calogiuri et al., 2015; Harte & Eifert, 1995), and exercise intensity (Mieras et al., 2014); and (3) exercise capacity (Lacharité-Lemieux et al., 2015; Pasek et al., 2020) and physical activity promotion in the form of exercise adherence (Lacharité-Lemieux et al., 2015). Unfortunately, for some people it is challenging or not feasible to engage in green exercise. Millions of people worldwide reside in health care facilities and hospitals with limited opportunities for engaging in real green exercise, or live with disabilities that may limit their ability to travel to natural environments (*AHA*, n.d.; *SSB*, n.d.; Harris-Kojetin et al., 2016; Okoro, 2018). In fact, health issues, limited access to quality natural environments, and time availability are among the commonly reported barriers for green exercise participation (Browning et al., 2020b; Calogiuri et al., 2016; Calogiuri & Chroni, 2014; Scott & Jackson, 1996; Selby et al., 2019). Virtual green exercise may be a valuable supplement to real green exercise for these groups of people, if VR technology is able to replicate the positive effects of real nature.

The additional effects of green exercise are usually embedded in a sound theoretical foundation. For instance, in describing the effects of green exercise, Rogerson et al. (2019) highlight how the restorative qualities of natural environments may reduce the perception of effort during exercise compared to urban environments. Based on previous research, they propose that mental fatigue makes exercise feel more strenuous and impairs exercise performance. The restorative qualities of nature exposure may reduce mental fatigue and, thus, reduce perceived effort during exercise (Rogerson et al., 2019). However, despite the findings of individual studies and the sound theoretical foundation, a systematic review of green exercise research found limited evidence for additional effects of green exercise compared to indoor or urban exercise (Lahart et al., 2019). The review found some evidence of lower perceived effort as well as improved affect and enjoyment compared to indoor exercise, but no other additional psychophysiological benefits (Lahart et al., 2019). The review also highlighted that a high risk of bias and low quality of evidence limited a clear interpretation of the findings (Lahart et al., 2019), which is a recurring theme in reviews of green exercise research (Kotera et al., 2021). Research within the field of green exercise has some inherent limitations that complicates the process of conducting robust and rigorously designed studies, such as standardization of temperature, lighting and weather conditions, and strict control of soundscape and encounters with people, birds, and animals. Due to the limited quality of evidence of additional effects of green exercise, studies of virtual green exercise may be aiming to identify an effect that is weak or does not exist, as outlined below.

The evidence for beneficial health effects of exercise are irrefutable (Garber et al., 2011; Warburton et al., 2006), and there has been an increasing amount of research confirming the beneficial effects of nature exposure in recent years (e.g., White et al., 2019; 2021). The main premise for green exercise is that one may achieve the synergistic effect of both nature and exercise (Gladwell et al., 2013; Rogerson et al., 2019). Whether this synergistic effect is achievable may relate to the pathways by which nature and exercise elicit positive health benefits. The origin of the psychophysiological benefits of nature exposure and exercise are generally considered to be different (i.e., physiological versus psychological), which supports the idea that green exercise provides the effects of both nature exposure and exercise. A quick example to illustrate this concept is the positive effects of exercise on bone mineral density (Garber et al., 2011). Increased bone mineral density does not occur during sedentary nature exposures, and the implications are that this effect will be an additional effect of green exercise compared to sedentary nature exposure. However, the pathways for some of the positive health effects of exercise and nature exposure may interact, which complicates the interpretation that green exercise will provide a synergistic effect. For example, some have noted that exercise may elicit feelings of “being away”, thereby leading to attention restoration (Breitenbecher & Fuegen, 2019) similar to the expected effects of nature exposure. Others have noted that nature exposure may affect the hypothalamic pituitary adrenal axis and regulation of cortisol (White et al., 2018), which is a well-known pathway for the beneficial effects of exercise (Anderson et al., 2019). This raises the question whether green exercise is able to induce an additive effect of nature exposure and exercise on, for instance, cortisol levels and attention restoration. In other words, it is unclear if the effects of green exercise result from the complementary effects of nature exposure and exercise, or if green exercise is capable of magnifying the effects of exercise on outcomes such as cortisol levels and attention restoration. In this regard, some may argue that it is premature to conduct research on virtual green exercise, as the effects of real green exercise are ambiguous. On the other hand, since one of the main limitations of green exercise research is limited experimental rigor, virtual green exercise may be a tool for conducting rigorous research and potentially adding evidence in support of green exercise (Frumkin et al., 2017).

1.3 Virtual nature and virtual green exercise

The basic premise for virtual green exercise is that VR technology is able to replicate some of the health benefits associated with exposure to real nature. Research within this field is relatively scarce, due to the recent inception of the modern wave of HMDs; nevertheless, the results are promising, as outlined below.

1.3.1 Health benefits of virtual nature

There is accumulating evidence demonstrating that sedentary experiences of virtual nature can indeed provide some of the health benefits associated with real nature exposure, at least when using highly immersive HMDs. Previous research has shown that virtual nature can increase positive affect and vigor and reduce negative affect, stress, and anxiety, when compared with other virtual environments (Hedblom et al., 2019; Liszio et al., 2018; Mostajeran et al., 2021; Schebella et al., 2020; Valtchanov et al., 2010; Yu et al., 2018). These results are promising, as they demonstrate positive effects of virtual nature and show that some of the benefits of nature exposure can be obtained without exposure to the chemical agents found in real nature. However, preliminary results already suggest that the lack of exposure to nature’s chemical agents and a general inability to replicate a holistic nature experience may limit the potential of virtual nature. Some studies show that virtual nature does not provide the full range of benefits as real nature does (Browning et al., 2019; Chirico & Gaggioli, 2019). Some researchers also suggest that the positive outcomes of virtual nature exposure are mainly associated with psychological benefits, due to the limited impact on physiological measures such as heart rate and blood pressure (Schebella et al., 2020; Yu et al., 2018). These studies suggest that the concept of virtual nature is somewhat limited, which also limits the potential of virtual green exercise. However, the reports also suggest that there is potential for beneficial psychophysiological outcomes when exposed to virtual nature, and potentially, to virtual green exercise. The higher level of immersion of modern HMDs also suggests that it will be more beneficial than older generation technologies (Figure 3).

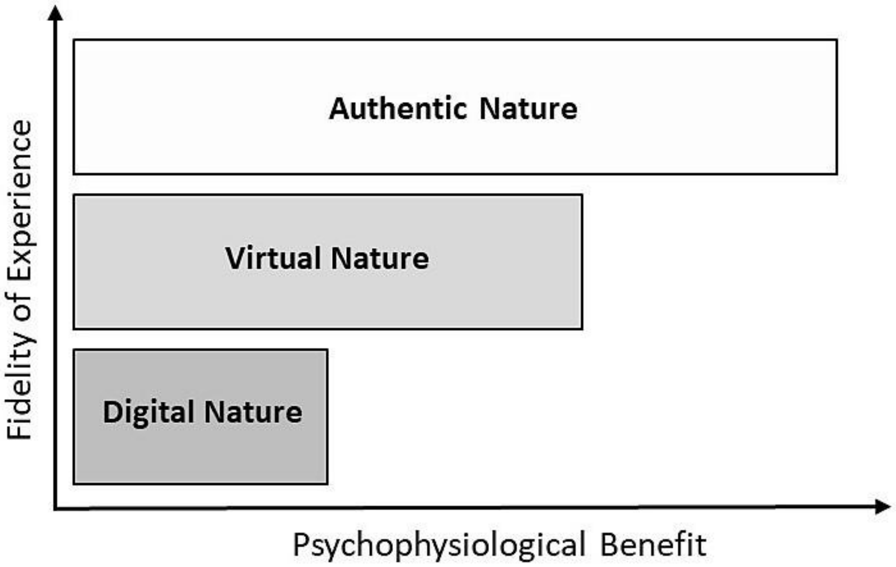


Figure 3: Predicted psychophysiological outcomes of nature experiences at different levels of fidelity. Virtual nature: HMDs that are able to track the movement of a person's head, allowing 360˚ vision of the virtual environment. Digital nature: less immersive technology such as TV screens and projections. From "Enable, Reconnect and Augment: A New ERA of Virtual Nature Research and Application" by S. Litleskare, T. Macintyre, G. Calogiuri, 2020, International Journal of Environmental Research and Public Health, 17(5), *p*. 5. (See appendix).

1.3.2 Virtual green exercise

Based on the previous sections, it is clear that there are some challenges in adopting virtual green exercise within research and health promotion. This may partly explain why there is only two previous study that has been conducted within this field (Alkahtani et al., 2019; Chan et al., 2021). Additional studies have compared digital green exercise to indoor or urban exercise over the last two decades, using widely different technologies. The evidence is still relatively limited, and most studies are based on technology with low levels of immersion.

Studies using digital technology (i.e. TV screens or projections on a flat wall) to present natural environments to participants during exercise have produced inconclusive results. In these studies, digital green exercise has been compared to indoor exercise (Duncan et al., 2014; Pretty et al., 2005; Rogerson & Barton, 2015; White et al., 2015; Wood et al., 2020; Wooller et al., 2018), digital urban exercise (Pretty et al., 2005; White et al., 2015) or exercise while watching self-selected entertainment (Yeh et al., 2017). These studies did indeed demonstrate the potential of digital green exercise by highlighting its restorative potential (Rogerson & Barton, 2015; Wooller et al., 2018). Some of these studies also reported superior effects of digital green exercise on psychological and physiological stress reduction (Duncan et al., 2014; Pretty et al., 2005; White et al., 2015; Wood et al., 2020; Wooller et al., 2018) and mood-related measures (White et al., 2015; Wood et al., 2020; Yeh et al., 2017). One study even revealed increased willingness to repeat the exercise after digital green exercise (White et al., 2015). However, there were also some contradictions, as some of the studies showed no additional effects of digital green exercise on diastolic blood pressure (Duncan et al., 2014), mood (Duncan et al., 2014; Pretty et al., 2005; Yeh et al., 2017), or physical engagement (Duncan et al., 2014; Rogerson & Barton, 2015). In general, the results from studies of digital green exercise are encouraging, but they also demonstrate inconsistent results and limited ability to elicit the full range of benefits associated with real nature. However, these limitations may be due to the low fidelity of the technology used in these studies. In this regard, some studies have attempted similar experiments with more immersive technology. In an early study, Plante et al. (2003) used a HMD with a limited field of view and without head tracking, which are factors that limit the levels of immersion of the HMD (by the definitions used in this thesis, this should be considered digital technology). The study compared psychological benefits across four different conditions: walking outside around campus, walking on a treadmill while watching a video of the same walk around campus in a HMD, walking on a treadmill without HMD and sedentary experience of the virtual walk in a HMD. The results showed indications of improved psychological state in the virtual green exercise condition, but the effects were generally larger in the real green exercise condition. These results were promising based on the limited levels of immersion of the HMD used in this study. Several years later, Alkahtani et al. (2019) conducted the second study using a HMD. This time using a modern HMD with a full field of view and head tracking, which was used to present 360° videos to participants. The study showed no differences in mood between 20 minutes of high-intensity virtual green exercise and indoor exercise. However, this may be due to reports of higher psychological distress in the virtual group (Alkahtani et al., 2019).

Unfortunately, the authors did not include a measure of cybersickness, but the malaise is a potential cause for the distress reported by the participants, especially since the authors reported that participants were allowed to take 30- second breaks to alleviate cybersickness symptoms (Alkahtani et al., 2019). Chan et al. (2021) continued the innovation within virtual green exercise and utilized a “walk in place” system combined with a 3D model of natural environment. The results showed virtual green exercise provided greater psychophysiological benefits when compared to a virtual urban walk, in addition to positive pre-post changes in negative affect. Thus, the two studies that has conducted research on virtual green exercise highlight both the potential and the issues in relation to this technology. The different outcomes of these two studies, and the fact that one study led to negative responses and the other to positive responses, suggest that the methodological and technical approach are key determining factors for the outcome of virtual green exercise. Unfortunately, these two studies alone are not enough to establish best practice, and there is little to gain from studies of digital nature due to inconsistent results.

When looking at previous research comparing digital or virtual green exercise to indoor or urban exercise, it is clear that the data are largely inconclusive. Similar reports are found in studies comparing virtual green exercise to real green exercise. A systematic review reported inconclusive evidence regarding the extent to which digital and virtual green exercise can provide similar psychological and physiological health benefits as real green exercise (Lahart et al., 2019). In this review, some studies were found that showed superior effects of real green exercise, while other studies reported no differences between real and virtual green exercise (Lahart et al., 2019). The discrepancy of findings in previous research of digital and virtual green exercise may be attributed to a number of limitations. For example, the different studies have performed exercise with different intensity and duration, and the natural environments used in the different studies range from university campuses to open natural landscapes. Additionally, most studies have used technology with limited levels of immersion (Duncan et al., 2014; Plante et al., 2003; Pretty et al., 2005; Rogerson & Barton, 2015; White et al., 2015; Wood et al., 2020; Wooller et al., 2018; Yeh et al., 2017); some have manipulated stress and mood levels by using a pre-stressor experience (Wood et al., 2020; Wooller et al., 2018) while the others have not; and some may have experienced issues with cybersickness (Alkahtani et al., 2019). Due to these differences in methodology, it is difficult to pinpoint any indications of best practice for virtual green exercise research. Thus, the methodological approach of the studies in this thesis was guided by a general knowledge of VR technology, exercise, and natural environments. Based on the previous sections, it is clear that experiences of virtual green exercise should aim to optimize immersion while minimizing the impact of cybersickness, and combine this with virtual natural environments that exhibit restorative qualities in experiences lasting 10 minutes or more. In addition to these methodological considerations, there are also some ethical issues that should be considered, such as the dystopian argument outlined below.

1.4 The dystopian argument

The concept of virtual nature and virtual green exercise has been met with some criticism. Early criticism feared that access to virtual representations of nature that are designed as "optimal" nature experiences may come at the cost of a devaluation of real nature and reduced interest in preserving real natural environments (Levi & Kocher, 1999). In this regard, it is important to note that natural environments have an intrinsic value and does not solely exist to serve the human population; nature is worth preserving even if virtual nature could provide the same benefits to human health as real nature. Nevertheless, in a series of studies, Levi and Kocher (1999) actually showed that virtual nature may increase the intention to preserve national parks, but at the cost of intending to preserve local natural environments. These results are in a sense reassuring, as they indicate that virtual nature can generate pro-environmental behaviors, while at the same time raising concerns regarding preservation of local natural areas. Some have taken these concerns one step further and describe a future where virtual nature will function as a replacement for real nature when access to nature becomes severely limited (Kahn et al., 2009). These concerns may seem dystopian, but current world trends are clearly pointing in the direction of a future where visits to natural environments will become a rare commodity for most people. It is estimated that approximately 55% of the world's population currently reside in cities and urban areas. This number is steadily increasing and is expected to reach 68% by 2050 (UN, 2018). Previous research suggests that increasing numbers of people living in the city will lead to more people replacing green exercise with gym exercise (Calogiuri et al., 2016). This trend is believed to accelerate as deforestation and unsustainable land use limits access to quality natural environments, which also leads to a rapid loss of biodiversity (IPBES, 2019). Some studies also indicate that people are becoming less and less connected with the natural world, which is believed to have a negative impact on pro-environmental behaviors and nature preservation (Capaldi et al., 2014; Geng et al., 2015). In the U.S., it is reported that inhabitants spend approximately 93% of their time indoors or in a vehicle (Klepeis et al., 2001), while in the

U.K. less than 40% of people visit natural environments during a regular week (White et al., 2016). Even in rural Norway, only 60% of adults engage in active visits to natural environment on a weekly basis (Calogiuri et al., 2016). These trends are expected to accelerate in the coming generations, as today’s children spend less time in nature compared to previous generations (Balci & Ahi, 2017; Clements, 2004). Virtual nature has not been available for a sufficient amount of time to be a catalyst for these trends; however, technology in general is considered to be part of the problem as research has shown that many replace experiences in nature with increased screen time (Clements, 2004; Larson et al., 2018). Since we already are moving towards a society more or less closed off from real nature, the question is not whether virtual nature will be the cause of a dystopian future for human-nature interactions, but whether it will accelerate this ongoing development. Thus, the urbanization and technological isolation is already here and should be considered additional reasons for the use of virtual nature. Most researchers share this viewpoint and have an optimistic outlook for the future of virtual nature (Browning et al., 2020b; Frumkin et al., 2017; Wang et al., 2019). Virtual nature and virtual green exercise are proposed as valuable supplements to real natural environments (e.g. Browning et al., 2020a; de Kort et al., 2006), and they may even be tools to reconnect people with real nature (Mayer et al., 2009). However, the concerns raised in the research community should not be overlooked as they highlight important ethical considerations within this area of research.

2. Aims

The thesis aims to understand how to maximize the psychophysiological responses of virtual green exercise (e.g., affect, blood pressure) while minimizing negative outcomes (e.g., cybersickness), to elicit positive effects similar to expected effects of real green exercise. Each study informed the design and procedures of the following study, resulting in a successive research path that together addressed the overarching aim of the thesis.

Study 1: The main aim of the study was to investigate the extent to which VR technology could be used to simulate a green exercise experience. The secondary aim was to assess potential benefits and challenges of virtual green exercise compared to a sedentary exposure to virtual nature.

Study 2: The aim of the study was to assess the extent to which improved camera stability in virtual green exercise could reduce cybersickness and improve presence and psychophysiological responses.

Study 3: The aim of the study was to examine whether measures of postural stability could be implemented as a practical tool in studies of virtual green exercise, either as a predictor or an objective measure of cybersickness.

Study 4: The aim of the study was to provide a review of relevant issues associated with VR technology, discuss three major areas of possible applications for virtual green exercise, and propose guidelines for further research based on existing evidence.

Study 5: The main aim of the study was to compare the positive and negative outcomes of virtual green exercise using two different techniques: 360˚ video and 3D model. The secondary aim was to assess the extent to which virtual green exercise could provide additional psychophysiological benefits compared to indoor exercise.

3. Methods

Four experimental studies (Studies 1, 2, 3 and 5) and one narrative review (Study 4) were conducted. The findings in each study guided the design and procedures of the next study in the sequence. This continuous developmental process implemented a combination of crossover and parallel group experimental designs, employing both quantitative- and mixed-methods. All experimental procedures were performed according to the Declaration of Helsinki. Study 5 was approved by the Regional Ethics Committee , while Studies 1-3 did not require ethical approval and were registered by the Norwegian Centre for research data. Detailed information regarding the individual studies are provided in the primary publications.

3.1 Recruitment and participants

Participants were recruited via announcements on Facebook, the university's official webpage, and by word of mouth. The majority of participants were students and non-scientific employees at the Faculty of Health and Social Sciences at the Inland Norway University of Applied Sciences, but the sample also included some participants with no connections to the university. In Study 1, participants were required to be between 20-45 years old, being able to walk for 10 minutes outdoors, and not being an elite athlete. For Studies 2, 3, and 5, all participants were required to be 18 years or older, have normal or corrected to normal sight, and without any diagnosis of balance impairments. In total, 136 people volunteered and participated in the studies. The gender distribution was balanced with 68 males and 68 females. The majority of participants were young, healthy, and active individuals. The participants were informed of associated benefits and risks before they gave their written consent to participate. The immediate health risk of participation in the individual studies was considered minimal as cybersickness represented the main risk in all experimental studies. The effects of cybersickness are uncomfortable but temporary, and participants were allowed to discontinue at any time.

3.2 Experimental environment and VR technology

Four different iterations of a virtual natural environment were used in the different experimental studies. The first version (v1) of the natural environment was used in study 1, the second version (v2) was used in Studies 2 and 3 alongside a slightly modified version of v1, and the third (v3) and fourth (v4) versions were used in study 5 (Table 1). All four versions replicated the same natural environment, and the real version of this environment was used in Study 1 alongside the virtual version (Table 3). Participants experienced a first-person view of this environment in all virtual conditions (Figure 4). The environment was a rather open urban green area with a walking path alongside the river Glomma in Elverum, Norway. In addition to the river, the environment consisted of other natural elements such as grass, trees and shrub, and also some built elements such as football fields and buildings (Figure 4). Thus, this environment was an approximation of the somewhat limited recommendations regarding natural environments outlined in the introduction; however it may be limited in its ability to elicit feelings of awe and amazement (section 1.2.2.1). All four versions consisted of dynamic content where participants would experience a first-person walk back and forth along the path. The path that was used for this purpose was fairly straight so as to limit the issue of cybersickness (Saredakis et al., 2020). The exposure duration in all studies lasted approximately 10 minutes, in line with the recommendations for both exercise dose, nature dose, and cybersickness, as outlined in the introduction (sections 1.1.2.3, 1.2.1, and 1.2.2). All indoor experimental conditions and assessments were performed at the Sport Physiology Laboratory of Inland Norway University of Applied Sciences (Campus Elverum), with standardized temperature, ventilation, and lighting, and a high degree of sound insulation.

Figure 4: The natural environment used in all experimental studies. The image on the top represents a first-person view, similar to what participants would experience in the different studies.

The 360˚ videos used for v1, v2, and v3 were developed in a similar manner using technology with different levels of fidelity. In v1, a Samsung gear 360 SM-c200 camera (3840 x 1920 resolution, 30 frames per second) was mounted on a modified mechanical Yelangu s60t handheld stabilizer. The camera operator walked along the path holding the mechanical camera stabilizer. This stabilizer reduced the amplitude and speed of camera movements, but movements due to the locomotion of the camera operator were still apparent. The approach of v2 iterated this concept by implementing an electronic stabilizer (Feiyu Tech G360). This stabilizer minimizes any camera movement due to the locomotion of the camera operator, by keeping the camera focused on a specific spot in the distance. The camera operator was also pushed along the path on a dolly to further reduce camera movements. The recording for v3 was made with a GoPro Fusion 360˚ camera with improved image resolution (5228 x 2624 resolution, 30 frames per second) and a built-in stabilizer that functions similar to the electronic stabilizer used for v2. The camera operator moved along the path on a hoverboard to further minimize camera movements. The creation of v4 applied a largely different approach as it was based on a 3D model. The 3D model was created using photogrammetry techniques and assembled for real-time playback in Unreal Engine 4.22 (Epic Games, Cary, North Carolina, USA). The basis for the creation of the 3D model was obtained from hoydedata.no (topology and elevation) and aerial drone scans of the area. Objects, trees, and vegetation were added using different types of software as described in Study 5. During the playback of v3 and v4, the movement speed in the virtual environment was matched with the movement speed of the treadmill using an USB output. Both v3 and v4 required considerable computing power, so a high-end computer was needed to handle the virtual environments. This led to the decision to exclude some objects in the environment in v4, such as some buildings in the distance and shrub by the river as shown in Figure 5. An overview of the technology used to develop the virtual environments are presented in Table 1.

Figure 5: Snapshot from the 360˚ video (left) and the 3D model (right) used in Study 5.

Table 1: Details of the techniques and technology used to develop the virtual natural environments in the different experimental studies.

Study	**Version**	**Development of the IVN**	**Soundscape**	**Playback**
Study 1	v1 - 360˚ video	Samsung gear 360 sm-c200 camera mounted on a modified Yelangu s60t handheld stabilizer. Post-production editing done in Adobe After Effects CC 2017, Warp Stabilizer VFX, and in Samsung Gear 360 ActionDirector.	Audio recorded simultaneously by the camera's microphone.	Samsung S7 with Android 7.0 mounted on a Samsung Gear VR mask with Sennheiser HD 201 headset.
Study 2 & 3	v1 (modified) - 360˚ video	Low stability video: Same video as in Study 1, but the video faded in and out when the camera operator turned around to walk back at the end of the stretch, instead of showing the actual turn.	Audio recorded simultaneously by the camera's microphone	Samsung S7, with Android 7.0, mounted on a Samsung Gear VR mask with Sennheiser HD 201 headset.
	v2 - 360˚ video	High stability video: Samsung gear 360 sm-c200 camera mounted on a Guru 360 camera stabilizer, with the camera operator standing on a dolly pushed by an assistant.		
Study 5	v3 - 360˚ video	GoPro Fusion with a built-in stabilizer and the camera operator standing on a hoverboard. The video was edited in GoPro Fusion Studio to apply the Full Stabilization filter. The edited video was imported to Adobe Premiere Pro to adjust the colors to a realistic look.	Audio recorded using a surround microphone with four channels	HTC Vive Pro HMD (field of view of 110˚; resolution of 2880 x 1600; refresh rate of 90 Hz) connected to a computer (Intel(R) i7-8700k processor, 16 gigabytes of RAM, NVIDIA Gforce RTX 2080 graphics card), and Sony WH-1000X M3 noise cancelling headphones.
	v4 - 3D model	3D reconstruction of the natural environment using a terrain model obtained from hoydedata.no and drone scans in 4K resolution.		

v1, v2, v3 and v4 represent different versions of virtual natural environments reproducing the same real environment (see section 3.2).

3.3 Measurements

Some measures were used across all experimental studies, while others were implemented in specific studies to obtain necessary data for that specific study. An overview of the different measures included in the different studies is given in Table 3.

Participants' background characteristics. Information regarding the participants' sex, age, body mass index (BMI), and physical activity habits were collected in Studies 1, 2, 3 and 5 and were used to describe the participants' health status and levels of physical activity. In Study 5, an additional measure of nature connectedness was included to indicate the participants' inclinations towards nature. Bodyweight was measured using the Seca 877 (SECA GmbH, Hamburg, Germany) and was used alongside measurements of height to calculate BMI by the following equation: kg/m^2. The participant's levels of physical activity were assessed using a version of the leisure time exercise questionnaire (Godin & Shephard, 1985) modified to include transportation physical activity (i.e., walking or biking as a means of transportation). This adjusted version of the questionnaire has been validated and compared to objective assessments of physical activity (Calogiuri et al., 2013). The participants' baseline level of nature connectedness was assessed by a version of the connectedness to nature scale modified to measure state connectedness (Mayer et al., 2009).

Cybersickness (Studies 1, 2, 3 and 5). The simulator sickness questionnaire was used to assess the severity of cybersickness symptoms (Kennedy et al., 1993). The questionnaire was developed to assess simulator sickness, but has been used extensively in studies of cybersickness as well (Chang et al., 2020). Participants were asked to rank the severity of 16 different symptoms on a 4-point Likert scale (e.g., nausea, dizziness, eyestrain, and sweating). The total score of these symptoms was calculated according to the recommendations of Kennedy et al. (1993). The original cut-off scores for the simulator sickness questionnaire were based on data from military pilots and suggest that scores between 10 and 15 indicate significant symptoms; scores between 15 and 20 are considered a concern, and scores above 20 indicate a problem simulator (Kennedy et al., 2003). Study 1 implemented a single item to assess the severity of cybersickness instead of the simulator sickness questionnaire. In this item, participants rated their response to the following statement on an 11-point Likert scale: "I got dizzy during the virtual walk."

Presence (Studies 1, 2 and 5). The assessment of the participants' sense of presence was based on the approach of Nichols et al. (Nichols et al., 2000). The participants were asked to rate the level of agreement to eight statements related to presence in virtual environments using an 11-point Likert scale. All eight items are explained in Table 2 as they do not combine into a common concept or construct.

Table 2. Items used to assess presence. Adapted from "Camera Stabilization in 360° Videos and Its Impact on Cyber Sickness, Environmental Perceptions, and Psychophysiological Responses to a Simulated Nature Walk: A Single-Blinded Randomized Trial" by S. Litleskare, G. Calogiuri, 2019, Frontiers in Psychology, 10, 2436. (See appendix).

Short name	**Item**
Being there	In the computer-generated world I had the sense of 'being there'.
Realism	I thought of the virtual environment as equal to the real environment.
Sense of reality	The virtual world became more real or present to me compared to the real world. NB: by 'real world' we mean the room where you were undergoing the test.
Awareness	During the 'virtual walk', I often thought of the other person(s) in the room with me.
Other persons	It would have been more enjoyable to engage with the 'virtual world' with no-one else in the room.
External noises	Whilst I was doing the 'virtual walk', I paid much attention to other noises around me in the room.
Flatness	The virtual world appeared flat and missing in depth.
Movement lag	The lag, delay or difference between my movements and the movements in the 'virtual walk' were disturbing.

Perceived environmental restorativeness (Studies 1, 2 and 5). The restorative potential of both the real and virtual environments were assessed using the perceived restorativeness scale (Hartig et al., 1997, 2003). This scale was used as an indicator of the virtual environment's potential to elicit cognitive restoration and consists of 16 items rated on an 11-point Likert scale. The 16 items correspond to the subjective perception of the four environmental qualities of the attention restoration theory, as outlined in the introduction — namely, fascination, being away, coherence (extent) and compatibility (R. Kaplan, 1989; S. Kaplan, 1995).

Affective responses (Studies 1, 2 and 5). Participants' affective responses was assessed by the physical activity affect scale (Lox et al., 2000). The scale consists of 12 items (e.g., "enthusiastic," "relaxed," "discouraged," and "fatigued") that are grouped in four components in accordance with Russell's circumplex model of affect (Russell, 1980): Positive affect (positive valence, high activation), tranquility (positive valence, low activation), negative affect (negative valence, high activation), and fatigue (negative valence, low activation). Affect is a commonly used measure in studies investigating the psychophysiological health benefits of nature exposure and green exercise (Browning et al., 2020b; Calogiuri & Chroni, 2014; Lahart et al., 2019).

Enjoyment (Studies 1, 2 and 5). The participants' level of enjoyment during each experimental condition was assessed using the following inquiry: "On a scale from 1 to 10, how enjoyable was the activity you engaged in?" The level of enjoyment during an exercise session is considered a strong motive for future exercise participation (Dishman et al., 1985)—also in the context of green exercise (Calogiuri & Chroni, 2014) —making it an important element to consider for promotion of physical activity and health.

Walking speed (Study 1 and 5). The walking speed was recorded during the full duration of the treadmill conditions in Studies 1 and 5 by the built-in treadmill computer. The walking speed in the outdoors condition in Study 1 was obtained using a wristwatch with a built-in GPS (Garmin Forerunner 310XT, Garmin International Inc. Olathe, Kansas, USA). The average walking speed was used for further analysis.

Heart rate (Studies 1, 2 and 5). Heart rate was recorded continuously during all conditions in Studies 1, 2, and 5 using a heart rate monitor (Garmin Forerunner 310XT, Garmin International Inc. Olathe, Kansas, USA) and extracted as beats per minute to be used as a measure of relative exercise intensity. The mean heart rate was automatically recorded by the heart rate monitor and used for further analyses.

Perceived exertion (Study 1 and 5). Participants reported their rating of perceived exertion after all conditions in Studies 1 and 5 using the 15-point version of the Borg scale (Borg, 1982) with verbal cues (Norwegian version: Hagströmer & Hassmén, 2009). The scale consists of values ranging from 6-20 with a corresponding description of the level of exertion (e.g., 11 = fairly light).

Blood pressure (Study 5). A semi-automatic blood pressure kit (The Watch BP Office Target, Microlife, Taipei, Taiwan) was used to measure blood pressure in Study 5. Blood pressure was measured in seated position after at least five minutes of sedentary time. Measures of blood pressure were implemented as an indicator of stress, which naturally align with the stress recovery theory (Ulrich et al., 1991).

Postural stability (Study 3). The participants' level of postural stability was assessed using a force platform (FP 4, Hur labs Oy, Tampere, Finland) and the associated software (HUR Labs Force Platform Software Suite) in Study 3. Postural stability was assessed over a 60-second period and participants were asked to stand still with hands hanging effortlessly at their sides during the full 60 seconds (Horlings et al., 2009). All trials were supervised to ensure that no unnecessary movements other than those required to maintain balance occurred. Total trace length (mm) and standard deviation velocity (mm/s) of the center of pressure during the 60-second measuring periods were used for further analysis, as research has shown that these measures are reliable measures of postural stability (T. Paillard & Noe, 2015). Total trace length represents the total distance traveled by the center of gravity, while standard deviation velocity represents the velocity of corrective postural actions.

Qualitative information (Studies 1 and 5). With the purpose of gaining further insight into the quantitative findings, a series of open-ended questions were presented to the participants in Studies 1 and 5. These questions were administered to gain a more in-depth understanding of the participants' perceptions and experiences. This was important to understand the quantitative outcomes and how to improve the concept of virtual green exercise, as the qualitative accounts could provide additional information that was not captured by the quantitative assessments and the statistical analysis. The open-ended questions were administered at the end of the experimentations after the quantitative questionnaires had been responded to. Participants responded in form of written essays, and the questions followed the structure of the quantitative assessments. Each question corresponded to the main quantitative variables in Studies 1 and 5, respectively. For example, "When you answered the question about how enjoyable the activity was, what determined where in the scale you put your mark?"

3.4 Design and procedures

The design of the individual studies was chosen in order to fit the research question of the specific study. An overview of the experimental conditions is given in Table 3.

3.4.1 Study 1

The study applied a mixed-methods approach designed as a randomized crossover trial with three conditions: a walk outdoors in the real natural environment (Figure 4), a sedentary exposure to a 360˚ video of the same natural environment (v1; Table 1), and a walk on a manually driven treadmill while being exposed to the same 360˚ video (v1; Table 1). The sample size was based on the sample sizes in similar studies and practical considerations in relation to the outdoor condition. The sample consisted of 26 healthy adults: 14 males and 12 females with a mean ± SD age of 26 ± 8 years, a mean BMI of 23 ± 5 kg/m^2, and a mean weekly physical activity level corresponding to 45 ± 22 METs. All participants started with the outdoor condition, thus avoiding confounding effects due to some participants being familiarized with the place during the virtual condition while others were not. Participants were then randomly allocated (by coin flip) to start with either one of the two virtual conditions; they were not informed about the order of treatments until the beginning of the trial. A wash-out period of 15 to 30 minutes was provided between each condition. Assessments were administered before and after performing the individual conditions.

3.4.2 Study 2

The study applied a quantitative approach designed as a single-blinded randomized trial with two parallel groups to limit carry-over and expectancy effects. Estimation of required sample size was based on cybersickness scores from a preliminary pilot study done in our laboratory. Based on a between-group difference in total cybersickness of 20 (as measured by the simulator sickness questionnaire), a pooled standard deviation of 30, an α-level of 0.05, and desired power of 80%, a sample size of 50 was deemed appropriate. The final sample of the study included 22 males and 28 females with a mean ± SD age of 30 ± 11 years, BMI of 25 ± 3 kg/m^2, and a mean weekly physical activity level corresponding to 57 ± 24 METs. Participants watched one of two different 360˚ videos. The two 360˚ videos differed only in the extent to which they contained scene oscillations. One video was a slightly edited version of the video used in Study 1 (Table 1), while the other was recorded with improved equipment for stabilization of the video recording (v2; Table 1). All participants were blinded to which condition they were allocated to and were unaware of the difference between the two conditions. The randomization was performed following a pre-established order and was stratified by gender to achieve a balanced distribution of males and females in each group, due to potential gender differences in cybersickness (Munafo et al., 2017). Assessments were administered before and after performing the assigned condition.

3.4.3 Study 3

The aim of the study was to examine whether measures of postural stability could be implemented as a practical tool in studies of virtual green exercise as either a predictor or an objective measure of cybersickness. A reliable predictor for cybersickness would be useful for excluding participants from future studies if the aim was to assess the effectiveness of virtual green exercise without the interference of cybersickness, or to include particularly prone participants if the aim is to identify strategies to alleviate the issue. On the other hand, an objective measure of cybersickness would be useful to avoid the limitations of self-reporting. Study 3 applied a quantitative approach based on the same sample and experimental conditions as Study 2, but all participants were pooled across the two experimental conditions and were additionally assessed for postural stability. Postural stability was measured with eyes open, with eyes closed, during the first minute of VR exposure in a standing position while wearing the HMD and watching the 360˚ video, after eight more minutes of sedentary VR exposure (also in a standing position while wearing the HMD and watching the 360˚ video), and a final measurement with eyes open before leaving the laboratory.

3.4.4 Study 4

Study 4 comprised a narrative approach, where relevant issues, areas of application, and guidelines for further research were identified by a review of literature across different disciplines, with a particular emphasis on recent research applying VR technology. Several studies applying this technology were published after or during the data collections in Studies 1, 2 and 3, and the findings provided crucial input to expand on the approach from these studies in order to optimize the experimental approach in Study 5.

3.4.5 Study 5

Study 5 applied both quantitative and qualitative methods and was designed as a blinded randomized trial with three parallel groups to limit carry-over and expectancy effects. The sample size calculation was based on negative affect, due to previous research showing that negative affect is a sensitive measure of the effects after exposure to virtual nature (Yeo et al., 2020). The expected effect size for between conditions differences for negative affect was set as a generic medium ($f = 0.25$), as previous research suggests that the typical effect of real green exercise on negative affect is equivalent to a medium effect size or larger (Lahart et al., 2019). Alpha was set to 0.05 and power was set to 90%, which suggested that a sample size of

54 participants would be adequate. Six additional participants were recruited to account for possible missing data. The sample of the study included 32 males and 28 females with a mean ± SD age of 30 ± 12 years, a mean BMI of 25 ± 3 kg/m^2, a mean weekly physical activity level corresponding to 57 ± 25 METs, and a connectedness to nature score of 4.0 ± 0.7. Participants performed a treadmill walk while watching the natural environment in the form of either a 360˚ video (v3; Table 1) or a 3D model (v4; Table 1), or while facing a blank wall (control). The participants walked at a self-selected speed, and the speed of the playback was matched with the speed of the treadmill. Before undergoing the experimental conditions, all participants were subjected to a 2’50’’ film clip designed to elicit feelings of sadness (Rottenberg et al., 2007). The quantitative assessments were performed at baseline, after the sad film clip, and after exposure to the assigned experimental condition. The open-ended questions were administered in the two virtual conditions after completing all quantitative assessments. The randomization (pick from a hat) was performed after completion of the assessments that were administered after watching the sad film clip.

Table 3: Overview of experimental conditions and outcomes in the different experimental studies.

Study	VR version	Experimental conditions	Activity level	Outcomes
Study 1	n/a	A walk in the actual natural environment	10 minutes of light intensity activity	Cybersickness, presence, perceived environmental restorativeness, affect, enjoyment, walking speed, rating of perceived exertion, heart rate, qualitative.
	v1	Exposure to a 360˚ video while sitting on a chair	Sedentary	
	v1	Exposure to a 360˚ video while walking on a manually driven treadmill at self-selected speed	10 minutes of light intensity activity	
Study 2	v1 (modified)	360˚ video containing oscillations on the horizontal and vertical axis (e.g., due to camera operator locomotion).	Sedentary	Cybersickness, presence, perceived environmental restorativeness, affect, enjoyment, heart rate.
	v2	360˚ video containing almost no oscillations, due to the use of an electronic stabilizer and a dolly.	Sedentary	
Study 3	Same as study 2	Same as study 2	Same as study 2	Cybersickness, postural stability.
Study 5	v3	Exposure to a 360° video while walking on a manually driven treadmill at self-selected speed. The speed of the virtual walk was synchronized with the treadmill speed.	10 minutes of light intensity activity	Cybersickness, presence, perceived environmental restorativeness, affect, enjoyment, walking speed, rating of perceived exertion, heart rate, blood pressure, qualitative.
	v4	Exposure to a 3D model while walking on a manually driven treadmill at self-selected speed. The speed of the virtual walk was synchronized with the treadmill speed.	10 minutes of light intensity activity	
	n/a	Walk on a treadmill while facing a blank wall, at self-selected speed.	10 minutes of light intensity activity	

3.5 Analysis

The statistical approach was adapted to suit the need of the individual studies. These adaptations were made based on the following approach. Parametric statistics were applied in studies assessing differences between more than two conditions (Studies 1 and 5), due to their additional functionality when assessing differences between more than two conditions, even though most measures in this thesis produced non-parametric data (Norman, 2010). Non-parametric statistics were applied in studies assessing differences between two conditions (Studies 2 and 3). All correlations were performed using the Spearman's rank correlation coefficient (r_s).

In Studies 1 and 5, one-way ANOVA, mixed ANOVA, and ANCOVA were applied when assessing differences between more than two conditions. All post-hoc analyses were performed applying a Bonferroni's correction of alpha. Student's t-test was applied in Study 5 when assessing difference between two virtual conditions. The Mann-Whitney U-test was applied in Studies 2 and 3 for assessments of potential differences between two groups, and a Wilcoxon signed-rank test was applied to assess pre-post changes. The statistical approach in each study was in accordance with the strategy set prior to the experiments. The level of significance was set at $p < 0.05$, and the statistical analyses were performed in SPSS (IBM Corp., New York, USA). The quantitative results in this thesis are presented as mean ± standard deviation (SD) for parametric variables, and median and interquartile range (IQR) for ordinal variables.

The qualitative data in Study 1 and 5 were analyzed in accordance with thematic approaches. This allowed the capture of possible themes to gain a more nuanced understanding of the quantitative findings. In order to facilitate the integration of the quantitative and qualitative findings, the questions were developed and analyzed based on the overarching themes of the quantitative assessments. The questions were developed such that the participants could elaborate further on the responses provided in the quantitative questionnaire and were phrased to allow for negative, positive as well as neutral viewpoints.

4. Results and discussion

The results of the individual studies will be described within the context of the developmental process and discussed across studies. Some comparisons will be made between studies, although direct comparisons between studies should be interpreted carefully due to differences in study design, research participants, methodology, and so forth.

4.1. Factors influencing the VR experience

4.1.1 Cybersickness (Studies 1-5)

The level of cybersickness was assessed by the simulator sickness questionnaire in Studies 2, 3, and 5. These results are summarized in Figure 6. In study 1, cybersickness was assessed by a single-item Likert scale. Based on this single-item and the qualitative reports in Study 1, it was clear that cybersickness disrupted the participants' experience. On a scale from 1-10, the median (IQR) level of cybersickness was 8.5 (4-10) in the seated condition and 7.5 (6-9) in the treadmill condition. These numbers were accompanied by concerning qualitative reports such as "It made me dizzy and sick" (Female, 42 years). Cybersickness was also correlated with several outcomes, including negative affective responses ($r_s = 0.43\text{-}0.77$, $p < 0.05$), positive affective responses ($r_s = -0.52\text{--}0.73$, $p < 0.01$), enjoyment ($r_s = -0.52\text{--}0.79$, $p < 0.01$) and rating of perceived exertion ($r_s = 0.41$, $p < 0.05$), which suggest that cybersickness may have masked potential positive effects of VR on these measures in Study 1. Because of these concerning outcomes, cybersickness was made the top priority in the process of developing a functional virtual green exercise protocol. The qualitative analysis and the correlation analysis from Study 1 identified two prominent factors leading to high levels of cybersickness, namely flatness (i.e., poor image quality) and movement lag (i.e., when movements in the virtual environment does not match the real-world movements of the participant). The issues related to flatness were believed to diminish as higher fidelity displays and 360° cameras eventually would become available. Movement lag, on the other hand, could be caused by several factors, including latency issues, the stability of the video recording, and a mismatch between the walking speed of the participant and the movement speed in the virtual environment. In this regard, previous provocation studies of computer-generated VR environments with severe levels of oscillations have found that scene oscillations increase cybersickness symptoms (Bonato et al., 2009; Lo & So, 2001). These reports alongside the results in Study 1 identified scene stability as a crucial and feasible factor to improve. Coincidentally, a new electronic stabilizer was released onto the market in the time window between Study 1 and 2. Thus, Study 2 compared the effect of a 360˚ video (v2) recorded with the new stabilizer to a slightly modified version of the 360˚ video (v1) used in Study 1. Study 2 confirmed the assumption that improving scene stability would reduce cybersickness (Bonato et al., 2009; Lo & So, 2001) and showed a significant reduction ($p = 0.009$) of the median (IQR) levels of cybersickness scores from 33.7 (1.87-35.53) in v1 (modified) to 18.7 in v2 (14.96-99.11).

Study 3 was primarily concerned with widening the current understanding of cybersickness etiology, and specifically to establish whether measurements of postural stability could be used as a practical tool in the process of developing a virtual green exercise protocol. Theoretically, measures of postural stability could be used either as a predictor or objective measure of cybersickness, and either outcome would be useful to the developmental process (refer to Study 3 for the theoretical framework). Measurements of postural stability did indeed emerge as a potential predictor of cybersickness. Participants who later reported cybersickness exhibited significantly higher levels of postural instability during the first minute of VR exposure compared to those who did not report cybersickness. Specifically, the median (IQR) trace length was significantly higher ($p = 0.017$) in participants who reported cybersickness; 844.7 (451.6-1312.7), compared to participants that did not report sickness; 405.0 (230.4-636.3). Standard deviation velocity was also significantly higher ($p = 0.008$) in cybersick participants; 7.7 (4.0-12.5), compared to participants who did not report sickness; 3.2 (2.1-6.3). However, the interquartile ranges and the range of individual values indicated a substantial overlap between sick and well participants; the results also indicated that some participants experienced cybersickness without postural instability. Thus, the practical application of these measures as predictor was limited as participants could not be categorized as susceptible to cybersickness based on postural stability alone. The findings regarding measures of postural stability as an objective measure of cybersickness followed a similar trend. The correlation between trace length and total scores on the simulator sickness questionnaire emerged as a possible objective measure as the correlation was significant ($p = 0.027$); but the strength of the association was limited ($r_s = 0.32$). The combination of these inconclusive results, and the fact that improving scene stability had solved a major part of the issues with cybersickness, led to the decision to not conduct any further research of the association between postural stability and cybersickness.

Study 4 was used to identify additional factors and procedures that could help alleviate cybersickness to optimize the outcomes of virtual green exercise for Study 5. In particular, Study 4 highlighted issues related to movement lag and suggested that the movement speed in the virtual environment should be synchronized with the treadmill speed. Study 4 further highlighted the important balancing act of achieving high levels of image resolution and sharpness while keeping frame rate and latencies at acceptable levels. The study also identified the potential of using 3D models to represent natural environments in virtual green exercise research. These considerations were implemented in Study 5, which featured a new HMD with improved resolution and image quality, a new 360˚ camera with a built-in electronic stabilizer and higher resolution, and a HMD that was connected to the treadmill to allow the participant's walking speed to determine the speed of the playback. Study 5 also implemented a 3D model, of the same natural environment, in addition to a 360˚ video (Tables 1 and 3). The visual fidelity of the 3D model was balanced to achieve an optimal tradeoff between realism and performance in order to minimize cybersickness symptoms. The results of Study 5 revealed relatively low levels of cybersickness with a median (IQR) score on the simulator sickness questionnaire of 24.3 (16.4-33.7) in the 360˚ video, 15.0 (11.2-31.8) in the 3D model (Figure 6) and 11.2 (3.74-18.7) in the control group walking on the treadmill without VR exposure. There were no significant differences between the three conditions (p = 0.174), suggesting that the levels of cybersickness symptoms among those who were exposed to VR were not different from those who were not exposed to VR. However, the qualitative reports indicated somewhat more pronounced cybersickness in the 360˚ video compared to the 3D model, as noted in the following statement: "[I felt] a little uncomfortable… was a bit dazed and a bit dizzy during the walk and the last minutes I was just looking forward to be finished." (Woman, 26 years, 360˚ video, v3)

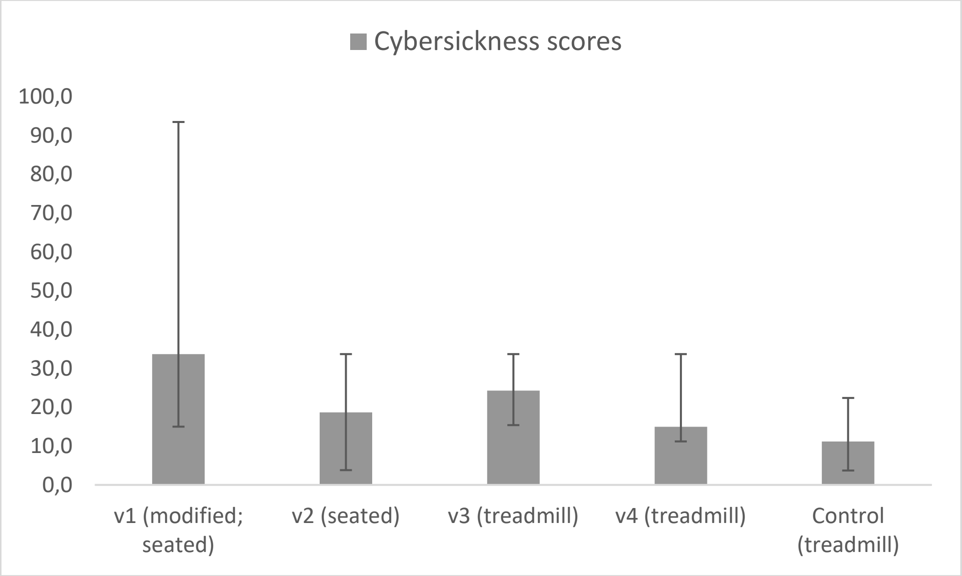


Figure 6: Scores on the simulator questionnaire across all experimental conditions that included this measure (median and interquartile range).

The reports from Studies 1-5 show that cybersickness is a concern in virtual green exercise, and that there was considerable individual variation in the severity of cybersickness symptoms (Figure 6); in particular, v1 that provoked severe symptoms in several participants. Cybersickness is a common finding in VR studies (e.g. B. Allen et al., 2016; Merhi et al., 2007; Murata, 2004), and is commonly attributed to either sensory conflict or postural instability (Oman, 1990; Reason, 1978; Reason & Brand, 1975; Riccio & Stoffregen, 1991; Stoffregen et al., 2010; Stoffregen & Smart, 1998). No definite statement can be made regarding the cause of cybersickness in the experimental studies of this thesis. However, Study 3 found that some participants experienced cybersickness without postural instability, which is a direct contradiction of the postural instability theory (Riccio & Stoffregen, 1991; Stoffregen et al., 2010), suggesting that sensory conflict is a more likely cause of cybersickness in these participants. The findings in Study 2, in which improved scene stability reduces cybersickness, also align with the sensory conflict theory, as improved scene stability would reduce the sensory conflict between visual and vestibular organs. This argument also applies to the findings in Study 4 regarding the importance of synchronized sensory input and minimizing latency issues, both of which would reduce sensory conflict between different sensory systems. However, there was no apparent reduction of cybersickness symptoms from v2 to v3 and v4, even though the movement speed in the virtual environment was matched with the speed of the treadmill to synchronize sensory input and reduce sensory conflict, which should reduce cybersickness according to both the sensory conflict theory (Oman, 1990; Reason, 1978; Reason & Brand, 1975) and the corresponding multimodal fidelity hypothesis (Chang et al., 2020). This observation may be explained by the fact that some of the items of the simulator sickness questionnaire, such as fatigue and sweating (Kennedy et al., 1993), can be influenced by physical exercise. In study 5 (v3 and v4), some participants walked at such a high speed that they started sweating despite the moderate temperature in the laboratory (18˚ C); this may have inflated the reported levels of cybersickness of v3 and v4 compared to the sedentary experience of v2. Another interesting outcome of Study 5, which relates to the cause of cybersickness, are the qualitative reports that indicated slightly more issues with cybersickness in the 360˚ video (v3) compared with the 3D model (v4). These reports align with the findings in the recent review of causes of cybersickness by Saredakis et al. (2020), who concluded that 3D models, in general, induce lower levels of cybersickness compared to 360˚ videos. Neither Saredakis et al. (2020) nor the results in Study 5 can explain these findings. However, it might be speculated that technical aspects may be the cause of such differences, as there were some differences in rendering between the 360˚ video (v3) and the 3D model (v4). For example, the 360˚ video (v3) was recorded with 30 frames per second, while the playback in the HMD was 90 frames per second. In order to compensate for this difference, each frame in the 360˚ video (v3) needed to be repeated three times to achieve a frame rate of 90. Technical factors such as frame rate are known to influence cybersickness, but primarily at frame rates below 20 (Chang et al., 2020; Pouke et al., 2018; Weech et al., 2019). Thus, it is speculative whether frame rate or any other technical factors caused any issues in Study 5. In summary, findings across the different studies in this thesis showed that cybersickness is a real concern in studies of virtual green exercise, but also that this issue may be reduced to a level below what is considered problematic: < 20 (Kennedy et al., 2003). The results also showed large individual variation in cybersickness, which suggests that some may experience sickness even in VR experiences optimized to reduce symptoms.

4.1.2 Presence (Studies 1, 2, 4, and 5)

The participants' responses to the quantitative measures of presence are summarized in Figures 7, 8, and 9. Figure 7 displays items that are positively associated with presence, while Figures 8 and 9 include items that are negatively associated with presence. The item "being there" was considered a key item since it is formulated directly after the definition of presence (i.e., *In the computer generated world I had the sense of "being there"*). Both "being there" and "realism" were positively correlated with perceived environmental restorativeness, affect, and enjoyment (Studies 1 and 2; $r_s = 0.28\text{-}0.66$, $p < 0.05$), confirming that presence should be considered a key factor for the effectiveness of virtual experiences (Botella et al., 2017; Bowman & McMahan, 2007; Grassini et al., 2020; Slater & Wilbur, 1997; Steuer, 1992; Triberti et al., 2014).

The quantitative measures in Study 1 showed that even relatively low-fidelity HMDs can elicit reasonably high levels of presence in terms of "being there" with a median (IQR) score of 5.0 (4.0-7.0) on a scale from 0-10 in the treadmill condition and 6.0 (3.0-6.8) in the seated condition (Figure 7). However, the results also revealed rather low levels of realism and rather high levels of flatness and movement lag that may have reduced the participants' sense of presence (Figure 8). The treadmill condition seemed to have additional issues with the noise of the treadmill reducing the sense of presence, as the median (IQR) scores for distractive noises were significantly higher ($p = 0.002$) in the treadmill condition 2.5 (1.0-5.75) compared to the seated condition 1.0 (0.0-2.0). The qualitative reports supported these assumptions, with the following list of factors that may have disrupted the participants' sense of presence: the poor quality of the image (e.g., "The video was very blurry"), the noise of the treadmill (e.g., "The noise from the treadmill was way too loud"), and the discrepancy between the walking speed of the participant and the movement speed in the virtual environment (e.g., "The discrepancy in the movements gave me a feeling of not having control"). In Study 2, v2 was developed with improved scene stability to reduce cybersickness, but it was also assumed that this improvement would increase presence. This assumption was based on a review of literature by Weech et al. (2019), which found an inverse relationship between presence and cybersickness, as well as early research that proposed the logical argument that reduced sensory conflict would lead to higher levels of presence (Slater et al., 1995). However, the results in Study 2 contradicted these assumptions and found no significant differences between v1 (modified) and v2 for any of the eight items of presence ($p = 0.179\text{-}0.899$), and no significant correlations between items of presence and cybersickness ($r_s = -0.15\text{-}0.19$, $p > 0.05$). Thus, further improvement was required in order to improve presence. Study 4 identified some key elements, in addition to those already mentioned, that could be implemented to improve presence. Again, most of these factors were the same as the ones believed to reduce cybersickness, such as frame rate, latency, and synchronizing the movement speed between the virtual environment and the treadmill. Study 5 implemented these improvements, including improved image quality to improve realism, synchronized speed between the virtual environment and the treadmill to reduce movement lag, the addition of noise canceling headphones to reduce external noises, and an emphasis on achieving acceptable frame rates and latencies despite improved graphical fidelity. About one third of participants in Study 5, and slightly more frequently in v4 (3D model) described experiences indicative of very high levels of presence. Some participants even appeared to be completely present in the virtual environment:

> "I felt like I was out in the virtual environment and focused on it, so I did not know what was happening in the room…It was fascinating how real it was... so I felt like I was walking for real." (Mann, 22 years, 360˚ video, v3)

> "For a few minutes I almost forgot where I was and just focused on walking and did not think about anything else." (Woman, 26 years, 3D model, v4)

The quantitative analysis showed no significant differences between conditions in Study 5 (v3, v4 and control) for any of the eight items of presence ($p > 0.05$ for all items), but there was a tendency for higher scores for the key item "being there" in the 3D model ($p = 0.072$). When asked to identify factors that contributed to reduced presence, participants registered complaints about poor graphics (e.g., "It was so clear it was not real"), feelings of mismatch between actual movements and the movements in the virtual environments, and poor soundscape or noticing external noises (e.g., the noise from the treadmill).

Surprisingly, there were only minor improvements of the items that are positively associated with presence, if any, during the developmental process despite improvements in graphical fidelity and synchronization of sensory input (Figure 7). The findings in the meta-analysis by Cummings and Bailenson (2016) may explain the lack of apparent improvement between the studies in this thesis. This meta-analysis identified three key technical features that contributes to presence, namely field of view, tracking level, and stereoscopic vision. In the studies in this thesis, field of view remained the same and could not influence the level of presence between studies. Tracking level, which refers to degrees of freedom and the quality of the input method for tracking the user's movement, was improved in Study 5 when compared to Studies 1 and 2 and may have contributed to some improvements of presence. Finally, the 360˚ videos in v1–v3 were all rendered in monoscopic vision, thus limiting the potential to increase presence between studies for these versions of the virtual environment. On the other hand, v4 was rendered in stereoscopic vision, which may explain why v4 was more frequently associated with high levels of presence in the qualitative analysis and the tendency for higher levels for the item “being there.” In addition, the qualitative reports of slightly more issues with cybersickness in v3 may have a negative influence on presence (Weech et al., 2019). It is also worth noting that all three items were characterized by large individual variation in all the studies (Figure 7), confirming that participants exposed to a VR experience with the same level of immersion may experience different levels of presence (Sacau et al., 2008; Weech et al., 2019).

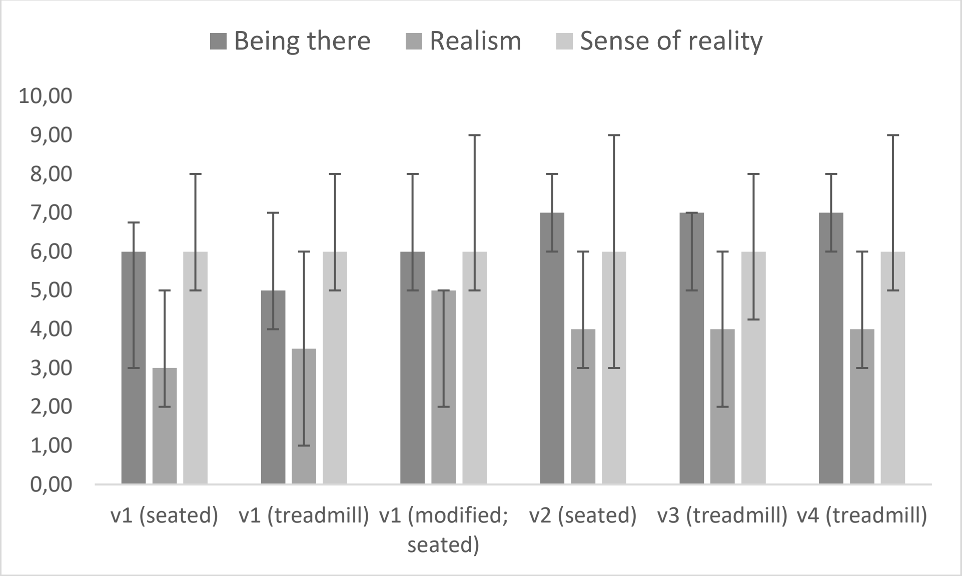


Figure 7: Scores for items of presence that are believed to increase presence across all versions of the virtual environment (median and interquartile range).

Negative outcomes related to presence (i.e., flatness and movement lag) are shown in Figure 8. It appears that flatness remained an issue throughout the experimental studies. Similar levels of flatness between v1 and v2 were expected because both versions utilized the same HMD and 360˚ camera (Table 2). The graphical fidelity of the HMD was improved in v3 and v4 (Table 2), which was expected to address the issue of flatness. The results in Figure 8 may indicate some improvements of flatness throughout the developmental process, but the issue still remained. Issues of flatness and image quality have been a limitation of VR since the first wave of HMDs, and current research suggests that modern HMDs still struggle to overcome this issue (Anthes et al., 2016). The results for movement lag followed a similar pattern. Despite no significant difference between v1 (modified) and v2 in Study 2 (p = 0.351), Figure 8 may indicate that there was some improvement in movement lag towards the later iterations of the virtual environment. However, the issue still remained in v3 and v4 with qualitative complaints regarding the difference between actual movements and the movements in the virtual environment. This issue may be reduced by introducing tracking and locomotion systems that allow participants to freely explore the virtual environment (Cummings & Bailenson, 2016), as outlined in the previous paragraph. These two items were also characterized by large individual variation across all studies (Figure 8).

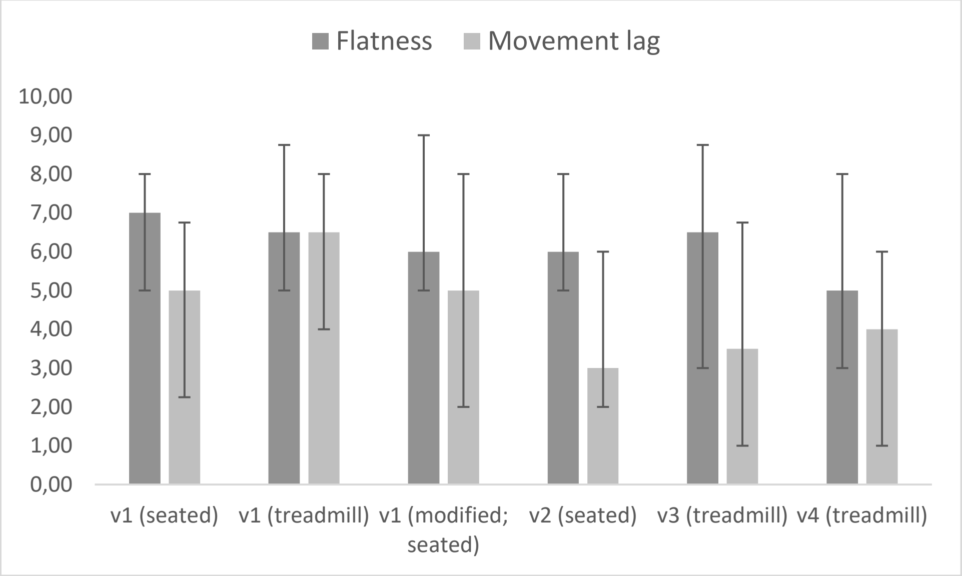


Figure 8: Scores for items of presence that are believed to reduce presence across all versions of the virtual environment (median and interquartile range).

Figure 9 summarizes the quantitative results across studies for factors that may be distractive in relation to presence. Some differences across studies were expected for these factors due to differences in experimental procedures; for example, v1 (treadmill), v3, and v4 were performed with the experience of treadmill noise, the assessor was present during the first and last minute of VR exposure in v1 (modified) and v2 to perform measurements of postural stability, and noise-canceling headphones were introduced in v3 and v4. It should be noted that the introduction of noise-canceling headphones eliminated the issue of external noise for the majority of participants. Again, individual variation was a recurring finding for these three items throughout the developmental process (Figure 9).

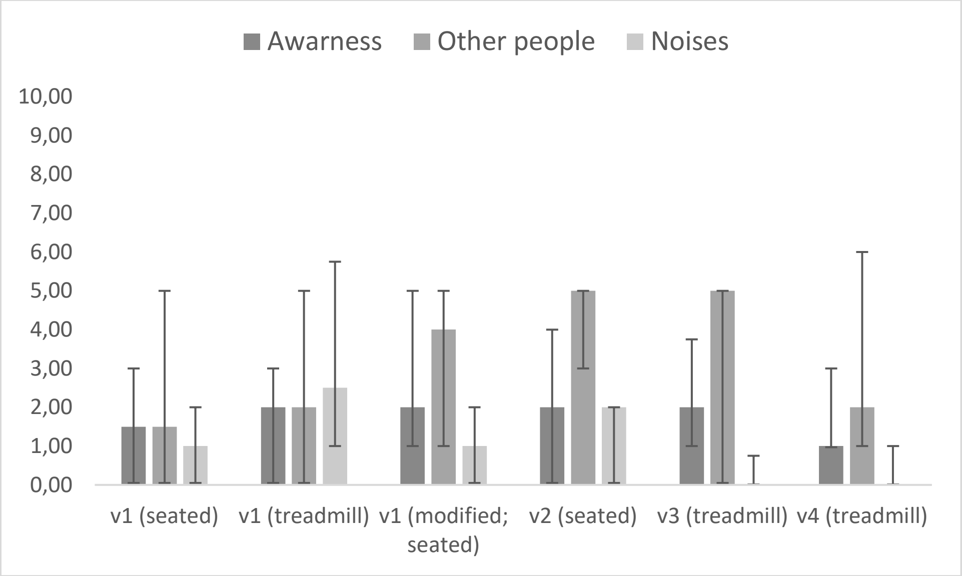


Figure 9: Scores for items of presence that are believed to be distracting in relation to presence across all versions of the virtual environment (median and interquartile range).

4.1.3 Perceived environmental restorativeness (Studies 1, 2, 4, and 5)

The environment's restorative potential was assessed by the perceived restorativeness scale. The results are summarized across studies in Figure 10. It should be noted that for the component "coherence," low values are considered positive. The perceived restorativeness scale is highly related to the characteristics of the environment and was expected to be similar between studies, as the same environment was used in all conditions. In support of this assumption, Study 1 found that there were no significant differences between the virtual and real natural environment for the two components that were included in this study (fascination, $p = 0.076$; being away, $p = 0.112$). However, there was a tendency for the item "fascination" in favor of the real natural environment, and from the qualitative analysis it emerged that participants felt that lack of a holistic nature experience in the virtual environment reduced its potential. For example, one participant (female, 21 years) wrote: "Air, smell, vision. I felt deprived of the elements of nature and senses." Interestingly, Study 1 also found significant correlations between perceived environmental restorativeness and enjoyment in the virtual conditions ($r_s = 0.40–0.54$, $p < 0.005$), similar to what is expected in real natural environments (Calogiuri et al., 2015). Study 2 showed similar results as Study 1, with fairly high levels of perceived environmental restorativeness in both v1 (modified) and v2 (Figure 10). There were no significant differences between conditions for any of the four components of perceived environmental restorativeness ($p = 0.589$-0.938; figure 10) despite the previously mentioned differences in scene stability and cybersickness in the two conditions. Study 4 was not primarily concerned with perceived restorativeness, but found evidence supporting the importance of the restorative qualities of virtual natural environments. However, no additional changes were made specifically to increase perceived environmental restorativeness in Study 5 due to the reasonably high levels of perceived environmental restorativeness in Studies 1 and 2 (Figure 10). Study 5 also found rather high levels of perceived environmental restorativeness in both v3 and v4 (Figure 10). There were no significant differences between the two conditions for the components' coherence (*p* = 0.733), compatibility (p = 0.110), but there was a tendency in favor of v4 for the component's fascination (*p* = 0.078) and being away (*p* = 0.064). Participants in Study 5 once again identified the lack of some sensory elements associated with real nature experiences as an issue, such as not feeling the wind blowing, the lack of smells, and other people. One male participant, for example, wrote: "The only thing I might have missed a bit in the virtual environment was more activity from people and/or animals, as I felt quite alone…. the virtual environment seemed a bit cold and lonely" (Male, 36 years, 360˚ video, v3).

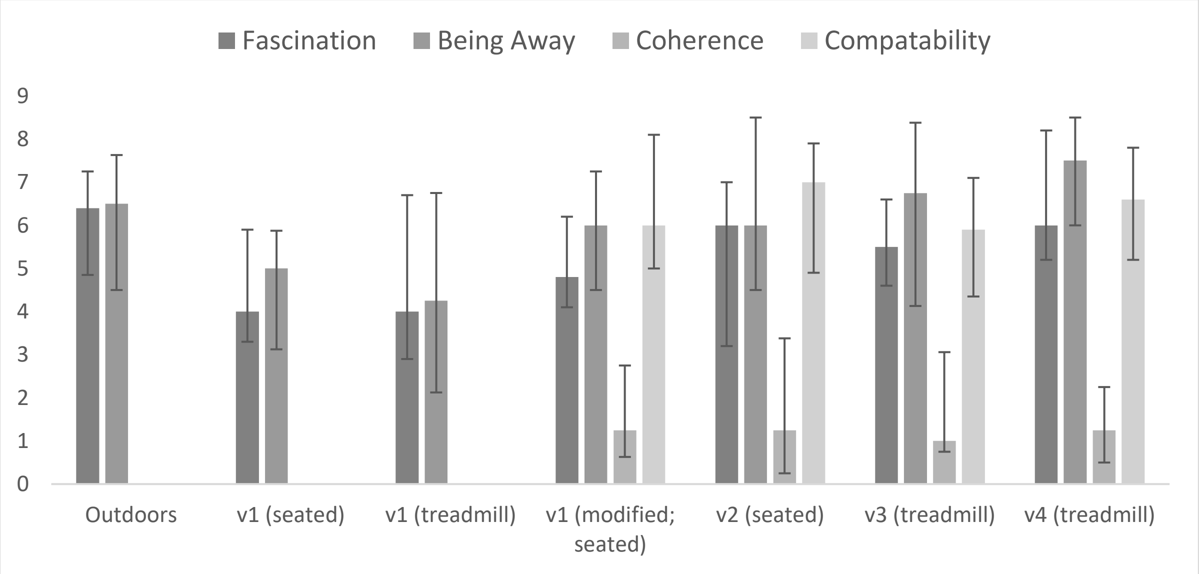


Figure 10: Scores for the components of perceived environmental restorativeness across all experimental conditions that included this measure (median and interquartile range).

The relatively high levels of perceived environmental restorativeness in the outdoors condition as well as the virtual conditions confirm the assumption in the methods section that the environment approximated an ideal natural environment. The results presented in Figure 10, and the tendency for a significant difference between v3 and v4, may indicate that perceived environmental restorativeness increased gradually as the fidelity of the technology improved. However, the lack of significant differences between conditions in Study 2 suggest otherwise. In light of these contradictions, previous research support that the fidelity of the experience does not influence the restorative potential of virtual natural environments, as previous studies of digital nature have found restorative effects in low fidelity displays (Rogerson & Barton, 2015; Wang et al., 2020; Wooller et al., 2018). Mostajeran et al. (2021) expanded on these findings and showed that watching a slideshow of nature images in a HMD is as restorative as watching a 360˚ nature video. However, the lack of a direct comparison between nature experiences in different types of HMDs limits any clear conclusion in this regard. Furthermore, the results of this thesis suggest that the restorative potential of virtual green exercise is similar to real green exercise. This finding is in accordance with a previous study of sedentary experiences of virtual nature, which have found no significant differences between the restorative potential of virtual and real nature (Browning et al., 2019). These findings are intriguing as they suggest a high potential of virtual nature for psychological restoration and emphasize the potential of virtual green exercise to be used to promote health and well-being through attention restoration.

4.2 Indicators of psychophysiological health

4.2.1 Affect (Studies 1, 2, 4, and 5)

Affective responses were assessed by pre-post changes in the physical activity affect scale. Affect was used as an indicator of the environments' ability to elicit psychophysiological health benefits, due the relationship between affect and human health (Darcy et al., 2019). In Study 1, there was a significant positive pre-post change in affect following the outdoors condition with a reduction of both negative affect ($p < 0.05$) and fatigue ($p < 0.05$), while positive affect and tranquility were unchanged ($p > 0.05$). These results confirmed that the chosen natural environment had the potential to elicit positive psychophysiological responses, which was a premise for the success of eliciting positive responses in the virtual conditions. However, the two virtual conditions in Study 1 actually inflicted negative changes in affect. Both positive affect and tranquility were reduced ($p < 0.05$), whereas negative affect and fatigue increased ($p < 0.05$). There was also a significant difference between the outdoors condition and the two virtual conditions for all four components of affect ($p < 0.01$). The correlation analysis revealed that cybersickness was negatively correlated with both positive affective outcomes ($r_{s} = -0.52 - -0.79$; $p < 0.05$) and positively correlated with negative affective outcomes ($r_{s} = 0.43-0.77$; $p < 0.05$). The qualitative reports gave further confirmation that cybersickness had a negative impact on affect with statements such as: "I quite enjoyed the outdoor walk, because of the weather, but in VR I felt sick and dizzy so it was not pleasure at all for me" (Female, 20 years). These findings emphasized the importance of reducing cybersickness in order to improve affective responses in virtual green exercise. Study 2 implemented improved scene stability to reduce cybersickness, which was expected to improve affective responses as well. The results in Study 2 confirmed the findings in Study 1 and showed that a virtual environment with low scene stability (v1, modified) does indeed lead to negative pre-post changes in affect. Three of the four components of affect significantly deteriorated after v1 (modified) with negative changes to positive affect ($p = 0.002$), tranquility ($p = 0.021$), and negative affect ($p = 0.014$), while fatigue remained unchanged ($p = 0.063$). In contrast, no significant pre-post changes were observed after v2 for any of the components of affect, neither negative nor positive ($p > 0.05$). Study 2 also revealed significant differences between v1 (modified) and v2 for positive affect ($p = 0.031$), negative affect ($p = 0.006$), and fatigue ($p = 0.028$), while no significant difference between the two conditions was found for tranquillity ($p = 0.196$). The results also confirmed that cybersickness was correlated with affect (positive affect, $r_s = -0.39$; tranquility, $r_s = -0.35$; negative affect, $r_s = 0.50$; fatigue, $r_s = 0.63$: $p < 0.05$). These results showed that improving scene stability and reducing cybersickness protects against negative affective responses, but also that other aspects of the VR experience needed to improve in order to elicit positive affective responses. Study 4 found further support that exposure to virtual nature can elicit positive affective responses, based on results from sedentary virtual experiences of nature. The study also identified virtual nature's potential for positive affective responses as one of the key areas for future application. Thus, Study 5 was conducted with affect as the primary outcome. Study 5 implemented a pre-exposure film clip designed to induce feelings of sadness. The aim of this procedure was to reduce individual variation in affect prior to VR exposure and potentially take advantage of the proposed restorative potential of virtual natural environments (Browning et al., 2019; Mostajeran et al., 2021; Schebella et al., 2020; Wang et al., 2019; Yu et al., 2018). The results showed that both v3 and v4 improved affective responses compared to measurements taken directly after the sad film clip ($p < 0.001$), and that tranquility even improved beyond baseline levels ($p < 0.001$). The qualitative responses also confirmed the positive impact of the virtual conditions on affect with statements such as: "[I feel] happy. Little surprised of how quickly I forgot about the sad movie" (Woman, 35 years, 3D model, v4)

However, there were no significant differences between the two virtual conditions and the control group (*p* = 0.446-0.742), which suggest that the beneficial effects were primarily caused by the exercise rather than the virtual environments.

Affect was measured under different circumstances in the different studies of this thesis, which complicates direct comparisons. The results demonstrate that negative affective responses in virtual green exercise were closely related to cybersickness and that the issue of cybersickness must be minimized to elicit positive affective responses. However, low levels of cybersickness did not seem to be sufficient to elicit positive pre-post changes in affect, as the results in Studies 2 and Study 5 suggest that the VR experiences did not cause any positive changes to affect beyond what is achievable by exercise alone. The two previous studies of virtual green exercise report conflicting results regarding affective outcomes. The study by Alkahtani et al. (2019) support the findings of this thesis, since the authors did not find any significant differences in mood after a VR 360° video cycling protocol compared to indoor exercise. The study by Chan et al. (2021), on the other hand, did indeed find positive affective outcomes after 3D model based virtual green exercise. As previously mentioned, these contradictory findings may relate to different methodology and differences in the technology used. Together, these findings suggest that virtual green exercise may be less effective than real green exercise in eliciting positive affective responses, as previous research generally finds improved affective state after real green exercise (Lahart et al., 2019). These findings also suggest that virtual green exercise is currently not an upgrade compared to digital green exercise, as some studies of digital green exercise have shown positive changes to affect and mood (Plante et al., 2003; White et al., 2015; Wood et al., 2020; Yeh et al., 2017). Virtual green exercise was expected to be an improvement compared to its digital counterpart, due to higher levels of immersion and promising reports of improved mood and affect in studies of sedentary experiences of virtual nature (Browning et al., 2019; Chirico & Gaggioli, 2019; Mostajeran et al., 2021; Nukarinen et al., 2020; Schebella et al., 2020; Valtchanov et al., 2010; Wang et al., 2019; Yeo et al., 2020; Yu et al., 2018). However, recent studies making direct comparisons between sedentary virtual and digital nature experiences generally show similar results between the two types of technology regarding mood and affect (Liszio et al., 2018; Mostajeran et al., 2021; Yeo et al., 2020), with the exception of positive affect in one study (Yeo et al., 2020), thus calling into question the effectiveness of virtual nature compared to digital nature. These studies, in combination with the findings of this thesis, show that virtual nature may still suffer from some limitations. One general limitation that may reduce the effectiveness of virtual nature in eliciting positive affective responses is the limited ability to replicate the multisensory and holistic experience provided by real nature. Specific limitations of the virtual environment used in this thesis may include low intensity of the nature dose (e.g., amount of greenery; Figure 4) and limited potential to induce a feeling of awe (Frumkin et al., 2017). Further improvements of virtual green exercise protocols may be able to increase the environment's effectiveness in eliciting positive affective responses that are more similar to real nature. The results of this thesis suggest that such efforts should focus on improving presence and reducing cybersickness, due to their previously mentioned correlations with affective outcomes.

4.2.2 Stress (Studies 2, 4, and 5)

Measures of physiological stress were introduced in Study 2 and expanded upon in Study 5. In Study 2, heart rate was used as an indicator of stress (Allen et al., 2014; Duzmanska et al., 2018). Measures of heart rate were also implemented in Studies 1 and 5, but not as an indicator of stress since the element of physical activity was expected to have a larger influence on heart rate compared to actual stress. The results in Study 2 showed no differences between v1 (modified) and v2 for either mean heart rate (v1: Median = 71.00, IQR = 64.00-77.00; v2: Median = 66.00, IQR = 62.00-77.00: $p = 0.551$) or peak heart rate (v1: Median = 81.00, IQR = 72.00-91.00, $p = 0.342$; v2: Median = 76.00, IQR = 68.00-89.00: $p = 0.584$). The lack of between group differences occurred despite the previously mentioned significant difference in cybersickness, suggesting that heart rate and cybersickness are unrelated. This assumption was further supported by a lack of significant correlations between heart rate and cybersickness in Study 2 (mean heart rate, $r_s = 0.11$; peak heart rate, $r_s = 0.14$: $p > 0,05$). Study 4 further investigated the potential of using virtual green exercise for stress reduction based on previous research. The findings identified stress-management in the workplace as one of the primary areas of application for virtual green exercise. Thus, a more accurate and sensitive measure of stress was included in Study 5, namely blood pressure. The results from Study 5 showed that both v3 and v4 significantly reduced systolic blood pressure ($p < 0.001$), but not diastolic ($p = 0.101$). Systolic blood pressure was reduced at 15 minutes after exposure to both v3 and v4. However, these reductions of blood pressure were not significantly different from the control condition that also reduced blood pressure ($p = 0.310$).

This finding is somewhat surprising based on the stress reduction theory (Ulrich et al., 1991), the rather consistent reports of reduced stress levels after exposure to real nature (Frumkin et al., 2017), and a recent review of artificial nature showing that both sedentary and active digital and virtual nature exposures can reduce stress (Browning et al., 2020b). However, when looking at previous studies of real and digital green exercise comparing the stress response to an active control group the results are less clear (Lahart et al., 2019). A review of studies comparing the stress reducing effect of real green exercise to indoor exercise found inconclusive results (Lahart et al., 2019), and studies comparing the stress response of digital and virtual green exercise to indoor exercise also display mixed evidence (Chan et al., 2021; Duncan et al., 2014; Pretty et al., 2005; White et al., 2015; Wooller et al., 2018). These findings, in combination with the results of this thesis, suggest that the stress-relieving effect of nature simulations diminish when they are compared to a control group that performs indoor exercise. A potential explanation for the mixed effects of both real, digital, and virtual green exercise when compared to indoor exercise is that nature exposure and exercise are both known to reduce stress, and potentially through the same pathways as outlined in the introduction (Anderson et al., 2019; White et al., 2018). It is unclear whether the stress reducing effects of nature and exercise combine into an additive effect or if there is no additive effect on stress reduction of either real or virtual green exercise. The mixed evidence reported above may suggest that there is no additive effect on stress reduction of neither real nor virtual green exercise. Other potential explanations of the limited effects on stress reduction in the studies of this thesis include the previously mentioned issues with replicating the holistic experience of real nature, limited intensity of the nature dose, and limited potential to elicit a feeling of awe. Further development of virtual green exercise may be a path to uncover additional effects on stress reduction and the associated health benefits compared to indoor exercise.

4.2.3 Enjoyment (Studies 1, 2, 4, and 5)

The level of enjoyment during an exercise session is considered a strong motive for future exercise participation (Dishman et al., 1985), also in the context of green exercise (Calogiuri & Chroni, 2014), making it an important element to consider for promotion of physical activity and health. The participants' level of enjoyment during the different experimental conditions was assessed post exposure by a single item on a scale from 0-10, in Studies 1, 2, and 5. The findings are summarized in Figure 11. The results from Study 1 showed that a walk in the real natural environment was considered highly enjoyable, as expected based on previous research (Lahart et al., 2019), with a median (IQR) of 8.0 (7.0-9.0). This finding was a premise for finding high levels of enjoyment in the virtual conditions. However, both virtual conditions in Study 1 were significantly less enjoyable compared to the outdoors condition ($p < 0.05$). In fact, the two virtual conditions were characterized by rather low levels of enjoyment with a median (IQR) level of enjoyment in the treadmill condition of 3.0 (3.0-5.0) and 2.0 (1.0-4.8) in the seated condition. One likely explanation for the low levels of enjoyment in the virtual conditions may be the previously mentioned issues with cybersickness. This malaise was negatively correlated with enjoyment in both the sedentary ($r_s = -0.79$, $p < 0.01$) and the treadmill ($r_s = -0.52$, $p < 0.01$) virtual condition. The qualitative reports further supported an association between cybersickness and enjoyment with statements such as “How I felt during the virtual condition – sick and dizzy – [determined my level of enjoyment]” (Male, 25 years). The results also showed that the components of perceived environmental restorativeness were positively correlated with enjoyment ($r_s = 0.40$-0.54, $p < 0.05$), as well as two items of presence in the treadmill condition (being there, $r_s = 0.80$; sense of reality, $r_s = 0.42$: $p < 0.05$). A few participants (n = 3) also reported that the novelty of the technology contributed positively to the ratings of enjoyment. One participant reported: “Just the fact that you are using virtual reality [made it enjoyable]” (Male, 20 years). The results from Study 1 once again demonstrated the importance of minimizing the impact of cybersickness in studies of virtual green exercise. Thus, it was expected that improving camera stability in Study 2 would reduce cybersickness and improve enjoyment. The results of Study 2 provided partial support for this assumption. There was no significant difference between v1 (Median = 8.0, IQR = 6.0-9.0) and v2 (Median = 6.0, IQR = 5.0-7.0) for enjoyment ($p = 0.136$), despite the previously mentioned difference in cybersickness. However, there was a moderately strong negative correlation between cybersickness and enjoyment, which suggest that reducing cybersickness may be a feasible strategy for improving enjoyment ($r_s = -0.48$: $p < 0.01$). The correlation analysis of Study 2 further supported that presence was associated with enjoyment and showed positive correlations between enjoyment and two items of presence (being there: $r_s = 0.28$; realism: $r_s = 0.30$: $p < 0.05$).

Study 4 found evidence for the possibility of using virtual green exercise as a tool to promote physical activity and health, supporting the importance of improving enjoyment in the virtual green exercise protocol. Study 5 did not implement any improvements to increase enjoyment, despite the findings in Study 4, but it was expected that the improvements that were implemented to reduce cybersickness would have a positive impact on enjoyment as well. In Study 5, the median (IQR) scores of enjoyment were 7.5 (5.0-8.8) in v3, 8.0 (7.0-10.0) in v4, and 6.0 (4.5-7.5) in the control condition. The one-way ANOVA revealed a significant effect of condition on enjoyment ($p = 0.007$), with the post-hoc analysis demonstrating that the 3D model was perceived as more enjoyable compared to control ($p = 0.006$). No significant differences were found between 360˚ video and control ($p = 0.533$) or between 360˚ video and 3D model ($p = 0.189$). The qualitative data further supported that most participants in the virtual conditions enjoyed the experience, which were labelled as "fun," "exciting," or "interesting". However, a few participants also described the virtual walk as lacking stimulation ("A little boring," "There was little going on,") and some appeared to be more excited by the novelty of the technology:

> "VR is something I have tried before, and being able to actually move over longer distances while it happens in VR was a new and exciting experience…the simulation itself was not very impressive, but the movement aspect made the VR experience new and exciting". (Male, 32 years, 360˚ video, v3)

The nature elements in the virtual environments were also recurrently associated with enjoyment (e.g., "The weather, the birds' singing and the river's rushing sound. Green grass and leaves [made the experience enjoyable for me]"), while built elements were reported as less enjoyable (e.g., "The less traffic noise the more pleasant"; "It was not very fascinating due to the large football pitches"). The element of self-pacing also appeared to be positively associated with enjoyment: "I liked that one could walk at the pace one wanted, and it was a big plus. I'm used to VR experiences that just move at a set rhythm." (Male, 29 years, 360˚ video, v3)

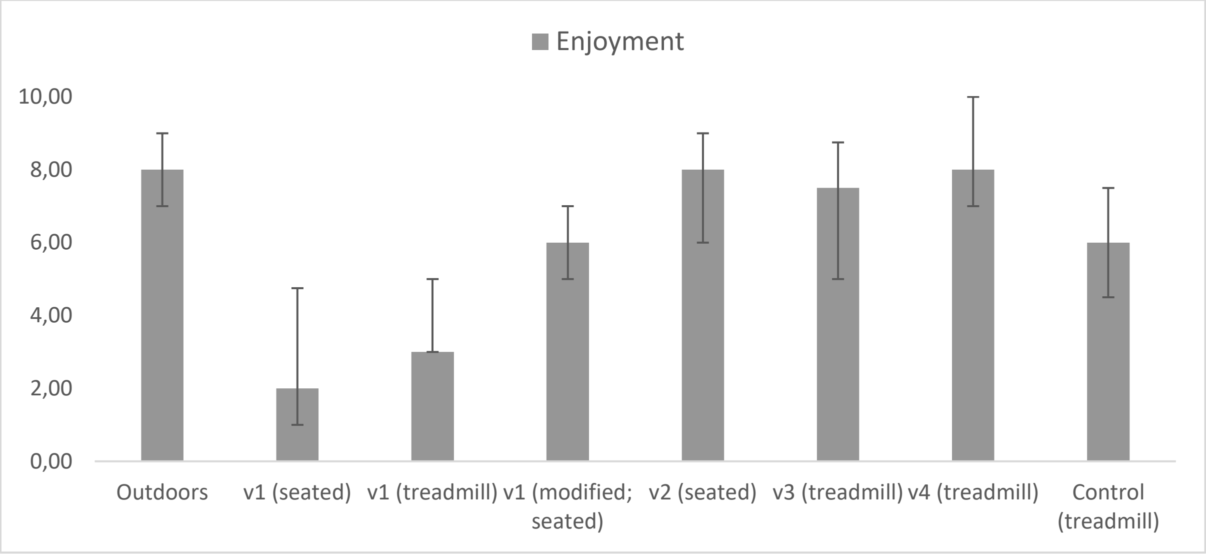


Figure 11: The level of enjoyment in all experimental conditions (median and interquartile range).

The results for enjoyment are summarized across all experimental conditions in Figure 11. These results indicate that the technological and methodological improvements throughout the developmental process lead to improved enjoyment. The significant correlations and the qualitative reports from the individual studies suggest that these improvements may be attributed to reduced levels of cybersickness, and possibly slight improvements to presence and perceived environmental restorativeness (Figures 7-10). It is also possible that the increased technological fidelity contributed to increased enjoyment directly, as some participants mentioned that the novelty of the experience contributed to their enjoyment. However, the importance of novelty in explaining positive outcomes of VR experiences is debated in the literature (Browning et al., 2019). The results across all experimental conditions also indicate that high levels of enjoyment are achievable in virtual green exercise, and that the level of enjoyment is comparable to real green exercise. This interpretation of findings across the studies of this thesis is somewhat controversial, as a review of previous research conclude that real green exercise elicits higher levels of enjoyment compared to virtual and digital green exercise (Lahart et al., 2019). Thus, some caution is advised when interpreting these cross-study findings. More importantly, the levels of enjoyment of v4 were significantly higher compared to indoor exercise. This finding demonstrates that a 3D model of nature (v4), but not a 360˚ video (v3), enhances the level of enjoyment during exercise. This dichotomy may relate to the qualitative reports of more issues with cybersickness in v3. It is likely that the nature elements in the v4 contributed to improved enjoyment, as reported in the qualitative analysis in Study 5. Exactly how nature and nature elements contribute to enjoyment is unknown, but both stress reduction theory and the attention restoration theory have been linked with enhanced mental states (R. Kaplan, 1989; S. Kaplan, 1995; Ulrich et al., 1991). The lack of positive effects on stress-related measures in this thesis might suggest that improved enjoyment was primarily caused by attention restoration and not stress reduction. In relation to previous research, no other study has measured enjoyment after a bout of virtual green exercise, but there are two reports from studies comparing digital green exercise to indoor exercise. White et al. (2015) found higher levels of enjoyment after a bout of digital green exercise compared to indoor exercise, while Wood et al. (2020) dispute this finding and report no significant difference between digital green exercise and indoor exercise. These limited findings suggest that it is too early to make definite conclusions regarding the general effectiveness of artificial representations of nature, but the results of this thesis definitely support that virtual green exercise is more enjoyable than indoor exercise when presented as a 3D model. These results support the use of virtual green exercise as a tool to increase exercise participation and well-being.

4.3 Physical engagement

4.3.1 Walking speed (Studies 1, 4, and 5)

Walking speed was assessed and used as a measure of absolute exercise intensity in the two experimental studies that included physical activity, Studies 1 and 5. In Study 1, the mean ± standard deviation walking speed during virtual green exercise was 5.5 ± 2.0 km/h. This was similar to the mean walking speed of 5.7 ± 0.8 km/h during the real green exercise condition, and no significant difference was observed between the two conditions ($p = 0.072$). At a glance, these numbers suggest that physical engagement is similar between virtual and real green exercise. However, there was a tendency in favor of the outdoors condition and there was a large individual variation in the virtual green exercise condition (Figure 12). The slowest and fastest walking speed in the virtual green exercise condition was 2.48 and 11.30 km/h, respectively, while it was 4.09 and 7.74 km/h in the real green exercise condition. Both the qualitative analysis and anecdotal reports from the participants suggest that cybersickness was the cause of this seemingly larger variation in the virtual green exercise condition. Some reported that they were not able to walk faster due to dizziness, while others reported that they walked as fast as they could to alleviate discomfort associated with cybersickness (e.g., “[The treadmill condition] was very stressful and tiring because I had to hold on to the handlebar very hard”). The correlation analysis in Study 1, however, indicated that walking speed and cybersickness were unrelated ($r_s = -0.33$, $p > 0.05$). The lack of a significant correlation can be explained by the previously mentioned reports from the participants, which suggest there was a non-linear association between walking speed and cybersickness that would not be detected by a correlation analysis designed to detect linear associations. Study 4 aimed to identify potential solutions to these issues. Again, these solutions were the same as those identified to reduce cybersickness. Most notable was the synchronization of the treadmill speed and the movement speed in the virtual environment. This feat was implemented in Study 5, and the results demonstrate that this improvement by itself was not enough to eliminate issues related to walking speed, as the walking speed in v3 (6.56 ± 1.37 km/h) was significantly lower compared to control (8.31 ± 1.76 km/h: $p = 0.02$). Once again, the lower walking speed in v3 compared to control was associated with qualitative reports of issues related to cybersickness, as stated by one of the participants:

“I held on pretty tight with my hands [on the support-bars] and certainly could not have managed to walk without holding myself … may have felt a little discomfort with my sight ... during the [first half of the walk] it was easier to walk than the [last half]” (Male, 20 years, 360˚ video, v3).

On the other hand, v4 was associated with less cybersickness and the results show that the mean walking speed in this condition (7.74 ± 1.50 km/h) was similar to the mean walking speed in control (8.31 ± 1.76 km/h: $p = 0.762$).

The results for walking speed in all experimental conditions that included walking are summarized in Figure 12. When the impact of cybersickness was minimized, it was possible to achieve walking speeds during virtual green exercise that were comparable to indoor exercise. This finding suggest that there is no additional effect of virtual green exercise for absolute exercise intensity, which contradicts previous research of real green exercise (Carvalho et al., 2010; Mieras et al., 2014). Mieras et al. (2014) found that power outputs during outdoor cycling were higher compared to indoor cycling, and Carvalho et al. (2010) found evidence of higher walking speed in real green exercise compared to indoor exercise. However, a systematic review on this topic found inconclusive evidence regarding the effect of real green exercise on absolute exercise intensity (Lahart et al., 2019). Thus, it is uncertain whether the findings of this thesis failed to reproduce a positive effect of green exercise on absolute exercise intensity or if there is no additional effect of green exercise. Previous studies of virtual green exercise cannot provide any insight regarding this topic, as no studies of either virtual or digital green exercise have compared absolute exercise intensities to indoor exercise.

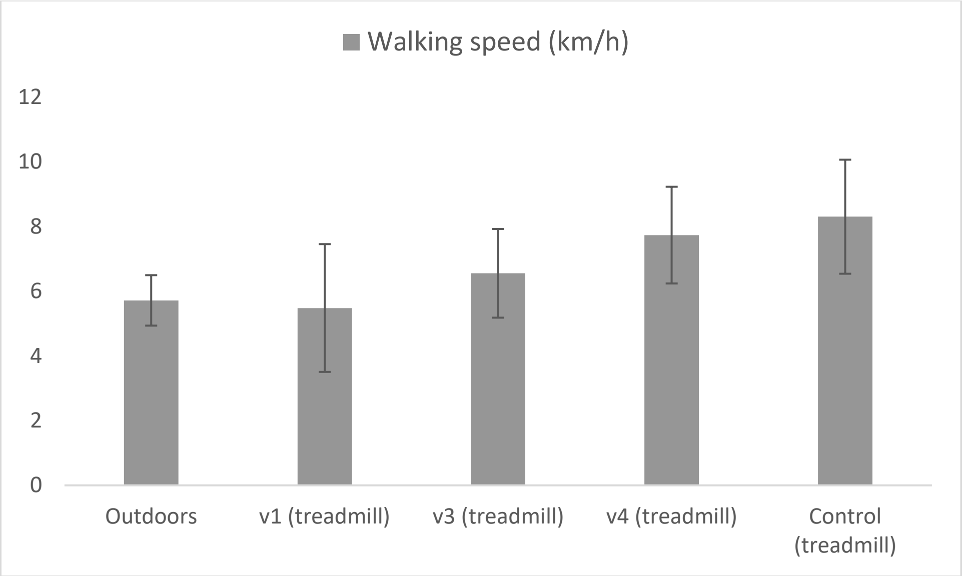


Figure 12: Walking speed in all experimental conditions that included walking exercise (mean ± standard deviation).

4.3.2 Heart rate (Studies 1 and 5)

Heart rate was used as a measure of relative exercise intensity in Studies 1 and 5. This measure is closely related to absolute exercise intensity (e.g., walking speed) and is expected to increase with increased absolute intensity. In Study 1, the values for mean heart rate (101.8 ± 21.1) in the virtual green exercise condition were not significantly different ($p > 0.05$) from the mean heart rate in the outdoors condition (103.9 ± 16.3). Importantly, this finding was observed across two different conditions with fairly similar walking speeds. In study 5, walking speed was not similar across all three experimental conditions, which highlighted the need to control for walking speed in this study when analyzing heart rate. The results showed no significant difference ($p > 0.05$) between v3 (98.4 ± 17.4 beats/min), v4 (112.6 ± 16.6 beats/min) and control (121.8 ± 23.8 beats/min). Overall, these results indicate that the environment used in this thesis did not influence heart rate (Figure 13), although the results regarding heart rate in Study 1 should be interpreted carefully due to the potential impact of cybersickness. Previous studies of sedentary exposure to virtual natural environments suggest that virtual nature has the potential to influence heart rate (Gatersleben & Andrews, 2013; Wang et al., 2019), but when combining nature exposure with physical activity the evidence suggests otherwise (Lahart et al., 2019). Previous studies of real green exercise comparing heart rate responses to indoor exercise generally show no difference in heart rate between green and indoor exercise (Lahart et al., 2019). This notion is also supported by studies of both virtual (Alkahtani et al., 2019) and digital green exercise (Duncan et al., 2014; Pretty et al., 2005; White et al., 2015). These studies, in combination with the results of this thesis, suggest that the positive effect of nature exposure on heart rate diminish when combined with physical activity.

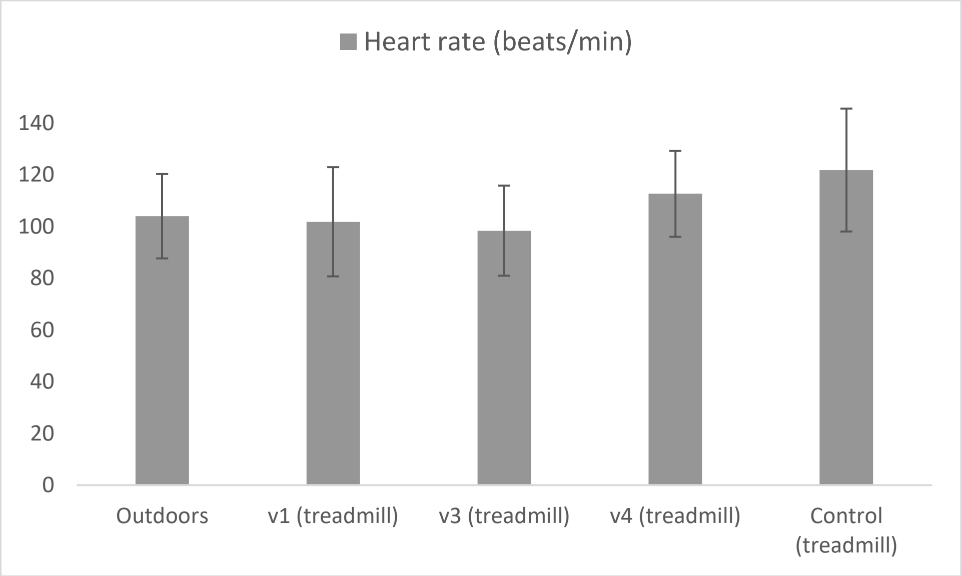


Figure 13: Mean heart rate in all experimental conditions that included walking exercise (mean ± standard deviation).

4.3.1 Perceived exertion (Studies 1 and 5)

In Study 1, the median (IQR) rating of perceived exertion was significantly higher ($p = 0.001$) during virtual green exercise; 11.0 (9.0-13.0), compared to outdoor exercise; 9.0 (8.0-9.0). This significant difference was accompanied by a significant correlation between rating of perceived exertion and cybersickness ($r_s = 0.41$, $p < 0.05$), which suggest that cybersickness contributed to higher perceived exertion during the virtual green exercise condition. The results from Study 5 showed no differences between v3 (median = 9.5, IQR = 7.0-13.0), v4 (median = 12.0, IQR = 10.0-13.0) and control (median = 11.0, IQR = 8.0-13.0) for perceived exertion when adjusting for walking speed ($p = 0.290$).

The results regarding perceived exertion are summarized across conditions in Figure 14. The higher levels of perceived exertion during virtual green exercise in Study 1 compared to real green exercise (Figure 14), alongside the significant correlation with cybersickness, suggest that the combination of physical activity and cybersickness lead to increased levels of exertion. Some of the symptoms of cybersickness are closely related to exertion, such as “fatigue” and “general discomfort” (Kennedy et al., 1993). It is likely that some participants experienced these symptoms, which lead to an increase of perceived exertion. In Study 5, it was expected, based on previous research (Lahart et al., 2019), that both v3 and v4 would be characterized by lower perceived exertion when adjusted for walking speed compared to the control group. The expectation was not met, as there were no differences between the three conditions. This finding was surprising based on the expectation of fewer issues with cybersickness compared to Study 1, and findings from a recent systematic review of lower perceived exertion during real green exercise (Lahart et al., 2019). The findings of lower perceived exertion during real green exercise by Lahart et al. (2019) were admittedly weak, but they were consistent with theoretical frameworks linking nature exposure and perceived exertion (Gladwell et al., 2013; Rogerson et al., 2019). Gladwell et al. (2013) identifies perceived exertion as an outcome of the combined input from both internal and external sensory feedback. During exercise, internal signals of increased levels of metabolic byproducts, increased blood flow to muscles, and increased body temperature alert the brain of increased biological demands, which influence the perception of effort. Gladwell et al. (2013) suggest that nature exposure acts as a distraction from these internal signals, which leads to lower perceived effort. Rogerson et al. (2019) propose a slightly different pathway, suggesting that mental fatigue makes exercise feel more strenuous and impairs exercise performance. The restorative qualities of natural environments may reduce the perception of effort during exercise by reducing mental fatigue trough attention restoration (Rogerson et al., 2019). However, the results of this thesis do not support any of these theories and further dispute the already weak experimental findings of lower perceived effort during real green exercise (Lahart et al., 2019). This finding is in agreement with previous research into digital green exercise that finds no effect of digital green exercise on perceived effort compared to indoor exercise (Rogerson & Barton, 2015; Yeh et al., 2017). No other study has measured perceived exertion during virtual green exercise. Thus, similar to findings regarding heart rate, walking speed, and stress levels, it is uncertain whether the findings of this thesis failed to reproduce a positive effect of green exercise on perceived exertion or if there is no additional effect of green exercise.

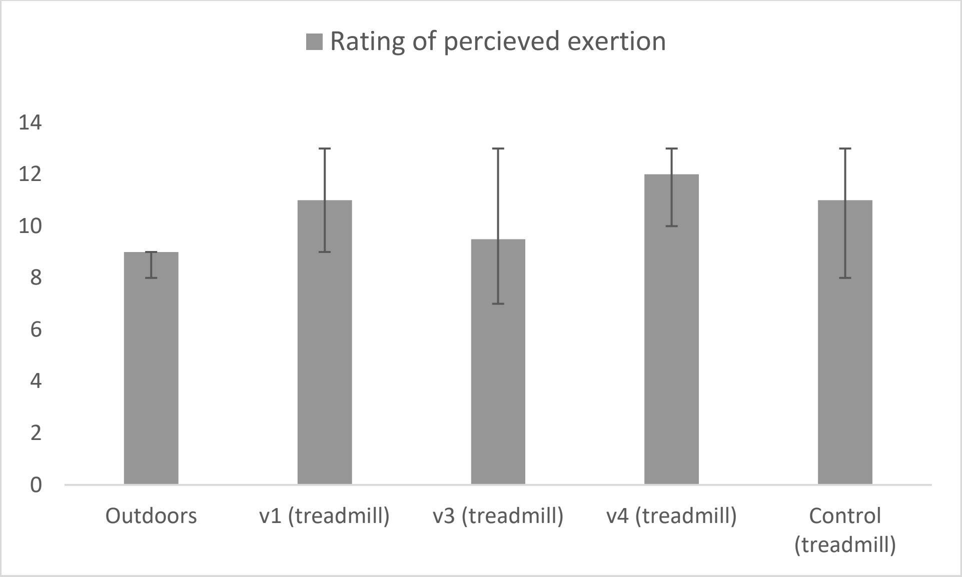


Figure 14: Rating of perceived exertion in all experimental conditions that included walking exercise (median and interquartile range).

4.4 Methodological considerations

The methodological approach of this thesis was in the mold of, but not informed by, critical realism. Critical realism posits that the observations made in this thesis are not necessarily a direct observation of reality, but rather a confident estimate (Danermark et al., 2019). For example, the results of this thesis are largely multifactorial and individual, and possibly shaped by social constructs such as connectedness to nature and affinity for natural environments and might not apply to all people in all situations as further outlined below. In line with critical realism, the thesis also recognized the reductionistic nature of quantitative measures when assessing psychological factors such as enjoyment (Danermark et al., 2019). The combination of quantitative and qualitative methods was implemented to address this issue in Studies 1 and 5, as these studies were particularly concerned with the psychophysiological outcomes of virtual green exercise.

None of the experimental studies included a VR control group. The lack of a control group of non-nature content in VR may limit any clear conclusion that positive findings, such as higher levels of enjoyment, can be attributed specifically to the virtual natural environment and not the VR technology by itself. However, previous research has compared the effects of different types of content in VR and concluded that the combination of the content and the technology is decisive for the type of outcome after a VR experience (Anderson et al., 2017; Chung et al., 2018; Mostajeran et al., 2021; Schebella et al., 2020; Wang et al., 2020; Yu et al., 2018). For example, Chung et al. (2018) compared a virtual natural environment to an experience of virtual fireworks and found that the nature VR elicited a larger degree of cognitive restoration. These reports suggest that the findings of the present thesis are indeed specific to the environment used in the experimental studies.

The generalization of the findings may be limited. There were large individual variations for most of outcomes measured in this thesis, including the three main factors influencing virtual nature experiences: cybersickness, presence and perceived environmental restorativeness. This suggests that effects of virtual green exercise may vary depending on personality traits and personal preference, as shown by previous research (Senese et al., 2020). For example, it is likely that people with high anxiety levels will respond more negatively to VR exposure compared to the participants of this thesis (Mittelstaedt, 2020). Additionally, all experimental studies utilized a convenience sample which limits generalization. This decision was deemed appropriate since the aim of the thesis was not to apply the technology to elicit health benefits, but rather develop a protocol for virtual green exercise. Thus, the findings may not be generalizable to neither the general population nor specific target groups for virtual green exercise.

5. Conclusion

This thesis demonstrates that adopting virtual green exercise within healthcare, physical activity promotion, research projects, and so forth, requires use of appropriate techniques to create and deliver enjoyable experiences without causing cybersickness and other negative outcomes. Scene stability emerged as a major factor contributing to cybersickness and negative affective responses. When scene stability was improved and appropriate techniques were used, the results of this thesis support the use of virtual green exercise within physical activity promotion, due to higher levels of enjoyment compared to indoor exercise. The thesis also highlights the limitations of virtual green exercise and its current inability to reproduce the range of reported effects of exposure to real nature, and further questions whether some of the reported effects of real green exercise are legitimate.

5.1 Perspective

Further research and optimization of virtual green exercise is required to achieve its full potential. The findings of this thesis suggest a few things that should be addressed to optimize experiences in virtual green exercise. Presence should be targeted, possibly through increased "tracking level" by allowing participants to freely explore the natural environment, due to its association with psychophysiological outcomes. Some tweaking to minimize negative outcomes is also required—for example, low image quality and cybersickness. On the content side of things, a better understanding of which types of natural environments and nature elements that elicit positive responses would be useful for creating effective virtual environments. Luckily, VR technology should be an excellent tool to study the effects of different natural environments to discover the most advantageous properties. During this search for the optimal virtual nature experience, it is important to remember Levi and Kocher's (Levi & Kocher, 1999) warning that virtual experiences of optimal natural environments may come at the cost of a devaluation of local natural environments. Measures should be taken to avoid this scenario, such as using local natural environments as a template for these virtual experiences. Researchers should also keep in mind the concerns expressed by some authors that virtual nature may drive society towards a dystopian future where we replace real nature with virtual nature (Kahn et al., 2009). However, it is unlikely that virtual nature ever will be able to replicate the holistic experience of real nature, as it was stated by one of the participants:

> "Nature will always win for me. It is less stressful, you know where you are, you can stop and look, for example, at birds anytime."

References

Alkahtani, S., Eisa, A., Kannas, J., & Shamlan, G. (2019). Effect of acute high-intensity interval cycling while viewing a virtual natural scene on mood and eating behavior in men: A randomized pilot trial. *Clinical Nutrition Experimental*, *28*, 92–101. https://doi.org/10.1016/j.yclnex.2019.10.003

Allen, A. P., Kennedy, P. J., Cryan, J. F., Dinan, T. G., & Clarke, G. (2014). Biological and psychological markers of stress in humans: Focus on the Trier Social Stress Test. *Neuroscience and Biobehavioral Reviews*, *38*, 94–124. https://doi.org/10.1016/j.neubiorev.2013.11.005

Allen, B., Hanley, T., Rokers, B., & Green, C. S. (2016). Visual 3D motion acuity predicts discomfort in 3D stereoscopic environments. *Entertainment Computing*, *13*, 1–9. https://doi.org/10.1016/j.entcom.2016.01.001

Anderson, A. P., Mayer, M. D., Fellows, A. M., Cowan, D. R., Hegel, M. T., & Buckey, J. C. (2017). Relaxation with Immersive Natural Scenes Presented Using Virtual Reality. *Aerospace Medicine and Human Performance*, *88*(6), 520–526. https://doi.org/10.3357/Amhp.4747.2017

Anderson, T., Berry, N. T., & Wideman, L. (2019). Exercise and the hypothalamic–pituitary–adrenal axis: A special focus on acute cortisol and growth hormone responses. *Current Opinion in Endocrine and Metabolic Research*, *9*, 74–77. https://doi.org/10.1016/j.coemr.2019.08.002

Anthes, C., García-Hernández, R. J., Wiedemann, M., & Kranzlmüller, D. (2016). State of the art of virtual reality technology. *2016 IEEE Aerospace Conference*, 1–19. https://doi.org/10.1109/AERO.2016.7500674

Arcioni, B., Palmisano, S., Apthorp, D., & Kim, J. (2019). Postural stability predicts the likelihood of cybersickness in active HMD-based virtual reality. *Displays*, *58*, 3–11. https://doi.org/10.1016/j.displa.2018.07.001

Balci, S., & Ahi, B. (2017). Mind the gap! Differences between parents' childhood games and their children's game preferences. *Contemporary Issues in Early Childhood*, *18*(4), 434–442. https://doi.org/10.1177/1463949117742788

Berto, R. (2005). Exposure to restorative environments helps restore attentional capacity. *Journal of Environmental Psychology*, *25*(3), 249–259. https://doi.org/10.1016/j.jenvp.2005.07.001

Bonato, F., Bubka, A., & Paumisano, S. (2009). Combined Pitch and Roll and Cybersickness in a Virtual Environment. *Aviation Space and Environmental Medicine*, *80*(11), 941–945. https://doi.org/10.3357/Asem.2394.2009

Borg, G. A. V. (1982). Psychophysical bases of perceived exertion: *Medicine & Science in Sports & Exercise*, *14*(5), 377???381. https://doi.org/10.1249/00005768-198205000-00012

Botella, C., Fernandez-Alvarez, J., Guillen, V., Garcia-Palacios, A., & Banos, R. (2017). Recent Progress in Virtual Reality Exposure Therapy for Phobias: A Systematic Review. *Curr Psychiatry Rep*, *19*(7), 42. https://doi.org/10.1007/s11920-017-0788-4

Bowler, D. E., Buyung-Ali, L. M., Knight, T. M., & Pullin, A. S. (2010). A systematic review of evidence for the added benefits to health of exposure to natural environments. *BMC Public Health*, *10*, 456. https://doi.org/10.1186/1471-2458-10-456

Bowman, D. A., & McMahan, R. P. (2007). Virtual reality: How much immersion is enough? *Computer*, *40*(7), 36-+. https://doi.org/Doi 10.1109/Mc.2007.257

Breitenbecher, K. H., & Fuegen, K. (2019). Nature and Exercise Interact to Influence Perceived Restorativeness. *Ecopsychology*, *11*(1), 33–42. https://doi.org/10.1089/eco.2018.0056

Browning, M. H. E. M., Mimnaugh, K. J., van Riper, C. J., & Laurent, H. K. (2019). Can Simulated Nature Support Mental Health? Comparing Short, Single-Doses of 360-Degree Nature Videos in Virtual Reality With the Outdoors. *Frontiers in Psychology*. https://doi.org/10.3389/fpsyg.2019.02667

Browning, M. H. E. M., Saeidi-Rizi, F., McAnirlin, O., Yoon, H., & Pei, Y. (2020). The Role of Methodological Choices in the Effects of Experimental Exposure to Simulated Natural Landscapes on Human Health and Cognitive Performance: A Systematic Review. *Environment and Behavior*, 0013916520906481. https://doi.org/10.1177/0013916520906481

Browning, M. H. E. M., Shipley, N., McAnirlin, O., Becker, D., Yu, C.-P., Hartig, T., & Dzhambov, A. M. (2020). An Actual Natural Setting Improves Mood Better Than Its Virtual Counterpart: A Meta-Analysis of Experimental Data. *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.02200

Calogiuri, G., & Chroni, S. (2014). The impact of the natural environment on the promotion of active living: An integrative systematic review. *BMC Public Health*, *14*. https://doi.org/Artn 873 10.1186/1471-2458-14-873

Calogiuri, G., Mikkila, S., & Weydahl, A. (2013). *Can Promotion of Outdoor Activities Impact People's Vitamin D Levels? Promising Findings from a Pilot Study*. In EIIC - Proceedings in EIIC - The 2nd Electronic International Interdisciplinary Conference.

Calogiuri, G., Nordtug, H., & Weydahl, A. (2015). The Potential of Using Exercise in Nature as an Intervention to Enhance Exercise Behavior: Results from a Pilot Study. *Perceptual and Motor Skills*, *121*(2), 350–370. https://doi.org/10.2466/06.PMS.121c17x0

Calogiuri, G., Patil, G. G., & Aamodt, G. (2016). Is Green Exercise for All? A Descriptive Study of Green Exercise Habits and Promoting Factors in Adult Norwegians. *International Journal of Environmental Research and Public Health*, *13*(11). https://doi.org/Artn 1165 10.3390/Ijerph13111165

Capaldi, C. A., Dopko, R. L., & Zelenski, J. M. (2014). The relationship between nature connectedness and happiness: A meta-analysis. *Frontiers in Psychology*, *5*, 976. https://doi.org/10.3389/fpsyg.2014.00976

Carvalho, C., Sunnerhagen, K. S., & Willén, C. (2010). Walking speed and distance in different environments of subjects in the later stage post-stroke. *Physiotherapy Theory and Practice*, *26*(8), 519–527. https://doi.org/10.3109/09593980903585042

Chan, S. H. M., Qiu, L., Esposito, G., Mai, K. P., Tam, K.-P., & Cui, J. (2021). Nature in virtual reality improves mood and reduces stress: Evidence from young adults and senior citizens. *Virtual Reality*. https://doi.org/10.1007/s10055-021-00604-4

Chang, E., Kim, H. T., & Yoo, B. (2020). Virtual Reality Sickness: A Review of Causes and Measurements. *International Journal of Human–Computer Interaction*, *0*(0), 1–25. https://doi.org/10.1080/10447318.2020.1778351

Chardonnet, J. R., Mirzaei, M. A., & Merienne, F. (2017). Features of the Postural Sway Signal as Indicators to Estimate and Predict Visually Induced Motion Sickness in Virtual Reality. *International Journal of Human-Computer Interaction*, *33*(10), 771–785. https://doi.org/10.1080/10447318.2017.1286767

Chirico, A., & Gaggioli, A. (2019). When Virtual Feels Real: Comparing Emotional Responses and Presence in Virtual and Natural Environments. *Cyberpsychol Behav Soc Netw*, *22*(3), 220–226. https://doi.org/10.1089/cyber.2018.0393

Chung, K., Lee, D., & Park, J. Y. (2018). Involuntary Attention Restoration During Exposure to Mobile-Based 360 degrees Virtual Nature in Healthy Adults With Different Levels of Restorative Experience: Event-Related Potential Study. *Journal of Medical Internet Research*, *20*(11). https://doi.org/ARTN e11152 10.2196/11152

Clements, R. (2004). An Investigation of the Status of Outdoor Play. *Contemporary Issues in Early Childhood*, *5*(1), 68–80. https://doi.org/10.2304/ciec.2004.5.1.10

Corazon, S. S., Sidenius, U., Poulsen, D. V., Gramkow, M. C., & Stigsdotter, U. K. (2019). Psycho-Physiological Stress Recovery in Outdoor Nature-Based Interventions: A Systematic Review of the Past Eight Years of Research. *International Journal of Environmental Research and Public Health*, *16*(10). https://doi.org/10.3390/ijerph16101711

Cummings, J. J., & Bailenson, J. N. (2016). How Immersive Is Enough? A Meta-Analysis of the Effect of Immersive Technology on User Presence. *Media Psychology*, *19*(2), 272–309. https://doi.org/10.1080/15213269.2015.1015740

Danermark, B., Ekström, M., & Karlsson, J. C. (2019). *Explaining Society: Critical Realism in the Social Sciences*. Routledge.

Darcy, P., Jones, M., & Gidlow, C. (2019). Affective responses to natural environments. In *Physical activity in natural settings* (1st ed., Vol. 1, pp. 128–151). Routledge.

de Kort, Y. A. W., Meijnders, A. L., Sponselee, A. A. G., & IJsselsteijn, W. A. (2006). What's wrong with virtual trees? Restoring from stress in a mediated environment. *Journal of Environmental Psychology*, *26*(4), 309–320. https://doi.org/10.1016/j.jenvp.2006.09.001

Dishman, R. K., Sallis, J. F., & Orenstein, D. R. (1985). The determinants of physical activity and exercise. *Public Health Reports*, *100*(2), 158–171.

Duncan, M. J., Clarke, N. D., Birch, S. L., Tallis, J., Hankey, J., Bryant, E., & Eyre, E. L. J. (2014). The Effect of Green Exercise on Blood Pressure, Heart Rate and Mood State in Primary School Children. *International Journal of Environmental Research and Public Health*, *11*(4), 3678–3688. https://doi.org/10.3390/ijerph110403678

Duzmanska, N., Strojny, P., & Strojny, A. (2018). Can Simulator Sickness Be Avoided? A Review on Temporal Aspects of Simulator Sickness. *Frontiers in Psychology*, *9*. https://doi.org/ARTN 2132 10.3389/fpsyg.2018.02132

Ekkekakis, P., Hall, E. E., VanLanduyt, L. M., & Petruzzello, S. J. (2000). Walking in (affective) circles: Can short walks enhance affect? *Journal of Behavioral Medicine*, *23*(3), 245–275. https://doi.org/10.1023/a:1005558025163

Fast Facts on U.S. Hospitals, 2021 | AHA. (n.d.). Retrieved June 16, 2021, from https://www.aha.org/statistics/fast-facts-us-hospitals

Focht, B. C. (2009). Brief Walks in Outdoor and Laboratory Environments: Effects on Affective Responses, Enjoyment, and Intentions to Walk for Exercise. *Research Quarterly for Exercise and Sport*, *80*(3), 611–620.

Frumkin, H., Bratman, G. N., Breslow, S. J., Cochran, B., Kahn, P. H., Lawler, J. J., Levin, P. S., Tandon, P. S., Varanasi, U., Wolf, K. L., & Wood, S. A. (2017). Nature Contact and Human Health: A Research Agenda. *Environmental Health Perspectives*, *125*(7). https://doi.org/Artn 075001 10.1289/Ehp1663

Fulvio, J. M., Ji, M., & Rokers, B. (2019). Variability in Sensory Sensitivity Predicts Motion Sickness in Virtual Reality. *BioRxiv*, 488817. https://doi.org/10.1101/488817

Garber, C. E., Blissmer, B., Deschenes, M. R., Franklin, B. A., Lamonte, M. J., Lee, I. M., Nieman, D. C., Swain, D. P., & American College of Sports, M. (2011). American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: Guidance for prescribing exercise. *Med Sci Sports Exerc*, *43*(7), 1334–1359. https://doi.org/10.1249/MSS.0b013e318213fefb

Gatersleben, B., & Andrews, M. (2013). When walking in nature is not restorative-the role of prospect and refuge. *Health & Place*, *20*, 91–101. https://doi.org/10.1016/j.healthplace.2013.01.001

Gavgani, A. M., Nesbitt, K. V., Blackmore, K. L., & Nalivaiko, E. (2017). Profiling subjective symptoms and autonomic changes associated with cybersickness. *Auton Neurosci*, *203*, 41–50. https://doi.org/10.1016/j.autneu.2016.12.004

Gene, M., Travis, J., Doug, C., & Erinn, M. (n.d.). *Next mega tech theme is virtual reality*. Retrieved May 7, 2021, from https://docplayer.net/39687573-Next-mega-tech-theme-is-virtual-reality.html

Geng, L., Xu, J., Ye, L., Zhou, W., & Zhou, K. (2015). Connections with nature and environmental behaviors. *PLoS One*, *10*(5), e0127247. https://doi.org/10.1371/journal.pone.0127247

Ghadieh, A. S., & Saab, B. (2015). Evidence for exercise training in the management of hypertension in adults. *Canadian Family Physician*, *61*(3), 233–239.

Gladwell, V. F., Brown, D. K., Wood, C., Sandercock, G. R., & Barton, J. L. (2013). The great outdoors: How a green exercise environment can benefit all. *Extrem Physiol Med*, *2*(1), 3. https://doi.org/10.1186/2046-7648-2-3

Godin, G., & Shephard, R. (1985). A simple method to assess exercise behavior in the community. *Canadian Journal of Applied Sport Science*, *10*(3), 141–146.

Grassini, S., Laumann, K., & Rasmussen Skogstad, M. (2020). The Use of Virtual Reality Alone Does Not Promote Training Performance (but Sense of Presence Does). *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.01743

Guna, J., Gersak, G., Humar, I., Song, J., Drnovsek, J., & Pogacnik, M. (2019). Influence of video content type on users’ virtual reality sickness perception and physiological response. *Future Generation Computer Systems-the International Journal of Escience*, *91*, 263–276. https://doi.org/10.1016/j.future.2018.08.049

Hagströmer, M., & Hassmén, P. (2009). Vurdere og styre fysisk aktivitet. In *Aktivitetshåndboken. Fysisk aktivitet i forebygging og behandling* (pp. 117–135). Helsedirektoratet.

Haluza, D., Schönbauer, R., & Cervinka, R. (2014). Green Perspectives for Public Health: A Narrative Review on the Physiological Effects of Experiencing Outdoor Nature. *International Journal of Environmental Research and Public Health*, *11*(5), 5445–5461. https://doi.org/10.3390/ijerph110505445

Harris-Kojetin, L., Sengupta, M., Park-Lee, E., Valverde, R., Caffrey, C., Rome, V., & Lendon, J. (2016). Long-Term Care Providers and services users in the United States: Data from the National Study of Long-Term Care Providers, 2013-2014. *Vital & Health Statistics. Series 3, Analytical and Epidemiological Studies*, *38*, x–xii; 1–105.

Harte, J. L., & Eifert, G. H. (1995). The effects of running, environment, and attentional focus on athletes' catecholamine and cortisol levels and mood. *Psychophysiology*, *32*(1), 49–54.

Hartig, T., Evans, G. W., Jamner, L. D., Davis, D. S., & Garling, T. (2003). Tracking restoration in natural and urban field settings. *Journal of Environmental Psychology*, *23*(2), 109–123. https://doi.org/10.1016/S0272-4944(02)00109-3

Hartig, T., Korpela, K., Evans, G. W., & Gärling, T. (1997). A measure of restorative quality in environments. *Scandinavian Housing and Planning Research*, *14*(4), 175–194. https://doi.org/10.1080/02815739708730435

Hartig, T., Mang, M., & Evans, G. W. (1991). Restorative effects of natural environment experiences. *Environment and Behavior*, *23*(1), 3–26. https://doi.org/10.1177/0013916591231001

Hedblom, M., Gunnarsson, B., Iravani, B., Knez, I., Schaefer, M., Thorsson, P., & Lundstrom, J. N. (2019). Reduction of physiological stress by urban green space in a multisensory virtual experiment. *Scientific Reports*, *9*. https://doi.org/ARTN 10113 10.1038/s41598-019-46099-7

Horlings, C. G., Carpenter, M. G., Kung, U. M., Honegger, F., Wiederhold, B., & Allum, J. H. (2009). Influence of virtual reality on postural stability during movements of quiet stance. *Neurosci Lett*, *451*(3), 227–231. https://doi.org/10.1016/j.neulet.2008.12.057

Hunter, M. R., Gillespie, B. W., & Chen, S. Y.-P. (2019). Urban Nature Experiences Reduce Stress in the Context of Daily Life Based on Salivary Biomarkers. *Frontiers in Psychology*, *10*. https://doi.org/10.3389/fpsyg.2019.00722

IPBES. (2019). *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.*

Jiang, B., He, J., Chen, J., Larsen, L., & Wang, H. (2020). Perceived Green at Speed: A Simulated Driving Experiment Raises New Questions for Attention Restoration Theory and Stress Reduction Theory. *Environment and Behavior*, 0013916520947111. https://doi.org/10.1177/0013916520947111

Joseph, A., Browning, M. H. E. M., & Jiang, S. (2020). Using Immersive Virtual Environments (IVEs) to Conduct Environmental Design Research: A Primer and Decision Framework. *HERD*, 1937586720924787. https://doi.org/10.1177/1937586720924787

Kahn, P. H., Severson, R. L., & Ruckert, J. H. (2009). The Human Relation With Nature and Technological Nature. *Current Directions in Psychological Science*, *18*(1), 37–42. https://doi.org/10.1111/j.1467-8721.2009.01602.x

Kajosaari, A., & Pasanen, T. P. (2021). Restorative benefits of everyday green exercise: A spatial approach. *Landscape and Urban Planning*, *206*, 103978. https://doi.org/10.1016/j.landurbplan.2020.103978

Kaplan, R. (1989). *The Experience of Nature: A Psychological Perspective*. Cambridge University Press.

Kaplan, S. (1995). The Restorative Benefits of Nature—Toward an Integrative Framework. *Journal of Environmental Psychology*, *15*(3), 169–182. https://doi.org/Doi 10.1016/0272-4944(95)90001-2

Kennedy, R. S., Drexler, J., & Kennedy, R. C. (2010). Research in visually induced motion sickness. *Applied Ergonomics*, *41*(4), 494–503. https://doi.org/10.1016/j.apergo.2009.11.006

Kennedy, R. S., Drexler, J. M., Compton, D. E., Stanney, K. M., Lanham, D. S., & Harm, D. L. (2003). Configural scoring of simulator sickness, cybersickness, and space adaptation syndrome: Similarities and differences. In *Virtual and adaptive environments: Applications, implications, and human performance issues* (pp. 247–278). Lawrence Erlbaum Associates Publishers. https://doi.org/10.1201/9781410608888.ch12

Kennedy, R. S., Lane, N., Berbaum, K., & Lilienthal, M. (1993). Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology*, *3*(3), 203–220.

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., Behar, J. V., Hern, S. C., & Engelmann, W. H. (2001). The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants. *Journal of Exposure Analysis and Environmental Epidemiology*, *11*(3), 231–252. https://doi.org/10.1038/sj.jea.7500165

Kober, S. E., & Neuper, C. (2013). Personality and Presence in Virtual Reality: Does Their Relationship Depend on the Used Presence Measure? *International Journal of Human–Computer Interaction*, *29*(1), 13–25. https://doi.org/10.1080/10447318.2012.668131

Kotera, Y., Lyons, M., Vione, K. C., & Norton, B. (2021). Effect of Nature Walks on Depression and Anxiety: A Systematic Review. *Sustainability*, *13*(7), 1–17.

Krefis, A. C., Augustin, M., Schlünzen, K. H., Oßenbrügge, J., & Augustin, J. (2018). How Does the Urban Environment Affect Health and Well-Being? A Systematic Review. *Urban Science*, *2*(1), 21. https://doi.org/10.3390/urbansci2010021

Kuo, M. (2015). How might contact with nature promote human health? Promising mechanisms and a possible central pathway. *Frontiers in Psychology*, *6*. https://doi.org/ARTN 1093 10.3389/fpg.2015.01093

Lacharité-Lemieux, M., Brunelle, J.-P., & Dionne, I. J. (2015). Adherence to exercise and affective responses: Comparison between outdoor and indoor training. *Menopause (New York, N.Y.)*, *22*(7), 731–740. https://doi.org/10.1097/GME.0000000000000366

Lackner, J. R. (2014). Motion sickness: More than nausea and vomiting. *Experimental Brain Research*, *232*(8), 2493–2510. https://doi.org/10.1007/s00221-014-4008-8

Lahart, I., Darcy, P., Gidlow, C., & Calogiuri, G. (2019). The Effects of Green Exercise on Physical and Mental Wellbeing: A Systematic Review. *Int J Environ Res Public Health*, *16*(8). https://doi.org/10.3390/ijerph16081352

Larson, L., Szczytko, R., Bowers, E., Stephens, L., Stevenson, K., & Floyd, M. (2018). Outdoor Time, Screen Time, and Connection to Nature: Troubling Trends Among Rural Youth? *Environment and Behavior*, 1–26. https://doi.org/10.1177/0013916518806686

LaViola, J. (2000). A Discussion of Cybersickness in Virtual Environments. *ACM SIGCHI Bull.*, *32*(1), 47–56. https://doi.org/10.1145/333329.333344

Levi, D., & Kocher, S. (1999). Virtual nature—The future effects of information technology on our relationship to nature. *Environment and Behavior*, *31*(2), 203–226. https://doi.org/Doi 10.1177/00139169921972065

Lindquist, M., Maxim, B., Proctor, J., & Dolins, F. (2020). The effect of audio fidelity and virtual reality on the perception of virtual greenspace. *Landscape and Urban Planning*, *202*, 103884. https://doi.org/10.1016/j.landurbplan.2020.103884

Liszio, S., Graf, L., & Masuch, M. (2018). The Relaxing Effect of Virtual Nature: Immersive Technology Provides Relief in Acute Stress Situations. *Annual Review of Cybertherapy and Telemedicine*, *16*, 87–93.

Lo, W. T., & So, R. H. Y. (2001). Cybersickness in the presence of scene rotational movements along different axes. *Applied Ergonomics*, *32*(1), 1–14. https://doi.org/Doi 10.1016/S0003-6870(00)00059-4

Lox, C., Jackson, S., Tuholski, S., Wasley, D., & Treasure, D. (2000). Revisiting the measurement of exercise-induced feeling states: The physical activity affect scale (PAAS). *Meas. Phys. Educ. Exerc. Sci.*, *4*, 79–95. https://doi.org/10.1207/S15327841Mpee0402_4

Mach, C., Foster, C., Brice, G., Mikat, R. P., & Porcari, J. P. (2005). Effect of exercise duration on postexercise hypotension. *Journal of Cardiopulmonary Rehabilitation*, *25*(6), 366–369. https://doi.org/10.1097/00008483-200511000-00010

Mayer, F. S., Frantz, C. M., Bruehlman-Senecal, E., & Dolliver, K. (2009). Why Is Nature Beneficial? The Role of Connectedness to Nature. *Environment and Behavior*, *41*(5), 607–643. https://doi.org/10.1177/0013916508319745

McCauley, M. E., & Sharkey, T. J. (1992). Cybersickness: Perception of Self-Motion in Virtual Environments. *Presence: Teleoperators and Virtual Environments*, *1*(3), 311–318. https://doi.org/10.1162/pres.1992.1.3.311

McMahan, E. A., & Estes, D. (2015). The effect of contact with natural environments on positive and negative affect: A meta-analysis. *The Journal of Positive Psychology*, *10*(6), 507–519. https://doi.org/10.1080/17439760.2014.994224

Meredith, G. R., Rakow, D. A., Eldermire, E. R. B., Madsen, C. G., Shelley, S. P., & Sachs, N. A. (2020). Minimum Time Dose in Nature to Positively Impact the Mental Health of College-Aged Students, and How to Measure It: A Scoping Review. *Frontiers in Psychology*, *10*. https://doi.org/10.3389/fpsyg.2019.02942

Merhi, O., Faugloire, E., Flanagan, M., & Stoffregen, T. A. (2007). Motion sickness, console video games, and head-mounted displays. *Human Factors*, *49*(5), 920–934. https://doi.org/10.1518/001872007X230262

Mieras, M. E., Heesch, M. W. S., & Slivka, D. R. (2014). Physiological and Psychological Responses to Outdoor vs. Laboratory Cycling. *The Journal of Strength & Conditioning Research*, *28*(8), 2324–2329. https://doi.org/10.1519/JSC.0000000000000384

Mittelstaedt, J. M. (2020). Individual predictors of the susceptibility for motion-related sickness: A systematic review. *Journal of Vestibular Research: Equilibrium & Orientation*, *30*(3), 165–193. https://doi.org/10.3233/VES-200702

Moeller, C., King, N., Burr, V., Gibbs, G. R., & Gomersall, T. (2018). Nature-based interventions in institutional and organisational settings: A scoping review. *International Journal of Environmental Health Research*, *28*(3), 293–305. https://doi.org/10.1080/09603123.2018.1468425

Mostajeran, F., Krzikawski, J., Steinicke, F., & Kühn, S. (2021). Effects of exposure to immersive videos and photo slideshows of forest and urban environments. *Scientific Reports*, *11*(1), 3994. https://doi.org/10.1038/s41598-021-83277-y

Munafo, J., Diedrick, M., & Stoffregen, T. A. (2017). The virtual reality head-mounted display Oculus Rift induces motion sickness and is sexist in its effects. *Experimental Brain Research*, *235*(3), 889–901. https://doi.org/10.1007/s00221-016-4846-7

Murata, A. (2004). Effects of duration of immersion in a virtual reality environment on postural stability. *International Journal of Human-Computer Interaction*, *17*(4), 463–477. https://doi.org/DOI 10.1207/s15327590ijhc1704_2

Nichols, S., Haldane, C., & Wilson, J. R. (2000). Measurement of presence and its consequences in virtual environments. *International Journal of Human-Computer Studies*, *52*(3), 471–491. https://doi.org/DOI 10.1006/ijhc.1999.0343

Nishiike, S., Okazaki, S., Watanabe, H., Akizuki, H., Imai, T., Uno, A., Kitahara, T., Horii, A., Takeda, N., & Inohara, H. (2013). The effect of visual-vestibulosomatosensory conflict induced by virtual reality on postural stability in humans. *The Journal of Medical Investigation*, *60*, 236–239.

Norman, G. (2010). Likert scales, levels of measurement and the “laws” of statistics. *Advances in Health Sciences Education*, *15*(5), 625–632. https://doi.org/10.1007/s10459-010-9222-y

Nukarinen, T., Istance, H. O., Rantala, J., Mäkelä, J., Korpela, K., Ronkainen, K., Surakka, V., & Raisamo, R. (2020). Physiological and Psychological Restoration in Matched Real and Virtual Natural Environments. *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*, 1–8. https://doi.org/10.1145/3334480.3382956

Okoro, C. A. (2018). Prevalence of Disabilities and Health Care Access by Disability Status and Type Among Adults—United States, 2016. *MMWR. Morbidity and Mortality Weekly Report*, *67*. https://doi.org/10.15585/mmwr.mm6732a3

Oman, C. M. (1990). Motion sickness: A synthesis and evaluation of the sensory conflict theory. *Can J Physiol Pharmacol*, *68*(2), 294–303. https://doi.org/10.1139/y90-044

Paillard, A. C., Quarck, G., Paolino, F., Denise, P., Paolino, M., Golding, J. F., & Ghulyan-Bedikian, V. (2013). Motion sickness susceptibility in healthy subjects and vestibular patients: Effects of gender, age and trait-anxiety. *J Vestib Res*, *23*(4–5), 203–209. https://doi.org/10.3233/VES-130501

Paillard, T., & Noe, F. (2015). Techniques and Methods for Testing the Postural Function in Healthy and Pathological Subjects. *Biomed Res Int*, *2015*, 891390. https://doi.org/10.1155/2015/891390

Palmisano, S., Arcioni, B., & Stapley, P. J. (2018). Predicting vection and visually induced motion sickness based on spontaneous postural activity. *Experimental Brain Research*, *236*(1), 315–329. https://doi.org/10.1007/s00221-017-5130-1

Pasek, M., Szark-Eckardt, M., Wilk, B., Zuzda, J., Żukowska, H., Opanowska, M., Kuska, M., Dróżdż, R., Kuśmierczyk, M., Sakłak, W., & Kupcewicz, E. (2020). Physical Fitness as Part of the Health and Well-Being of Students Participating in Physical Education Lessons Indoors and Outdoors. *International Journal of Environmental Research and Public Health*, *17*(1), 309. https://doi.org/10.3390/ijerph17010309

Patient statistics. (n.d.). SSB. Retrieved June 16, 2021, from https://www.ssb.no/en/helse/helsetjenester/statistikk/pasienter-pa-sykehus

Pinchoff, J., Mills, C. W., & Balk, D. (2020). Urbanization and health: The effects of the built environment on chronic disease risk factors among women in Tanzania. *PLOS ONE*, *15*(11), e0241810. https://doi.org/10.1371/journal.pone.0241810

Plante, T. G., Frazier, S., Tittle, A., Babula, M., Ferlic, E., & Riggs, E. (2003). Does virtual reality enhance the psychological benefits of exercise? *Journal of Human Movement Studies*, *45*(6), 485–507.

Pouke, M., Tiiro, A., LaValle, S. M., & Ojala, T. (2018). Effects of Visual Realism and Moving Detail on Cybersickness. *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 665–666. https://doi.org/10.1109/VR.2018.8446078

Pretty, J., Griffin, M., Sellens, M., & Pretty, C. (2003). *Green Exercise: Complementary Roles of Nature, Exercise and Diet in Physical and Emotional Well-Being and Implications for Public Health Policy*.

Pretty, J., Peacock, J., Sellens, M., & Griffin, M. (2005). The mental and physical health outcomes of green exercise. *International Journal of Environmental Health Research*, *15*(5), 319–337. https://doi.org/10.1080/09603120500155963

Reason, J. T. (1978). Motion sickness adaptation: A neural mismatch model. *J R Soc Med*, *71*(11), 819–829.

Reason, J. T., & Brand, J. J. (1975). *Motion Sickness*. Cambridge, MA: Academic Press.

Rebenitsch, L., & Owen, C. (2016). Review on cybersickness in applications and visual displays. *Virtual Reality*, *20*(2), 101–125. https://doi.org/10.1007/s10055-016-0285-9

Riccio, G. E., & Stoffregen, T. A. (1991). An ecological theory of motion sickness and postural instability. *Ecological Psychology*, *3*(3), 195–240.

Risi, D., & Palmisano, S. (2019). Effects of postural stability, active control, exposure duration and repeated exposures on HMD induced cybersickness. *Displays*, *60*, 9–17. https://doi.org/10.1016/j.displa.2019.08.003

Rogerson, M., & Barton, J. (2015). Effects of the Visual Exercise Environments on Cognitive Directed Attention, Energy Expenditure and Perceived Exertion. *International Journal of Environmental Research and Public Health*, *12*(7), 7321–7336. https://doi.org/10.3390/ijerph120707321

Rogerson, M., Barton, J., Pretty, J., & Gladwell, V. (2019). The green exercise concept: To intertwining pathways to health and well-being. In *Physical activity in natural setting: Green and blue exercise* (1st ed., pp. 75–94). Routledge.

Rogerson, M., Wood, C., Pretty, J., Schoenmakers, P., Bloomfield, D., & Barton, J. (2020). Regular Doses of Nature: The Efficacy of Green Exercise Interventions for Mental Wellbeing. *International Journal of Environmental Research and Public Health*, *17*(5). https://doi.org/10.3390/ijerph17051526

Rottenberg, J., Ray, R. D., & Gross, J. J. (2007). Emotion elicitation using films. In *Handbook of emotion elicitation and assessment* (pp. 9–28). Oxford University Press.

Russell, J. A. (1980). A Circumplex Model of Affect. *Journal of Personality and Social Psychology*, *39*(6), 1161–1178. https://doi.org/DOI 10.1037/h0077714

Sacau, A., Laarni, J., & Hartmann, T. (2008). Influence of individual factors on presence. *Computers in Human Behavior*, *24*(5), 2255–2273. https://doi.org/10.1016/j.chb.2007.11.001

Saredakis, D., Szpak, A., Birckhead, B., Keage, H. A. D., Rizzo, A., & Loetscher, T. (2020). Factors Associated With Virtual Reality Sickness in Head-Mounted Displays: A Systematic Review and

Meta-Analysis. *Frontiers in Human Neuroscience*, *14*. https://doi.org/10.3389/fnhum.2020.00096

Schebella, M. F., Weber, D., Schultz, L., & Weinstein, P. (2020). The Nature of Reality: Human Stress Recovery during Exposure to Biodiverse, Multisensory Virtual Environments. *International Journal of Environmental Research and Public Health*, *17*(1), 56. https://doi.org/10.3390/ijerph17010056

Scott, D., & Jackson, E. L. (1996). Factors That Limit and Strategies That Might Encourage People's Use of Public Parks. *Journal of Park and Recreation Administration*, *14*(1), Article 1. https://js.sagamorepub.com/jpra/article/view/1722

Selby, S., Hayes, C., O'Sullivan, N., O'Neil, A., & Harmon, D. (2019). Facilitators and barriers to green exercise in chronic pain. *Irish Journal of Medical Science (1971 -)*, *188*(3), 973–978. https://doi.org/10.1007/s11845-018-1923-x

Senese, V. P., Pascale, A., Maffei, L., Cioffi, F., Sergi, I., Gnisci, A., & Masullo, M. (2020). The Influence of Personality Traits on the Measure of Restorativeness in an Urban Park: A Multisensory Immersive Virtual Reality Study. In A. Esposito, M. Faundez-Zanuy, F. C. Morabito, & E. Pasero (Eds.), *Neural Approaches to Dynamics of Signal Exchanges*. Springer.

Shanahan, D. F., Fuller, R. A., Bush, R., Lin, B. B., & Gaston, K. J. (2015). The Health Benefits of Urban Nature: How Much Do We Need? *BioScience*, *65*(5), 476–485. https://doi.org/10.1093/biosci/biv032

Sharples, S., Cobb, S., Moody, A., & Wilson, J. R. (2008). Virtual reality induced symptoms and effects (VRISE): Comparison of head mounted display (HMD), desktop and projection display systems. *Displays*, *29*(2), 58–69. https://doi.org/10.1016/j.displa.2007.09.005

Sherman, W. R., & Craig, A. B. (2003). *Understanding virtual reality. Interface, application, and design*. Morgan Kaufmann Publishers.

Slater, M., Usoh, M., & Steed, A. (1995). Taking Steps: The influence of a Walking Technique on Presence in Virtual Reality. *ACM Transactions on Computer-Human Interaction*, *2*(3), 201–219.

Slater, M., & Wilbur, S. (1997). A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments. *Presence-Teleoperators and Virtual Environments*, *6*(6), 603–616. https://doi.org/DOI 10.1162/pres.1997.6.6.603

Smith, J. W. (2015). Immersive Virtual Environment Technology to Supplement Environmental Perception, Preference and Behavior Research: A Review with Applications. *International Journal of Environmental Research and Public Health*, *12*(9), 11486–11505. https://doi.org/10.3390/ijerph120911486

Somrak, A., Humar, I., Hossain, M. S., Alhamid, M. F., Hossain, M. A., & Guna, J. (2019). Estimating VR Sickness and user experience using different HMD technologies: An evaluation study. *Future Generation Computer Systems-the International Journal of Escience*, *94*, 302–316. https://doi.org/10.1016/j.future.2018.11.041

Steuer, J. (1992). Defining Virtual Reality—Dimensions Determining Telepresence. *Journal of Communication*, *42*(4), 73–93. https://doi.org/DOI 10.1111/j.1460-2466.1992.tb00812.x

Stoffregen, T. A., & Smart, L. J. (1998). Postural instability precedes motion sickness. *Brain Research Bulletin*, *47*(5), 437–448. https://doi.org/Doi 10.1016/S0361-9230(98)00102-6

Stoffregen, T. A., Yoshida, K., Villard, S., Scibora, L., & Bardy, B. G. (2010). Stance Width Influences Postural Stability and Motion Sickness. *Ecological Psychology*, *22*(3), 169–191. https://doi.org/Pii 925052743 10.1080/10407413.2010.496645

Thompson, P. D., Crouse, S. F., Goodpaster, B., Kelley, D., Moyna, N., & Pescatello, L. (2001). The acute versus the chronic response to exercise. *Medicine & Science in Sports & Exercise*, *33*(6), S438.

Triberti, S., Repetto, C., & Riva, G. (2014). Psychological factors influencing the effectiveness of virtual reality-based analgesia: A systematic review. *Cyberpsychol Behav Soc Netw*, *17*(6), 335–345. https://doi.org/10.1089/cyber.2014.0054

Twohig-Bennett, C., & Jones, A. (2018). The health benefits of the great outdoors: A systematic review and meta-analysis of greenspace exposure and health outcomes. *Environmental Research*, *166*, 628–637. https://doi.org/10.1016/j.envres.2018.06.030

Ulrich, R. S., Simons, R. F., Losito, B. D., Fiorito, E., Miles, M. A., & Zelson, M. (1991). Stress recovery during exposure to natural and urban environments. *Journal of Environmental Psychology*, *11*(3), 201–230. https://doi.org/10.1016/S0272-4944(05)80184-7

UN. (2018). *World Urbanization Prospects: The 2018 Revision [key facts]*.

Valtchanov, D., Barton, K. R., & Ellard, C. (2010). Restorative Effects of Virtual Nature Settings. *Cyberpsychology Behavior and Social Networking*, *13*(5), 503–512. https://doi.org/10.1089/cyber.2009.0308

Virtual Boy. (2021). In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Virtual_Boy&oldid=1021498219

Wang, T.-C., Sit, C. H.-P., Tang, T.-W., & Tsai, C.-L. (2020). Psychological and Physiological Responses in Patients with Generalized Anxiety Disorder: The Use of Acute Exercise and Virtual Reality Environment. *International Journal of Environmental Research and Public Health*, *17*(13), 4855. https://doi.org/10.3390/ijerph17134855

Wang, X., Shi, Y., Zhang, B., & Chiang, Y. (2019). The Influence of Forest Resting Environments on Stress Using Virtual Reality. *International Journal of Environmental Research and Public Health*, *16*(18), 3263. https://doi.org/10.3390/ijerph16183263

Warburton, D. E. R., Nicol, C. W., & Bredin, S. S. D. (2006). Health benefits of physical activity: The evidence. *CMAJ : Canadian Medical Association Journal*, *174*(6), 801–809. https://doi.org/10.1503/cmaj.051351

Weech, S., Kenny, S., & Barnett-Cowan, M. (2019). Presence and Cybersickness in Virtual Reality Are Negatively Related: A Review. *Frontiers in Psychology*, *10*. https://doi.org/ARTN 158 10.3389/fpsyg.2019.00158

Weech, S., Varghese, J. P., & Barnett-Cowan, M. (2018). Estimating the sensorimotor components of cybersickness. *Journal of Neurophysiology*, *120*(5), 2201–2217. https://doi.org/10.1152/jn.00477.2018

White, M. P., Alcock, I., Grellier, J., Wheeler, B. W., Hartig, T., Warber, S. L., Bone, A., Depledge, M. H., & Fleming, L. E. (2019). Spending at least 120 minutes a week in nature is associated with good health and wellbeing. *Sci Rep*, *9*(1), 7730. https://doi.org/10.1038/s41598-019-44097-3

White, M. P., Elliott, L. R., Grellier, J., Economou, T., Bell, S., Bratman, G. N., Cirach, M., Gascon, M., Lima, M. L., Lõhmus, M., Nieuwenhuijsen, M., Ojala, A., Roiko, A., Schultz, P. W., van den Bosch, M., & Fleming, L. E. (2021). Associations between green/blue spaces and mental health across 18 countries. *Scientific Reports*, *11*(1), 8903. https://doi.org/10.1038/s41598-021-87675-0

White, M. P., Elliott, L. R., Taylor, T., Wheeler, B. W., Spencer, A., Bone, A., Depledge, M. H., & Fleming, L. E. (2016). Recreational physical activity in natural environments and implications for health: A population based cross-sectional study in England. *Preventive Medicine*, *91*, 383–388. https://doi.org/10.1016/j.ypmed.2016.08.023

White, M. P., Pahl, S., Ashbullby, K. J., Burton, F., & Depledge, M. H. (2015). The Effects of Exercising in Different Natural Environments on Psycho-Physiological Outcomes in Post-Menopausal Women: A Simulation Study. *International Journal of Environmental Research and Public Health*, *12*(9), 11929–11953. https://doi.org/10.3390/ijerph120911929

White, M. P., Yeo, N. L., Vassiljev, P., Lundstedt, R., Wallergard, M., Albin, M., & Lohmus, M. (2018). A prescription for “nature”—The potential of using virtual nature in therapeutics. *Neuropsychiatric Disease and Treatment*, *14*, 3001–3013. https://doi.org/10.2147/Ndt.S179038

Wood, C., Flynn, M., Law, R., Naufahu, J., & Smyth, N. (2020). The effect of the visual exercise environment on the response to psychological stress: A pilot study. *Anxiety, Stress, & Coping*, 1–14. https://doi.org/10.1080/10615806.2020.1770231

Wooller, J. J., Rogerson, M., Barton, J., Micklewright, D., & Gladwell, V. (2018). Can Simulated Green Exercise Improve Recovery From Acute Mental Stress? *Frontiers in Psychology*, *9*. https://doi.org/ARTN 2167 10.3389/fpsyg.2018.02167

Yeh, H. P., Stone, J. A., Churchill, S. M., Brymer, E., & Davids, K. (2017). Physical and Emotional Benefits of Different Exercise Environments Designed for Treadmill Running. *International Journal of Environmental Research and Public Health*, *14*(7). https://doi.org/ARTN 752 10.3390/ijerph14070752

Yeo, N. L., White, M. P., Alcock, I., Garside, R., Dean, S. G., Smalley, A. J., & Gatersleben, B. (2020). What is the best way of delivering virtual nature for improving mood? An experimental comparison of high definition TV, 360° video, and computer generated virtual reality. *Journal of Environmental Psychology*, *72*. https://doi.org/10.1016/j.jenvp.2020.101500

Yildirim, C. (2020). Don’t make me sick: Investigating the incidence of cybersickness in commercial virtual reality headsets. *Virtual Reality*, *24*(2), 231–239. https://doi.org/10.1007/s10055-019-00401-0

Yu, C. P., Lee, H. Y., & Luo, X. Y. (2018). The effect of virtual reality forest and urban environments on physiological and psychological responses. *Urban Forestry & Urban Greening*, *35*, 106–114. https://doi.org/10.1016/j.ufug.2018.08.013

Errata

Page	Line	Original text	Corrected text
7	19	*Submitted to Virtual Reality.*	*Virtual Reality.* https://doi.org/10.1007/s10055-022-00670-2
19	31	… primarily interested in the the acute psychophysiological …	… primarily interested in the acute psychophysiological …
25	13	… these two studies alone is not enough to establish best practice, and there is …	… these two studies alone are not enough to establish best practice, and there is …
31	17	… for the creation of the 3d model was obtained from …	… for the creation of the 3D model was obtained from …
31	22	Both v3 and v4 were required considerable computing power and required …	Both v3 and v4 required considerable computing power …
35	23	… using the 20-point version of the Borg scale	using the 15-point version of the Borg scale
51	10	… participants felt that that lack of a holistic nature experience …	… participants felt that lack of a holistic nature experience …
55	18	… outcomes after 3d model based virtual green exercise …	… outcomes after 3D model based virtual green exercise …
65	13	… identifyies perceived exertion as an outcome …	… identifies perceived exertion as an outcome …
66	2	… (median and standard deviation)	… (median and interquartile range)
Appendix: Paper V	First page	*Submitted to Virtual reality*	*Virtual reality.* https://doi.org/10.1007/s10055-022-00670-2
Appendix: Paper V			Included the published version of paper V

Appendix: Paper I

Calogiuri, G., Litleskare, S., Fagerheim, K. A., Rydgren, T. L., Brambilla, E., & Thurston, M. (2018). Experiencing Nature through Immersive Virtual Environments: Environmental Perceptions, Physical Engagement, and Affective Responses during a Simulated Nature Walk. Frontiers in Psychology, 8. https://doi.org/Artn 2321 10.3389/Fpsyg.2017.02321

frontiers
in Psychology

ORIGINAL RESEARCH
published: 23 January 2018
doi: 10.3389/fpsyg.2017.02321

Experiencing Nature through Immersive Virtual Environments: Environmental Perceptions, Physical Engagement, and Affective Responses during a Simulated Nature Walk

Giovanna Calogiuri[1]*, Sigbjørn Litleskare[2], Kaia A. Fagerheim[1], Tore L. Rydgren[1,3], Elena Brambilla[1,4] and Miranda Thurston[1]

[1] Department of Public Health, Faculty of Social and Health Sciences, Inland Norway University of Applied Sciences, Elverum, Norway, [2] Inland Norway School of Sport Sciences, Faculty of Social and Health Sciences, Inland Norway University of Applied Sciences, Elverum, Norway, [3] IT Department, Inland Norway University of Applied Sciences, Elverum, Norway, [4] Department of Biomedical Science for Health, University of Milan, Milan, Italy

OPEN ACCESS

Edited by:
Eric Brymer,
Leeds Beckett University,
United Kingdom

Reviewed by:
Hsiaopu Yeh,
Sheffield Hallam University,
United Kingdom
Susana Alves,
Çankaya University, Turkey

***Correspondence:**
Giovanna Calogiuri
giovanna.calogiuri@inn.no

Specialty section:
This article was submitted to
Environmental Psychology,
a section of the journal
Frontiers in Psychology

Received: 23 October 2017
Accepted: 20 December 2017
Published: 23 January 2018

Citation:
Calogiuri G, Litleskare S,
Fagerheim KA, Rydgren TL,
Brambilla E and Thurston M (2018)
Experiencing Nature through
Immersive Virtual Environments:
Environmental Perceptions, Physical
Engagement, and Affective
Responses during a Simulated Nature
Walk. Front. Psychol. 8:2321.
doi: 10.3389/fpsyg.2017.02321

By combining physical activity and exposure to nature, *green exercise* can provide additional health benefits compared to physical activity alone. Immersive Virtual Environments (IVE) have emerged as a potentially valuable supplement to environmental and behavioral research, and might also provide new approaches to green exercise promotion. However, it is unknown to what extent green exercise in IVE can provide psychophysiological responses similar to those experienced in real natural environments. In this study, 26 healthy adults underwent three experimental conditions: nature walk, sitting-IVE, and treadmill-IVE. The nature walk took place on a paved trail along a large river. In the IVE conditions, the participants wore a head-mounted display with headphones reproducing a 360° video and audio of the nature walk, either sitting on a chair or walking on a manually driven treadmill. Measurements included environmental perceptions (presence and perceived environmental restorativeness – PER), physical engagement (walking speed, heart rate, and perceived exertion), and affective responses (enjoyment and affect). Additionally, qualitative information was collected through open-ended questions. The participants rated the IVEs with satisfactory levels of 'being there' and 'sense of reality,' but also reported discomforts such as 'flatness,' 'movement lag' and 'cyber sickness.' With equivalent heart rate and walking speed, participants reported higher perceived exertion in the IVEs than in the nature walk. The nature walk was associated with high enjoyment and enhanced affect. However, despite equivalent ratings of PER in the nature walk and in the IVEs, the latter were perceived as less enjoyable and gave rise to a poorer affect. Presence and PER did not differ between the two IVEs, although in the treadmill-IVE the negative affective responses had slightly smaller magnitude than in the sitting-IVE. In both the IVEs, the negative affective responses were mainly associated with cyber sickness, whereas PER was positively associated with enjoyment. From the qualitative analysis, it emerged that poor postural control and lack of a holistic sensory experience can also hinder immersion in the IVE. The results indicate that IVE technology might in future be a useful instrument in green exercise research and promotion, but only if image quality and cyber sickness can be addressed.

Keywords: environmental perception, green exercise, physical activity promotion, restorative environments, virtual reality

INTRODUCTION

By combining physical activity and exposure to nature, green exercise can provide several health benefits (Pretty et al., 2003). Studies have, for example, shown that green exercise can provide greater benefits compared to physical activity performed indoors or in an urban setting, which include a reduction in psychophysiological stress and enhanced mental health (Bowler et al., 2010; Thompson Coon et al., 2011). In particular, a meta-analysis (Bowler et al., 2010) showed that green exercise studies consistently found significant reductions in negative emotional states such as fatigue, anger and sadness. Green exercise has also been consistently associated with lower perceived exertion compared to exercising indoors while at the same time inducing people to engage in more vigorous physical activity (Focht, 2009; Calogiuri et al., 2015). This implies that green exercise can increase the likelihood of higher exercise intensities being reached, which in turn can lead to a number of health benefits (Gladwell et al., 2013).

The attention-restoration theory (ART) of Kaplan (1989, 1995) has been used to explain the positive psychological effects of green exercise. ART postulates that some environments can elicit restoration from mental fatigue by triggering a spontaneous (and therefore effortless) form of attention, which is referred to as *fascination*. Some specific features of the natural world such as clouds in the sky or leaves in a breeze are hypothesized to have particular advantages in prompting attention-restoration mechanisms. Moreover, being outdoors in a natural environment can provide a sense of *being away* from everyday problems, thus contributing to restorative experiences. The theory specifies two additional components: *extent* and *compatibility,* the former representing the degree to which an environment is perceived as being coherently ordered and having substantial scope, while the latter represents the degree to which the environment matches a person's inclinations at the time. A number of studies have found that exercising in natural environments has greater potential for restoration compared to indoor (Hug et al., 2009; Calogiuri et al., 2016a) and urban (Bodin and Hartig, 2003; Hartig et al., 2003) environments, while also giving rise to improved cognitive performance (Hartig et al., 1991, 2003), enhanced psychological states (Hartig et al., 1991, 2003; Calogiuri et al., 2015), and reduction of psychophysical stress (Hartig et al., 2003; Aspinall et al., 2015; Calogiuri et al., 2015).

Immersive Virtual Environments (IVEs) consist of synthetic sensory information that provide a surrounding and continuous stream of stimuli, creating the illusory perception of being enclosed within and interacting with a real environment (Loomis et al., 1999; Smith, 2015). IVEs are becoming increasingly popular, especially in the form of head-mounted displays (HMD), a device with a motion sensor that allows a 360° vision of a virtual world while eliminating the visual contact with external reality. The popularity of IVEs and HMDs follows the introduction of relatively affordable technology that not only provides the opportunity to immerse oneself in pre-set IVEs, but also allows the creation of new IVEs using special 360° cameras and freely available and customizable applications. One of the potential advantages of HMD is that they can provide relatively intense immersive experiences. In IVE sciences, immersion is defined as the extent to which a computer-generated environment is "capable of delivering an inclusive, extensive, surrounding, and vivid illusion of reality to the senses of a human participant" (Slater and Wilbur, 1997), and it is commonly evaluated by assessing participants' feelings of presence. The concept of presence, i.e., the subjective feeling of "being in the virtual environment" (Slater and Wilbur, 1997), is therefore a key element in research related to the effectiveness of virtual reality technology, including (but not limited to) its application in the physical activity and exercise sciences (Pasco, 2013).

Green exercise research faces a number of challenges, especially in relation to the extent to which studies can control for possible confounders when comparing indoor and outdoor environments (Lee and Maheswaran, 2011; Rogerson et al., 2016). Different weather conditions and terrains (e.g., a paved trail as opposed to a treadmill), for example, might lead to differences in physical engagement and influence psychophysiological responses. IVEs, however, can engage research participants in highly controlled immersive environmental experiences (Smith, 2015). Furthermore, IVE could, in the future, provide a simple way of integrating experiences of nature into people's everyday lives, as well as supplement rehabilitation and health promotion programs: in an urbanized society, a large number of individuals do not (or cannot) engage in green exercise on a regular basis: recent estimates show that in Norway, for instance, almost half of the population do not engage in any green exercise in a typical week (Calogiuri et al., 2016b), while in the United Kingdom this reaches 80% (White et al., 2016). Yet the application of and research into this technology in relation to environmental or exercise sciences is still in its infancy. In particular it is not clear, in terms of participants' perceptions, to what extent IVE technology can reproduce life-like experiences of green exercise. Research suggests, for example, that watching images or videos of nature can provide a similar, although smaller, burst of positive affect compared with a walk in real nature (Plante et al., 2006; Mayer et al., 2009). Furthermore, positive psychophysiological and cognitive effects have also been demonstrated in a study by Valtchanov et al. (2010), in which the participants were exposed to a virtual environment constructed as a photo-realistic forest (i.e., a high quality computer-generated representation of a forest). However, to the best of our knowledge, no research has yet investigated how people respond and interact with IVEs that are more encompassing and dynamic, such as watching a first-person 360° video of a nature walk.

Engaging in physical activity while being exposed to virtual nature might provide additional benefits: physical movement might contribute to more positive affective responses as compared with a sedentary exposure to virtual nature, as in fact physical activity alone is known to provide affective benefits (Ekkekakis et al., 2011); having the possibility of moving might also elicit more immersive experiences in the IVE, as this might provide greater engagement with the virtual environment; furthermore, physical movement might prevent discomfort caused by the gap between the movements of virtual self and the movements of the real self. Studies have previously tested experimental conditions in which participants exercised on a treadmill or a stationary bike while watching images or videos of nature displayed on a screen (Pretty et al., 2005; Plante et al., 2006; Akers et al., 2012; White et al., 2015; Yeh et al., 2017). However, despite attempts within the gaming industry to combine HMDs with special ergometers and other devices, how best to combine IVE and physical movement in a controlled research environment remains underexplored. Since the 1990s, using different types of IVE technology, researchers have studied how to integrate physical movement with exposure to IVEs and how IVEs can influence people's physical activity patterns (Slater et al., 1995; Jaffe et al., 2004; Sheik-Nainar and Kaber, 2007; Peruzzi et al., 2016). However, to the best of our knowledge, few of these studies have attempted to combine physical activity with HMDs and none of them has investigated whether the additional component of physical movement can actually elicit feelings of presence or positive psychological states to a greater extent than a sedentary exposure. Besides the interest in understanding the extent to which physical movement can elicit more immersive experiences, it is also important to consider the effects that exercising in IVE conditions might have on the way people move and exercise. Wearing a HDM might, for example, lead participants to walking or exercising at a slower pace than they would normally do in a real natural environment, reducing some of the potential benefits of simulated green exercise experiences. Moreover, because the subjective experience of exercise intensity is often associated with health outcomes as well as motivation for regular exercise (Ekkekakis et al., 2011), it is important to consider people's responses to simulated green exercise in terms of perceived exertion.

The purpose of the current study was to investigate the extent to which commercially available IVE technology used under laboratory conditions can simulate green exercise experience, reproducing similar psychophysiological responses. In addition, we investigated whether physical movement (i.e., walking on a treadmill) could elicit greater engagement with the virtual natural environment, leading to higher positive affective responses compared to sedentary exposure.

MATERIALS AND METHODS

Participants

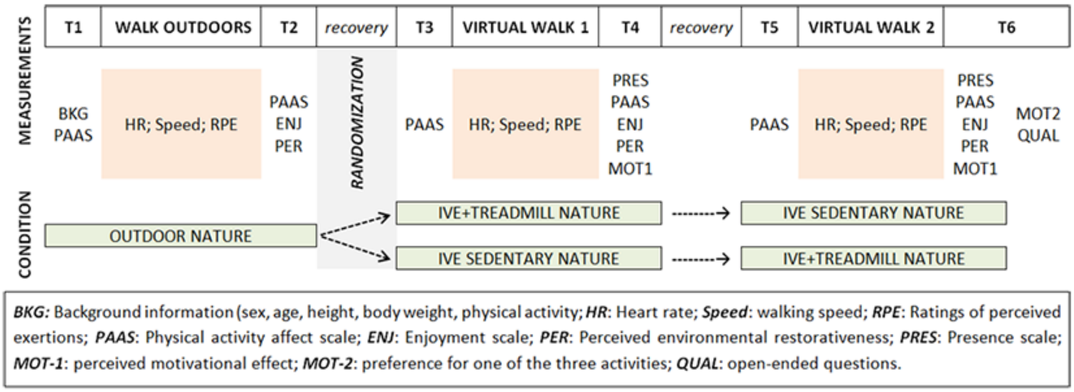
Participants were recruited among students and employees at the Faculty of Social and Health Sciences at the Inland Norway University of Applied Sciences through announcements on the University's webpage and presentations to students during classes. The inclusion criteria for participation were: (1) age 20–45 years; (2) able to walk for 10 min outdoors and on a treadmill; (3) not being an elite athlete (i.e., individuals currently competing in sports at a national level or above). Initially, 65 individuals responded to the researchers' invitation, 34 of whom met the inclusion criteria and confirmed their intention to participate in the study. Eight individuals dropped-out (i.e., did not attend on the scheduled day of the experiment). Thus, the final sample included 26 participants (14 males, 12 females; age: 26 ± 8 years; BMI: 23.12 ± 5.03), all of whom completed the full set of experiments and assessments. All participants were informed in writing about the purpose of the study and associated risks before they provided their written consent. The study was approved by the Norwegian Centre for Research Data and was performed according to the Declaration of Helsinki.

IVE Technology

The IVE was constructed as a 360° video reproducing a nature walk in the exact same location used for the 'outdoor walk' condition; this allowed us to reduce confounders such as different characteristics of the two environments (see section "Design and Procedure"). The video was filmed using a Samsung gear 360 sm-c200 camera 2 days before the beginning of the experimentations. The audio was recorded simultaneously in order to capture sounds such as footsteps, the voices of people passing by and other natural events. The camera was mounted on a modified Yelangu s60t handheld stabilizer. The video was then run through two software stabilizing programs – first in Adobe After Effects CC 2017, Warp Stabilizer VFX and then in Samsung Gear 360 ActionDirector, build 1.0.0.2423, in order to further improve the stability of the images in the post-production phase. Finally, the video was adjusted for being viewed using a 360 VR video in Samsung Gear 360 ActionDirector. The playback was made via Samsung S7, with Android 7.0, mounted on a Samsung Gear VR mask. To reproduce the sounds and minimize external noises, during the experimentation participants wore a Sennheiser HD 201 headset together with the head-mounted display.

Design and Procedure

A schematic overview of the experimental design and data collection process is shown in **Figure 1**. All participants underwent three conditions: (a) a walk outdoors in a natural environment, (b) a sedentary exposure to a IVE video, and (c) a treadmill walk whilst being exposed to the same IVE video (**Figure 2**). Each condition lasted 10 min, as this span was previously shown to provide the largest effects on psychological outcomes in green exercise experiments (Barton and Pretty, 2010). Furthermore, according to the World Health Organization's guidelines, bouts of at least 10 min constitute the



BKG: Background information (sex, age, height, body weight, physical activity; ***HR***: Heart rate; ***Speed***: walking speed; ***RPE***: Ratings of perceived exertions; ***PAAS***: Physical activity affect scale; ***ENJ***: Enjoyment scale; ***PER***: Perceived environmental restorativeness; ***PRES***: Presence scale; ***MOT-1***: perceived motivational effect; ***MOT-2***: preference for one of the three activities; ***QUAL***: open-ended questions.

FIGURE 1 | Experimental design and data gathering organization.

FIGURE 2 | Experimental conditions: **(A)** Outdoor (walk in real nature); **(B)** Sitting-IVE (sedentary exposure to virtual walk in nature); **(C)** Treadmill-IVE (virtual walk in nature while walking on a manually activated treadmill). Written informed consent was obtained from the individual for the publication of these images.

minimum unit for health-enhancing physical activity (WHO, 2017). All participants completed the walk outdoors before undergoing the two other conditions, which were administered in a randomized counter-balanced order. Each participant underwent all three conditions on the same day, with a minimum break of 15 min provided between each condition in order for participants to recover from potential discomfort. After such time, participants were asked whether they felt sufficiently recovered and were comfortable to proceed with the experimentation, and additional resting time was provided if required. All experiments took place in the period between May 2nd and 10th 2017, with the IVE video recorded 2 days before the first session. The outdoor weather condition varied from sunny to overcast, with the temperature ranging between 7 and 17°C. The weather during the filming was sunny with a gentle breeze, which could be heard at times in the playback. The temperature in the laboratory was kept constant at 21°C.

The outdoor walk took place on a fairly straight paved trail along a large river in proximity to the university, where the IVE conditions were administered in the laboratory. The environment also included some built elements, such as buildings and a football field. The participants met the researchers in a building by the trail and were individually accompanied by one of the researchers to the starting point of the walk. The participants were equipped with a wristwatch with a heart rate monitor and GPS (Garmin, Forerunner 310XT), which had an alarm set-up for ringing after 5 min. They were instructed to walk at a comfortable pace on the trail until the alarm rang, at which point they turned around and walked back to the starting point. At completion of the outdoor walk, the participants were accompanied to the laboratory. In the treadmill condition, the participants walked on a manually driven treadmill (Woodway, Curve) equipped with a structure for the participants to hold on to by placing their hands in front of them. Unlike engine-driven treadmills, manually driven treadmills are activated by a person moving their feet while walking, similar to what happens when walking over ground. In this way, the participants could control their pace in a spontaneous manner. All participants underwent a short trial of walking on the treadmill before starting the IVE condition. In the sitting condition, the participants sat on a chair, in a separate room within the laboratory.

Instruments

Environmental Perceptions

Perceived environmental restorativeness was measured after completion of each condition using two subscales of the Perceived Restorativeness Scale (Hartig et al., 1997): 'fascination' (five items) and 'being away' (two items). The components 'extent' and 'compatibility' were not used, as preliminary testing suggested that these two items were not applicable to the IVE conditions and might have led to inaccurate assessments. Each item was rated on an 11-point Likert scale (0 = absolutely disagree, 10 = absolutely agree). When these questions were administered after the IVE conditions, a caption explicitly indicated "The following questions relate to the virtual environment." The scale showed, in general, adequate internal consistency for 'fascination' (α = 0.85–0.92), though poorer internal consistency was detected for the component 'being away' (α = 0.56–0.87). Additionally, eight items were used to assess the participants' feeling of presence after the two IVE conditions. Seven of these items were adapted from those used by Nichols et al. (2000), while an additional item was included that related to the extent to which participants experienced cyber sickness (**Table 1**). The items were formulated as statements, each participant being asked to rate the extent to which they agreed with each of them on an 11-point Likert scale (0 = absolutely disagree, 10 = absolutely agree).

TABLE 1 | Items used to assess presence in participants who underwent an IVE-based 'nature walk'[a].

Short name	Item
Being there	In the computer generated world I had the sense of 'being there'
Realism	I thought of the virtual environment as equal to the real environment
Sense of reality	The virtual world became more real or present to me compared to the real world. NB: by 'real world' we mean the room where you were undergoing the test
Awareness	During the 'virtual walk,' I often thought of the other person(s) in the room with me
Other persons	It would have been more enjoyable to engage with the 'virtual world' with no-one else in the room
External noises	Whilst I was doing the 'virtual walk,' I paid much attention to other noises around me in the room
Flatness	The virtual world appeared flat and missing in depth
Movement lag	The lag or delay between my movements and the moving in the 'virtual walk' were disturbing
Cyber sickness	During the 'virtual walk' I got dizzy

[a] *Each participant was exposed to the same IVE-based 'nature walks,' once while they sat on a chair and once while they walked on a manual treadmill.*

Physical Engagement

Heart rate (HR) was continuously measured during all experimental conditions using a HR-monitor (Garmin, Forerunner 310XT), while ratings of perceived exertion (RPE) were measured immediately after completing each experimental condition using a Borg scale in a 20-point version (Borg, 1982). The walking speed was also recorded using the Garmin GPS and the treadmill computer in the outdoor and treadmill conditions, respectively.

Affective Responses

Enjoyment was measured after each experimental condition using a single item question: "On a scale from 0 to 10, how enjoyable is the activity you have engaged in?" Participants gave their answer on a numbered line (0 = not enjoyable at all; 10 = absolutely enjoyable). Additionally, participants' affective responses were assessed by administering the Physical Activity Affect Scale (PAAS) (Lox et al., 2000) immediately before and immediately after undergoing each experimental condition. The PAAS consists of 12 items corresponding to different emotions (e.g., "energetic," "calm," "miserable," and "tired") and placed them within four quadrants, in line with Russell's circumplex model of affect and arousal (Russell, 1980): positive affect, tranquility, negative affect, and fatigue. Each item was measured on a 5-point rating scale (0 = strongly disagree; 4 = strongly agree). Reliability analysis, showed reasonably adequate internal consistency for most assessments (α = 0.64–0.86), though somewhat poor levels of internal consistency were detected for negative affect in the pre-condition assessments (α = 0.46–0.52).

Qualitative Data

As little is known about how people respond to virtual experiences of nature, especially in relation to the technology used in this particular study, qualitative information was collected using a series of open-ended questions, which were presented to the participants after completion of all three conditions and quantitative measurements. Such questions, to which the participants responded in written form, were inspired by the structure of the quantitative assessments: a question was developed for each of the quantitative variables in order to explore the meaning behind participants' responses in more detail, for example: "*In the questionnaire, you were asked to report the extent to which you felt the environments were 'fascinating' and gave you feelings of 'being away.' Could you say how well (or how* *poorly) did the IVE video reproduce such characteristics, compared with the outdoor/real environment?*" and "*When you answered the question about how 'enjoyable' the activity was, what determined where in the scale you put your mark? Please, describe the feelings you experienced in all three conditions separately*."

Analyses

Data were first explored for distribution, possible outliers and missing values. A one-way repeated measurements analysis of variance (ANOVA) was used to establish possible effects of 'condition' (i.e., outdoor, sitting, and treadmill) for the different study variables. For the PAAS components, a factorial (two-way) repeated ANOVA was used to investigate possible pre-post changes in interaction with the experimental conditions. If significance was achieved in the within-subjects test, a *post hoc* analysis with Bonferroni's adjustment of alpha was applied in order to examine possible differences across the individual conditions. Additionally, Spearman's rank correlation coefficient (ρ) was used to examine possible associations among all study variables. The PAAS components were run into the correlation analysis in form of *delta* values (i.e., the difference between post-values and pre-values). All statistical analyses was carried out using IMB Statistics SPSS version 21 (IBM Corp., New York). Significance was set at $p < 0.05$.

The qualitative data were analyzed in accordance with the 'framework approach' (Gale et al., 2013), which provides clear steps for summarizing qualitative data in a way that sheds light on the participants' responses to the quantitative questions. The method is systematic and transparent and provides a clear trail from raw data to thematic codes and quotations. These aspects of the method contribute toward evaluating the trustworthiness of the analysis. In addition, the process allows for the inclusion of more than one researcher at various points to discuss the emerging framework of codes, categories and themes. In this study, discussion took place between three members of the team in order to arrive at a more refined version of comments. Initially, a coding frame relating to the different overarching domains of the questionnaire was used (i.e., presence, perceived environmental restorativeness, physical engagement, and affective responses). Reiterative reading and recoding of the data led to refinement of the coding frame and the development of overarching themes.

RESULTS

Presence and Perceived Environmental Restorativeness

No significant difference among the three conditions was found for the two components of perceived environmental restorativeness, 'fascination' [$F(2,22) = 2,89$; $p = 0.076$] and 'being away' [$F(2,22) = 2.41$; $p = 0.112$]. In relation to the feelings of presence assessed in concomitance with the IVE conditions, the participants reported high ratings of 'flatness' medium-high ratings of 'being there' and 'sense of reality,' low levels of realism as well as low levels for the items depicting external disturbances such as 'awareness,' 'other persons,' and 'noises.' Furthermore, the participants reported quite high ratings of 'movement lag' and especially 'cyber sickness' (**Figure 3**). The ANOVA showed no significant difference between the sitting and the treadmill condition for all the presence domains, apart from 'noises' [$F(2,24) = 11.60$; $p = 0.002$], which had significantly higher ratings in the treadmill condition compared with the sitting condition.

Significant correlations were found among the different domains of perceived environmental restorativeness and presence, though different patterns of association emerged in the sitting and the treadmill conditions (**Table 2**). 'Fascination' and 'being away' were highly correlated with each other in both the sitting and the treadmill conditions. 'Fascination' was positively associated with 'being there' and 'realism' in both the sitting and the treadmill conditions, whereas it was positively associated with 'sense of reality' and negatively associated with 'awareness' only in the treadmill condition. 'Being away' was positively associated with 'realism' in both, the sitting and the treadmill conditions, while it was associated with 'being there' only in the sitting condition and with 'sense of reality' and 'other persons' only in the treadmill condition. Moreover, in the sitting condition, 'being there' was positively correlated with 'realism' and 'sense of reality,' while 'awareness' was positively correlated with 'noises.' In the treadmill condition, 'being there' was negatively correlated with 'awareness' and 'movement lag,' 'movement lag' was positively correlated with 'flatness' and 'cyber sickness,' and 'flatness' and 'cyber sickness' were positively correlated with each other.

The qualitative data supported the quantitative results, showing that a number of factors could disrupt the sense of presence: the noise of the treadmill ($n = 9$; e.g., "*The noise from the treadmill was way too loud*"), the lag between the pace of the individual and the pace in the IVE video ($n = 13$; e.g., "*The discrepancy in the movements gave me a feeling of not having control*"), cyber sickness or other physical discomforts ($n = 19$; e.g., "*It made me dizzy and sick*"), and the poor quality of the imaging ($n = 21$; e.g., "*The video was very blurry*"). The poor quality of the video was especially related by several participants with other elements of presence, such as cyber sickness ($n = 4$; e.g., "*The poor quality of the video made me [feel] sick*"), a feeling of (not) 'being there' ($n = 6$; e.g., "*The poor quality of the video made it less real*"), and to a certain extent the perceived environmental restorativeness ($n = 1$; e.g., "*The [settings in the] IVE were fascinating, but the poor quality of the video reduced their potential*"). It also emerged that because the IVE conditions only provided visual and auditory cues, it tended to reduce the achievement of a comparative outdoor nature experience ($n = 5$; e.g., "*Air, smell, vision. [In the IVE conditions] I felt deprived of the elements of nature and senses*"). The additional element of movement (treadmill condition) did not appear to have helped people feel more engaged with the natural environment, although in some cases it elicited greater feelings of 'being there' ($n = 2$; e.g., "*[In the treadmill condition] you could really feel that you were in that place because you can move while you are watching the video*"). On the other hand, the element of movement did not seem to provide a consistent protection from experiencing cyber sickness; in fact, only four participants reported they felt less sick

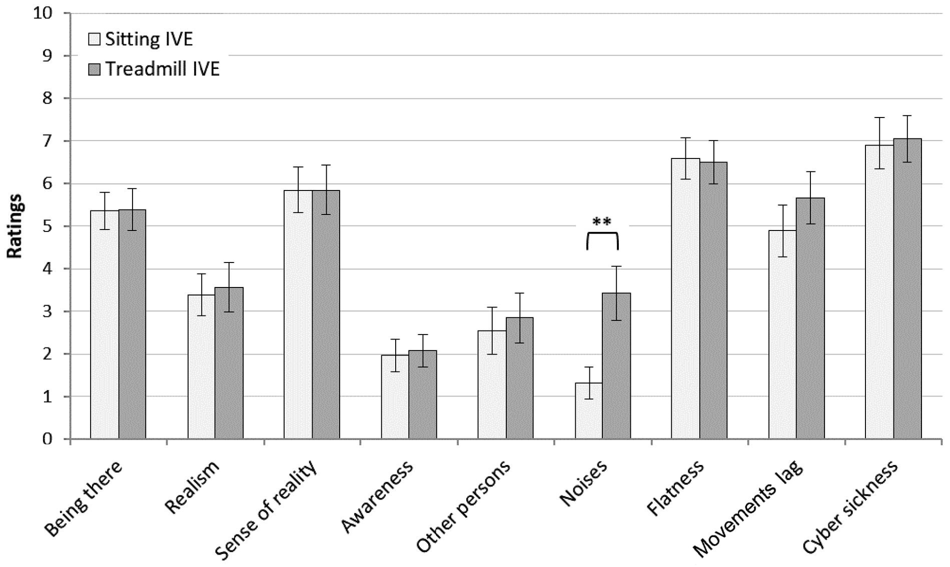


FIGURE 3 | Ratings of *presence* in a ‘sitting-IVE’ condition and a ‘treadmill-IVE’ condition (M ± SE; $n = 26$, repeated measurements). $^{**}p < 0.001$ in a *post hoc* comparison of sitting vs. treadmill.

in the treadmill condition than in the sitting condition, while two reported the opposite, and the remaining reported that they felt sick in "both IVE conditions” ($n = 13$).

Physical Engagement

Significant differences across conditions for HR mean [$F(2,24) = 70.84$; $p < 0.001$] and HR max [$F(2,24) = 71.71$; $p < 0.001$] were found. The pairwise comparison found a significant difference when comparing the outdoor condition with the sitting condition ($p < 0.001$ for both variables), but not with the treadmill condition. Significant differences were also found when comparing the two IVE conditions with each other, with higher HR values in the treadmill condition as compared with the sitting ($p < 0.001$ for both variables; **Figure 4**). There were no differences in speed [min/km; $F(1,25) = 3.52$; $p = 0.072$] when comparing the outdoor and the treadmill condition. On the other hand, a significant effect across conditions was found for RPE [$F(2,23) = 17.84$; $p < 0.001$], with higher RPE values in the treadmill condition compared with both the outdoor ($p < 0.001$) and the sitting condition ($p = 0.003$), while no significant difference was found between the outdoor and the sitting condition (**Figure 4**). As shown in **Table 3**, both HR mean and HR max were positively associated with ‘movement lag’ in the sitting condition, while in the treadmill condition, RPE and HR mean were positively correlated with ‘cyber sickness.’

From the qualitative data it emerged that the possibility of walking while being exposed to the IVE provided a ‘sense of liberation’ which made the participants feel less passive and more engaged with the virtual experience ($n = 8$; e.g., *“[In the treadmill condition] it was much better because I could move”; “[The sitting condition was] challenging and stressful as you can’t move*”). On the other hand, some participants reported physical discomforts due to poor postural control during the treadmill condition ($n = 4$; e.g., “*[The treadmill condition] was very stressful and tiring because I had to hold on to the handlebar very hard*”).

Affective Responses

Table 4 shows descriptive statistics for the affective responses, alongside the outcomes of the ANOVA and *post hoc* analysis. The ANOVA found significant differences across conditions for enjoyment, with a *post hoc* analysis showing that compared with the outdoor walk participants reported significantly less enjoyment in both the sitting and the treadmill conditions. The ANOVA also showed a significant interaction of ‘pre-post’ by ‘condition’ for positive affect, negative affect, and fatigue, whereas the interaction was not significant for tranquility. The affect profile assessed before the nature walk showed that the participants reported low ratings of negative affect, fatigue, and positive affect, whereas higher ratings were recorded for tranquility. A *post hoc* analysis applying a Bonferroni’s correction of alpha showed an improvement of the affect profile after completing the outdoor walk, with a significant reduction of the ratings of negative affect and fatigue. In contrast, the profile of affect worsened after both IVE conditions, with a slightly larger magnitude in the sitting condition: the ratings for positive affect and tranquility reduced (change significant in both conditions), whereas the ratings of negative affect and fatigue increased (change significant only in the sitting condition). A *post hoc* comparison on delta values across the different conditions showed a significant difference between the outdoor walk and both the IVE conditions for all PAAS components, whereas when comparing the two IVE conditions with each other, it was found that the reduction in positive affect was significantly larger in the sitting than in the treadmill condition.

As shown in **Table 3**, ‘cyber sickness’ was consistently associated with negative affective responses: ‘cyber sickness’

TABLE 2 | Spearman's correlation among different domains of environmental perceptions in participants exposed to an IVE video while sitting on a chair and while walking on a manually driven treadmill (M ± SE; *n* = 26, repeated measurements).

Sitting IVE	Fascination	Being away	Being there	Realism	Sense of reality	Awareness	Other persons	Noises	Flatness	Movement lag
Being away	0.76**									
Being there	0.70**	0.72**								
Realism	0.71**	0.44*	0.66**							
Sense of reality	0.19	0.19	0.43*	0.15						
Awareness	−0.09	0.04	−0.07	0.14	0.18					
Other persons	0.34	0.32	0.14	0.23	0.21	0.38				
Noises	−0.10	0.03	−0.21	0.11	0.04	0.73**	0.38			
Flatness	0.18	0.13	0.06	0.18	−0.17	0.25	0.14	0.15		
Movement lag	−0.19	0.02	−0.36	−0.30	0.04	0.18	0.32	0.22	0.16	
Cyber sickness	−0.20	−0.36	−0.06	−0.13	0.17	0.00	0.07	−0.32	0.20	0.11

Treadmill IVE	Fascination	Being away	Being there	Realism	Sense of reality	Awareness	Other persons	Noises	Flatness	Movement lag
Being away	0.73**									
Being there	0.54**	0.38								
Realism	0.51**	0.39*	0.37							
Sense of reality	0.41*	0.59**	0.37	0.31						
Awareness	−0.39*	−0.25	−0.39*	−0.27	0.07					
Other persons	0.14	0.41*	−0.11	0.18	0.35	0.28				
Noises	−0.04	0.05	−0.38	0.09	−0.13	0.38	0.27			
Flatness	0.02	0.02	−0.30	−0.04	−0.14	0.18	0.00	0.24		
Movement lag	−0.19	−0.22	−0.43*	−0.18	−0.01	0.17	0.26	−0.09	0.39*	
Cyber sickness	−0.07	−0.10	−0.29	0.00	−0.16	0.24	0.00	0.12	0.44*	0.47*

**Correlation is significant at the 0.05 level (2-tailed). **Correlation is significant at the 0.01 level (2-tailed).*

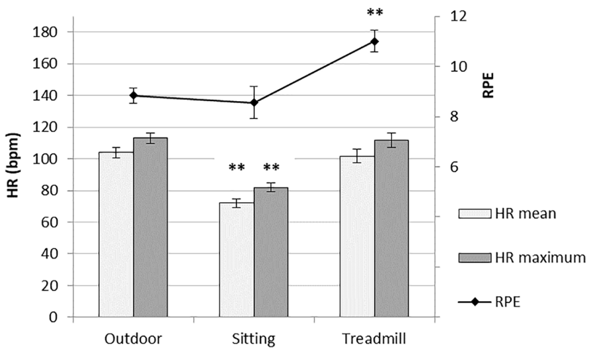


FIGURE 4 | Heart rate (mean and maximum) and Ratings of perceived exertion (RPE) in a walk outdoors, a ‘sitting-IVE’ condition, and a ‘treadmill-IVE’ condition (M ± SE; $n = 26$, repeated measurements). $^{**}p < 0.001$ in a *post hoc* comparison of the sitting or treadmill conditions with the outdoor condition, applying Bonferroni’s adjustment of alpha.

was negatively correlated with enjoyment, positive affect, and tranquility, whereas it was positively correlated with negative affect and fatigue (the latter only in the treadmill condition). Significant correlations were found also between different psychological variables and ‘being there,’ ‘realism,’ ‘sense of reality,’ and ‘fascination,’ though with different patterns of association for the sitting and the treadmill condition (**Table 3**).

The different emotional responses experienced in the outdoor walk and the IVE conditions were also found in the qualitative data. For example, participants expressed positive emotions such as feeling “relaxed” and “happy” ($n = 13$) during the outdoor condition, whereas negative emotions such as feeling “stressed” and “tired” were expressed ($n = 10$) in relation to the IVE conditions. Furthermore, the IVE conditions were viewed as “boring” ($n = 4$), compared to “fun” ($n = 1$) and “great/amazing” ($n = 2$) for their experience outdoors. Furthermore, some participants made reference to the physical reactions experienced during the IVE conditions, especially cyber sickness, which was viewed as having had a strong influence on their affective experience (e.g., “*How I felt during the IVE condition – sick and dizzy – [determined my level of enjoyment]*”). Some participants reported, however, that the novelty of trying the IVE technology by itself provided some degree of enjoyment ($n = 3$; e.g., “*Just the fact that you are using virtual reality [made it enjoyable]*”). Only two participants reported that the element of movement in the treadmill conditions elicited more positive affective responses (e.g., “*The sitting IVE was boring . . . Moving while the video was playing [made it more enjoyable]*”).

DISCUSSION

Our findings support, in part, the findings of previous studies showing that green exercise experiences in real natural environments, even in brief bouts (i.e., a 10-min walk), can lead to enhanced psychological states (Barton and Pretty, 2010; Bowler et al., 2010; Thompson Coon et al., 2011). We found in fact that the walk in real nature was associated with an enhanced profile of the participants’ emotional state, specifically in relation to a reduction of fatigue and negative affect, alongside high ratings of enjoyment. On the other hand, despite the participants reporting levels of perceived environmental restorativeness (‘fascination’ and ‘being away’) and physical engagement equivalent to those experienced in the real nature walk, alongside reasonably high levels of some aspects of presence (e.g., ‘being there’ and ‘sense of reality’), unlike the walk in real nature the IVEs led to *negative* affective responses. These latter findings differ from those of previous studies that have used *non-immersive* virtual nature in combination with physical activity, i.e., walking on a treadmill or cycling on a stationary bike whilst watching images or videos of nature projected on a screen (Pretty et al., 2005; Plante et al., 2006; Akers et al., 2012; White et al., 2015; Yeh et al., 2017). These studies found in fact that virtual nature can provide psychophysiological benefits such as improvement of affect states and restoration of mental fatigue. However, such benefits are not as large as those that can be obtained in real natural environments, as shown in studies that had participants visiting a real natural environment and/or viewing a video of the same nature (Plante et al., 2006; Mayer et al., 2009; Olafsdottir et al., 2017). Our findings also differ from those found by Valtchanov et al. (2010), which showed restorative effects in subjects who were exposed to an IVE using a HDM. It is, however, important to note some fundamental differences between our study and that of Valtchanov et al. (2010), which are likely to have played a role in the different outcomes of the two studies, especially resulting in our participants being more exposed to risk of incurring in cyber sickness: first, in the Valtchanov et al. (2010) study the participants sat at a computer station and controlled their movements using a mouse, whereas our participants were ‘passive’ observers of a first-person video; secondly, in the Valtchanov et al. (2010) study the HDM used allowed only a 65° vision, therefore not engaging the participants’ *peripheral* vision.

The negative affective responses that emerged in our study seem to be mainly associated with participants’ experience with IVE being commonly disrupted by the occurrence of cyber sickness. Cyber sickness is known to be a common problem with current IVE technology (Nichols et al., 2000), and a number of theories have been proposed to explain why it occurs. In spite of this, to date little is known about how to prevent it. Two of the most well-known theories on cyber sickness are the *sensory conflict theory*, which suggests cyber sickness is mainly caused by conflicting signals received by the visual and vestibular systems, and the *postural instability theory*, which states that long periods without postural control will cause cyber sickness (LaViola, 2000). In the present study, some participants reported that they struggled to maintain postural control during the treadmill condition, suggesting that postural control might indeed have contributed to the development of cyber sickness in some participants. However, triangulation of the qualitative and quantitative data revealed that those participants who reported challenges in maintaining postural control on the treadmill did not consistently report higher ratings of cyber sickness in the treadmill condition, and in all but one case, the ratings were *lower* than in the sitting condition. On the other hand, during the

TABLE 3 | Spearman's correlation of the different domains of presence and perceived environmental restorativeness with affective responses and physical engagement in participants exposed to an IVE video while sitting on a chair and while walking on a manual treadmill (M ± SE; $n = 26$, repeated measurements).

Sitting IVE	**Fascination**	**Being away**	**Being there**	**Realism**	**Sense of reality**	**Awareness**	**Other persons**	**Noises**	**Flatness**	**Movement lag**	**Cyber sickness**
HR mean	0.20	0.31	−0.02	−0.24	−0.03	−0.02	0.23	−0.03	0.24	0.45*	0.13
HR max	0.16	0.29	−0.00	−0.23	0.03	0.02	0.21	−0.07	0.40*	0.50**	0.23
RPE	−0.29	−0.44*	−0.10	−0.37	0.13	−0.15	−0.01	−0.33	−0.38	−0.11	0.38
Enjoyment	0.47*	0.46**	0.38	0.36	−0.10	0.03	0.02	0.18	−0.08	−0.24	−0.79**
Pos. affect (delta)	−0.09	0.09	−0.17	−0.16	−0.31	0.03	−0.01	0.19	−0.24	−0.15	−0.73**
Tranquility (delta)	0.18	0.29	0.10	0.46*	−0.34	0.20	0.05	0.45*	0.21	−0.15	−0.60**
Neg. affect (delta)	0.00	−0.12	0.07	0.11	0.25	−0.05	0.08	−0.20	−0.02	0.08	0.77**
Fatigue (delta)	0.39*	0.33	0.34	0.44*	0.02	0.10	0.27	0.10	0.20	0.04	0.05
Treadmill IVE	**Fascination**	**Being away**	**Being there**	**Realism**	**Sense of reality**	**Awareness**	**Other persons**	**Noises**	**Flatness**	**Movement lag**	**Cyber sickness**
Speed	0.07	0.06	0.37	−0.22	0.08	−0.13	−0.05	−0.18	−0.20	−0.35	−0.33
HR mean	0.08	−0.07	−0.18	0.07	0.16	0.29	0.21	0.28	0.11	0.30	0.40*
HR max	0.07	−0.07	−0.24	0.06	0.09	0.29	0.23	0.36	0.11	0.28	0.36
RPE	−0.16	−0.10	−0.05	0.17	−0.01	0.32	0.06	0.15	−0.08	0.16	0.41*
Enjoyment	0.54**	0.40*	0.80**	0.26	0.42*	−0.17	0.04	−0.23	−0.34	−0.62**	−0.52**
Pos. affect (delta)	0.14	0.14	0.02	0.19	0.09	−0.55**	−0.06	0.02	−0.16	−0.26	−0.56**
Tranquility (delta)	0.03	0.10	−0.08	0.01	−0.12	−0.51**	−0.17	−0.13	−0.17	−0.16	−0.52**
Neg. affect (delta)	0.25	0.32	−0.12	0.18	0.21	0.22	0.30	0.13	0.15	0.24	0.65**
Fatigue (delta)	−0.02	−0.10	0.05	−0.29	−0.11	0.26	0.06	0.00	−0.03	0.12	0.43*

**Correlation is significant at the 0.05 level (2-tailed). **Correlation is significant at the 0.01 level (2-tailed). HR = Heart rate; RPE = Ratings of perceived exertion.*

study it was noted that the participants who reported the highest levels of cyber sickness developed it very quickly after starting the IVE sessions. Again, triangulating the quantitative and qualitative data also revealed that, consistent with the sensory conflict theory, complaints of movement lag and flatness (i.e., poor quality of the imaging, including blurriness and lack of depth) were commonly associated with higher ratings of cyber sickness. This might also explain why the element of physical movement (treadmill condition) was unable to attenuate cyber sickness: in this condition, the participants still struggled with movement lag and flatness, which might have triggered a conflict between visual input and the vestibular system. It should be noted, however, that it is likely that inter-individual differences exist in why and how a person develops cyber sickness, and therefore different theories may be applicable to different individuals under diverse conditions (LaViola, 2000).

Our findings show that movement lag and, in particular, cyber sickness, also emerged as factors influencing the participants' affective responses, the latter being an important component underpinning green exercise behaviors as well as possibly mediating various health outcomes (Calogiuri and Chroni, 2014). Thus, this issue has important implications for studying the effectiveness of IVE technology in green exercise research. In a recent study, Kokkinara et al. (2016) demonstrated that watching a first-person IVE video of someone walking can create an illusory sense of agency (i.e., the subjective awareness of initiating, executing, and controlling an action), inducing a person to perceive that the movement is initiated by him or herself. It seems, however, that the discrepancy between a person's movements (or lack of movement, as in our sitting condition) and movements observed in the video can nevertheless result in uncomfortable, or even "frustrating" (as some participants defined it), conflicts between the 'real self' and the 'virtual self.' Cyber sickness had an even more dramatic impact on participants' psychophysiological responses, and was consistently associated with less enjoyment, reduced tranquility and positive affect, increased fatigue and negative affect, and (in the treadmill condition) higher HR and perceived exertion. The latter was especially surprising. Previous research shows that individuals tend to report higher RPE when walking/running on a treadmill as compared with walking/running outdoors (Harte and Eifert, 1995; Focht, 2009; Calogiuri et al., 2015). In the present study, it was hypothesized that being exposed to the IVE video whilst walking on the treadmill would have mitigated this effect by causing an 'attentional shift' from internal feelings of effort toward the virtual environment, which previous research suggests to be the reason for reporting lower RPE when engaging in green exercise as compared with indoor exercise (Harte and Eifert, 1995). The results, however, did not support this expectation. The higher perceived exertion might be linked to cyber sickness, but also the increased feelings of fatigue or the poor postural control that some participants experienced. The latter factor might, especially, have caused the participants to retain the attention focus toward internal feelings (e.g., keeping the balance of controlling the movements), therefore hindering the shift of focus towards the environment. More research is, however, needed in this field to better understand the reasons that underlie such phenomenon.

Despite the impact of cyber sickness and the different psychophysiological responses observed, our findings suggest some important lines of enquiry for future research and application in this area. In particular, we found that the IVE-related ratings of perceived environmental restorativeness (i.e., the extent to which the participants perceived the virtual environment as fascinating and providing the opportunity to experience 'being away') were quite consistently associated with

TABLE 4 | Affective responses to a walk outdoors in a real natural environment and two virtual nature walks (M ± SD; $n = 26$).

	Outdoor walk	Sitting IVE	Treadmill IVE	Pre vs. Post	Condition	Interaction
Enjoyment	7.69 ± 1.78	3.00 ± 2.59[a]	3.96 ± 2.32[a]	–	$F(2,24) = 29.93$**	–
Positive affect						
Pre	0.68 ± 0.16	0.62 ± 0.25[b]	0.57 ± 0.24[b]	$F(1,25) = 25.304$**	$F(2,50) = 20.232$**	$F(2,50) = 14.836$**
Post	0.70 ± 0.19	0.43 ± 0.25	0.49 ± 0.22			
Delta	0.02 ± 0.10	−0.19 ± 0.17[ac]	−0.08 ± 0.15[ac]			
Tranquility						
Pre	2.82 ± 0.91	2.59 ± 0.80[b]	2.54 ± 0.84[b]	$F(1,25) = 20.346$**	$F(2,50) = 14.114$**	$F(2,50) = 6.550$
Post	2.83 ± 0.75	2.03 ± 1.06	1.99 ± 0.89			
Delta	0.01 ± 0.67	−0.56 ± 0.69[a]	−0.55 ± 0.67[a]			
Negative affect						
Pre	0.32 ± 0.41[b]	0.29 ± 0.50[b]	0.28 ± 0.40	$F(1,25) = 8.824$	$F(2,50) = 5.430$*	$F(2,50) = 12.335$**
Post	0.18 ± 0.33	0.87 ± 1.01	0.58 ± 0.84			
Delta	−0.14 ± 0.21	0.58 ± 0.69[a]	0.29 ± 0.74[a]			
Fatigue						
Pre	0.86 ± 0.69[b]	0.76 ± 0.63[b]	0.69 ± 0.65	$F(1,25) = 2.345$	$F(2,50) = 2.117$	$F(2,50) = 12.106$**
Post	0.55 ± 0.55	1.15 ± 0.87	1.00 ± 0.81			
Delta	−0.31 ± 0.56	0.40 ± 0.63[a]	0.31 ± 0.71[a]			

*$p < 0.05$; **$p < 0.001$. [a]*Significant post hoc comparison with the outdoor walk, applying a Bonferroni's adjustment of alpha.* [b]*Significant post hoc pre-post comparison, applying a Bonferroni's adjustment of alpha.* [c]*Significant post hoc comparison between the two IVE conditions, applying a Bonferroni's adjustment of alpha.*

the rating of enjoyment the participants assigned to the IVE experiences. Perceived environmental restorativeness has been found to correlate with ratings of enjoyment during green exercise in real natural environments (Calogiuri et al., 2015). Thus, this finding suggests that in future studies it could be possible to elicit greater enjoyment by producing IVE videos showing natural environments with higher restorative value, as compared with the environment used in this particular study. Furthermore, it is likely that, in the relatively near future, technological developments will allow access to HMDs with higher resolution, which might also limit the occurrence of cyber sickness, and its consequent impact on affective responses.

Strengths and Limitations of the Study

The strength of our study is primarily ascribed to its novelty: to the best of our knowledge, this study is one of few using a HMD in combination with physical activity (i.e., walking on a treadmill), and the very first using such technology to simulate green exercise experiences. The within-subjects experimental design, with two different IVE conditions administered in counter-balanced order preceded by exposure to a corresponding real environment, also represents a strength of our study. Our design might, however, have led to some confounding effects: first, due to the large number of comparisons, we had to apply a restrictive significance level (i.e., Bonferroni's adjustment), which is likely to have increased the probability of incurring type-II errors; second, varying weather conditions might have influenced the participants' experience of the outdoor condition and, relatedly, the psychological outcomes. Most importantly, because the technology used in this study is quite novel, specific equipment that would have helped produce a more stable video was not available. We had to adapt a generic handheld stabilizer, but this was not optimal for a 360° camera, which is very light and symmetrical in shape: additional weights had to be added to the stabilizer, and we had to find solutions to avoid it rotating on its own axis. Furthermore, the program used to improve the stabilization of the video in post-production was at an early stage of development. The development of second-generation technology that will better address these challenges will increase possibilities in this field and might produce different findings.

CONCLUSION

Using commercially available IVE technology, we were unable to reproduce psychophysiological responses similar to those experienced during green exercise in a real natural environment. The main factors hindering positive psychophysiological responses during IVE-based green exercise were the occurrence of cyber sickness, the poor image quality, and the lack of a holistic engagement with the natural environment. The additional element of physical movement (i.e., walking on a treadmill) provided only limited benefit compared with the sedentary exposure to the virtual nature walk. IVE technology might in future be a useful instrument in green exercise research and promotion, but only if image quality and cyber sickness can be addressed. IVEs reproducing environments with higher restorative value might also contribute to more positive affective responses during IVE-based green exercise.

AUTHOR CONTRIBUTIONS

GC was the primary person responsible for the conception of the study and drafted the manuscript. SL and TR participated in the conception of the study, and provided major contributions in the conception of the experimental protocol and creation of the IVEs, respectively. KF and EB provided relevant administrative support, including carrying out the literature review, recruiting and maintaining contacts with the participants, and conducting the data analyses. GC, SL, KF, and EB also carried out the experimentations and data collection. MT provided substantial contributions to revision of the intellectual content and development of the qualitative analysis. All authors contributed to the writing up of the manuscript and have given approval to its final version.

FUNDING

This study was entirely funded by Inland Norway University of Applied Sciences.

ACKNOWLEDGMENTS

We thank Inland Norway University of Applied Sciences for funding this project and all participants who underwent the experiments. Thanks also to Lars-Christian Sørlie for the inspiration and assistance. This study has been presented at the 22th annual conference of the European College of Sport Sciences (Litleskare et al., 2017).

REFERENCES

Akers, A., Barton, J., Cossey, R., Gainsford, P., Griffin, M., and Micklewright, D. (2012). Visual color perception in green exercise: positive effects on mood and perceived exertion. *Environ. Sci. Technol.* 46, 8661–8666. doi: 10.1021/es301685g

Aspinall, P., Mavros, P., Coyne, R., and Roe, J. (2015). The urban brain: analysing outdoor physical activity with mobile EEG. *Br. J. Sports Med.* 49, 272–276. doi: 10.1136/bjsports-2012-091877

Barton, J., and Pretty, J. (2010). What is the best dose of nature and green exercise for improving mental health? A multi-study analysis. *Environ. Sci. Technol.* 44, 3947–3955. doi: 10.1021/es903183r

Bodin, M., and Hartig, T. (2003). Does the outdoor environment matter for psychological restoration gained through running? *Psychol. Sport Exerc.* 4, 141–153. doi: 10.1016/s1469-0292(01)00038-3

Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Med. Sci. Sports Exerc.* 14, 377–381. doi: 10.1249/00005768-198205000-00012

Bowler, D. E., Buyung-Ali, L. M., Knight, T. M., and Pullin, A. S. (2010). A systematic review of evidence for the added benefits to health of exposure to natural environments. *BMC Public Health* 10:456. doi: 10.1186/1471-2458-10-456

Calogiuri, G., and Chroni, S. (2014). The impact of the natural environment on the promotion of active living: an integrative systematic review. *BMC Public Health* 14:873. doi: 10.1186/1471-2458-14-873

Calogiuri, G., Evensen, K., Weydahl, A., Andersson, K., Patil, G., Ihlebaek, C., et al. (2016a). Green exercise as a workplace intervention to reduce job stress. Results from a pilot study. *Work* 53, 99–111. doi: 10.3233/wor-152219

Calogiuri, G., Nordtug, H., and Weydahl, A. (2015). The potential of using exercise in nature as an intervention to enhance exercise behavior: results from a pilot study. *Percept. Mot. Skills* 121, 350–370. doi: 10.2466/06.PMS.121c17x0

Calogiuri, G., Patil, G. G., and Aamodt, G. (2016b). Is green exercise for all? A descriptive study of green exercise habits and promoting factors in adult Norwegians. *Int. J. Environ. Res. Public Health* 13:E1165. doi: 10.3390/ijerph13111165

Ekkekakis, P., Parfitt, G., and Petruzzello, S. J. (2011). The pleasure and displeasure people feel when they exercise at different intensities: decennial update and progress towards a tripartite rationale for exercise intensity prescription. *Sports Med.* 41, 641–671. doi: 10.2165/11590680-000000000-00000

Focht, B. C. (2009). Brief walks in outdoor and laboratory environments: effects on affective responses, enjoyment, and intentions to walk for exercise. *Res. Q. Exerc. Sport* 80, 611–620. doi: 10.1080/02701367.2009.10599600

Gale, N. K., Heath, G., Cameron, E., Rashid, S., and Redwood, S. (2013). Using the framework method for the analysis of qualitative data in multi-disciplinary health research. *BMC Med. Res. Methodol.* 13:117. doi: 10.1186/1471-2288-13-117

Gladwell, V. F., Brown, D. K., Wood, C., Sandercock, G. R., and Barton, J. L. (2013). The great outdoors: how a green exercise environment can benefit all. *Extrem Physiol. Med.* 2:3. doi: 10.1186/2046-7648-2-3

Harte, J. L., and Eifert, G. H. (1995). The effects of running, environment, and attentional focus on athletes' catecholamine and cortisol levels and mood. *Psychophysiology* 32, 49–54. doi: 10.1111/j.1469-8986.1995.tb03405.x

Hartig, T., Evans, G. W., Jamner, L. D., Davis, D. S., and Garling, T. (2003). Tracking restoration in natural and urban field settings. *J. Environ. Psychol.* 23, 109–123. doi: 10.1016/s0272-4944(02)00109-3

Hartig, T., Korpela, K., Evans, G. W., and Garling, T. (1997). A measure of restorative quality in environments. *Scand. Hous. Plan. Res.* 14, 175–194. doi: 10.1080/02815739708730435

Hartig, T., Mang, M., and Evans, G. W. (1991). Restorative effects of natural environment experiences. *Environ. Behav.* 23, 3–26. doi: 10.1177/0013916591231001

Hug, S. M., Hartig, T., Hansmann, R., Seeland, K., and Hornung, R. (2009). Restorative qualities of indoor and outdoor exercise settings as predictors of exercise frequency. *Health Place* 15, 971–980. doi: 10.1016/j.healthplace.2009.03.002

Jaffe, D. L., Brown, D. A., Pierson-Carey, C. D., Buckley, E. L., and Lew, H. L. (2004). Stepping over obstacles to improve walking in individuals with poststroke hemiplegia. *J. Rehabil. Res. Dev.* 41, 283–292. doi: 10.1682/JRRD.2004.03.0283

Kaplan, R. (1989). *The Experience of Nature: A Psychological Perspective*. Cambridge: Cambridge University Press.

Kaplan, S. (1995). The restorative benefits of nature - Toward an integrative framework. *J. Environ. Psychol.* 15, 169–182. doi: 10.1016/0272-4944(95)90001-2

Kokkinara, E., Kilteni, K., Blom, K. J., and Slater, M. (2016). First person perspective of seated participants over a walking virtual body leads to illusory agency over the walking. *Sci. Rep.* 6:28879. doi: 10.1038/srep28879

LaViola, J. J. Jr. (2000). A discussion of cybersickness in virtual environments. *Newsl. ACM SIGCHI Bull.* 32, 47–56. doi: 10.1145/333329.333344

Lee, A. C., and Maheswaran, R. (2011). The health benefits of urban green spaces: a review of the evidence. *J. Public Health* 33, 212–222. doi: 10.1093/pubmed/fdq068

Litleskare, S., Fagerheim, K., Holthe, G. R., Rydgren, T. L., Brambilla, E., and Calogiuri, G. (2017). "Nature experiences in Immersive Virtual Environments (IVE): a new concept for green-exercise and health promotion research," in *Proceedings of the Annual Conference of the European College of Sport Sciences, 4th-7th July 2017*, Essen. doi: 10.13140/RG.2.2.33625.83042

Loomis, J. M., Blascovich, J. J., and Beall, A. C. (1999). Immersive virtual environment technology as a basic research tool in psychology. *Behav. Res. Methods Instrum. Comput.* 31, 557–564. doi: 10.3758/BF03200735

Lox, C. L., Jackson, S., Tuholski, S. W., Wasley, D., and Treasure, D. C. (2000). Revisiting the measurement of exercise-induced feeling states: the physical activity affect scale (PAAS). *Meas. Phys. Educ. Exerc. Sci.* 4, 79–95. doi: 10.1207/S15327841Mpee0402_4

Mayer, F. S., Frants, C. M., Bruehlman-Senecal, E., and Dolliver, K. (2009). Why is nature beneficial?: the role of connectedness to nature. *Environ. Behav.* 41, 607–643. doi: 10.1177/0013916508319745

Nichols, S., Haldane, C., and Wilson, J. R. (2000). Measurement of presence and its consequences in virtual environments. *Int. J. Hum. Comput. Stud.* 52, 471–491. doi: 10.1006/ijhc.1999.0343

Olafsdottir, G., Cloke, P., and Vögele, C. (2017). Place, green exercise and stress: an exploration of lived experience and restorative effects. *Health Place* 46(Suppl. C), 358–365. doi: 10.1016/j.healthplace.2017.02.006

Pasco, D. (2013). The potential of using virtual reality technology in physical activity settings. *Quest* 65, 429–441. doi: 10.1080/00336297.2013.795906

Peruzzi, A., Cereatti, A., Della Croce, U., and Mirelman, A. (2016). Effects of a virtual reality and treadmill training on gait of subjects with multiple sclerosis: a pilot study. *Mult. Scler. Relat. Disord.* 5, 91–96. doi: 10.1016/j.msard.2015.11.002

Plante, T. G., Cage, C., Clements, S., and Stover, A. (2006). Psychological benefits of exercise paired with virtual reality: outdoor exercise energizes whereas indoor virtual exercise relaxes. *Int. J. Stress Manag* 13, 108–117. doi: 10.1037/1072-5245.13.1.108

Pretty, J., Griffin, M., Sellens, M., and Pretty, C. (2003). *Green Exercise: Complementary Roles of Nature, Exercise and Diet in Physical and Emotional Well-Being and Implications for Public Health Policy*. Colchester: University of Essex.

Pretty, J., Peacock, J., Sellens, M., and Griffin, M. (2005). The mental and physical health outcomes of green exercise. *Int. J. Environ. Health Res.* 15, 319–337. doi: 10.1080/09603120500155963

Rogerson, M., Gladwell, V. F., Gallagher, D. J., and Barton, J. L. (2016). Influences of green outdoors versus indoors environmental settings on psychological and social outcomes of controlled exercise. *Int. J. Environ. Res. Public Health* 13:363. doi: 10.3390/ijerph13040363

Russell, J. A. (1980). A circumplex model of affect. *J. Pers. Soc. Psychol.* 39, 1161–1178. doi: 10.1037/h0077714

Sheik-Nainar, M. A., and Kaber, D. B. (2007). The utility of a virtual reality locomotion interface for studying gait behavior. *Hum. Factors* 49, 696–709. doi: 10.1518/001872007X215773

Slater, M., Usoh, M., and Steed, A. (1995). Taking steps: the influence of a walking technique on presence in virtual reality. *ACM Trans. Comput. Hum. Interact.* 2, 201–219. doi: 10.1145/210079.210084

Slater, M., and Wilbur, S. (1997). A framework for immersive virtual environments (FIVE): speculations on the role of presence in virtual environments. *Presence* 6, 603–616. doi: 10.1162/pres.1997.6.6.603

Smith, J. W. (2015). Immersive virtual environment technology to supplement environmental perception, preference and behavior research: a review with applications. *Int. J. Environ. Res. Public Health* 12, 11486–11505. doi: 10.3390/ijerph120911486

Thompson Coon, J., Boddy, K., Stein, K., Whear, R., Barton, J., and Depledge, M. H. (2011). Does participating in physical activity in outdoor natural environments have a greater effect on physical and mental wellbeing than physical activity indoors? A systematic review. *Environ. Sci. Technol.* 45, 1761–1772. doi: 10.1021/es102947t

Valtchanov, D., Barton, K. R., and Ellard, C. (2010). Restorative effects of virtual nature settings. *Cyberpsychol. Behav. Soc. Netw.* 13, 503–512. doi: 10.1089/cyber.2009.0308

White, M., Elliott, L., Taylor, T., Wheeler, B., Spencer, A., Bone, A., et al. (2016). Recreational physical activity in natural environments and implications for health: a population based cross-sectional study in England. *Prev. Med.* 91, 383–388. doi: 10.1016/j.ypmed.2016.08.023

White, M. P., Pahl, S., Ashbullby, K. J., Burton, F., and Depledge, M. H. (2015). The effects of exercising in different natural environments on psycho-physiological outcomes in post-menopausal women: a simulation study. *Int. J. Environ. Res. Public Health* 12, 11929–11953. doi: 10.3390/ijerph120911929

WHO (2017). *Physical Activity – Fact Sheet*. Available at: http://www.who.int/mediacentre/factsheets/fs385/en/ [accessed February, 2017].

Yeh, H.-P., Stone, J. A., Churchill, S. M., Brymer, E., and Davids, K. (2017). Physical and emotional benefits of different exercise environments designed for treadmill running. *Int. J. Environ. Res. Public Health* 14:752. doi: 10.3390/ijerph14070752

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix: Paper II

Litleskare, S., & Calogiuri, G. (2019). Camera Stabilization in 360 degrees Videos and Its Impact on Cyber Sickness, Environmental Perceptions, and Psychophysiological Responses to a Simulated Nature Walk: A Single-Blinded Randomized Trial. *Frontiers in Psychology*, *10*, 2436. https://doi.org/10.3389/fpsyg.2019.02436

frontiers
in Psychology

ORIGINAL RESEARCH
published: 01 November 2019
doi: 10.3389/fpsyg.2019.02436

Camera Stabilization in 360° Videos and Its Impact on Cyber Sickness, Environmental Perceptions, and Psychophysiological Responses to a Simulated Nature Walk: A Single-Blinded Randomized Trial

Sigbjørn Litleskare and Giovanna Calogiuri*

Faculty of Social and Health Sciences, Inland Norway University of Applied Sciences, Elverum, Norway

OPEN ACCESS

Edited by:
Francesco Aletta,
University College London,
United Kingdom

Reviewed by:
Jooyoung Hong,
Nanyang Technological University,
Singapore
Alexia Galati,
University of North Carolina
at Charlotte, United States

***Correspondence:**
Sigbjørn Litleskare
sigbjorn.litleskare@inn.no

Specialty section:
This article was submitted to
Environmental Psychology,
a section of the journal
Frontiers in Psychology

Received: *31 May 2019*
Accepted: *14 October 2019*
Published: *01 November 2019*

Citation:
Litleskare S and Calogiuri G
(2019) Camera Stabilization in 360°
Videos and Its Impact on Cyber
Sickness, Environmental Perceptions,
and Psychophysiological Responses
to a Simulated Nature Walk:
A Single-Blinded Randomized Trial.
Front. Psychol. 10:2436.
doi: 10.3389/fpsyg.2019.02436

Immersive virtual environments (IVEs) technology has emerged as a valuable tool to environmental psychology research in general, and specifically to studies of human–nature interactions. However, virtual reality is known to induce cyber sickness, which limits its application and highlights the need for scientific strategies to optimize virtual experiences. In this study, we assessed the impact of improved camera stability on cyber sickness, presence, and psychophysiological responses to a simulated nature walk. In a single-blinded trial, 50 participants were assigned to watch, using a head-mounted display, one of two 10-min 360° videos showing a first-person nature walk: one video contained small-magnitude scene oscillations associated with cameraman locomotion, while in the other video, the oscillations were drastically reduced thanks to an electric stabilizer and a dolly. Measurements of cyber sickness (in terms of both occurrence and severity of symptoms), perceptions of the IVE (presence and perceived environmental restorativeness), and indicators of psychophysiological responses [affect, enjoyment, and heart rate (HR)] were collected before and/or after the exposure. Compared to the low-stability (LS) condition, in the high-stability (HS) condition, participants reported lower severity of cyber sickness symptoms. The delta values for pre–post changes in affect for the LS video revealed a deterioration of participants' affect profile with a significant increase in ratings of negative affect and fatigue, and decrease in ratings of positive affect. In contrast, there were no pre–post changes in affect for the HS video. No differences were found between the HS and LS conditions with respect to presence, perceived environmental restorativeness, enjoyment, and HR. Cyber sickness was significantly correlated with all components of affect and enjoyment, but not with presence, perceived environmental restorativeness, or HR. These findings demonstrate that improved camera stability in 360° videos is crucial to reduce cyber sickness symptoms and negative affective responses in IVE users. The lack of associations between improved stability and presence, perceived environmental restorativeness, and HR suggests that other aspects of IVE technology must be taken into account in order to improve virtual experiences of nature.

Keywords: green exercise, virtual reality, restorative environments, environmental perception, immersive virtual environments

INTRODUCTION

Nature is believed to have intrinsic qualities that promote health and well-being (Bowler et al., 2010; Bosch and Bird, 2018), which has led to increased interest in nature exposure as a research area. In the past two decades, interest and concerns have been raised regarding the possibility of using *virtual nature* to supplement exposure to real nature. Virtual nature might be a tool to increase the exposure to restorative nature experiences in an increasingly urbanized population and might even contribute to the reconnection of people to real nature, as studies show that acute bouts of green exercise (i.e., any physical activity performed while being exposed to nature) can increase people's feelings of nature connectedness (Mayer et al., 2009) and future intention to exercise and/or visit natural environments (Hug et al., 2008; Calogiuri and Chroni, 2014; Calogiuri et al., 2015). The effectiveness of this technology as an instrument in palliative care has been documented (Chirico et al., 2016; White et al., 2018). This technology could also address some of the major methodological issues inherent to environmental research (Smith, 2015), particularly in studies of natural environments (Lahart et al., 2019), as research related to outdoor environments does not allow strict control of confounding factors such as weather conditions, temperature, ambient noises, etc. To date, however, it remains unclear to what extent virtual nature can provide benefits equivalent to those provided by experiences in real nature, while on the other hand, concerns have been raised regarding the possible undesired effect of further distancing people from real nature (Levi and Kocher, 1999). Moreover, in spite of the fact that virtual reality has become a phenomenon of mass consumption, a series of side effects that can undermine the quality of users' experience yet remain to be addressed. These side effects are also known to mask potential effects in studies of virtual environments, thus limiting the usefulness of virtual technology in environmental research.

The Effectiveness of Virtual Nature

The potential of and the interest in virtual nature have been accelerated by the upcoming and continuous development of immersive virtual environments (IVEs) technology. IVEs are virtual environments that "surround an individual and create the perception that they are enclosed within and interacting with environments that provide a continuous stream of stimuli" (Smith, 2015). Head-mounted displays, devices with a motion sensor that allows a 360° vision of a virtual world while eliminating the visual contact with external reality, are central elements of IVE technology. These displays are considered more immersive than traditional displays and are believed to increase *presence*, i.e., the illusion of "being there" (Weech et al., 2019), which is considered a key element of the effectiveness of virtual environments (Steuer, 1992). The popularity of IVEs and head-mounted displays follows the introduction of affordable technology that not only provides the opportunity to immerse oneself in pre-set IVEs, but also allows the creation of new IVEs using special 360°cameras and freely available and customizable applications. *Static* IVEs (i.e., IVEs in which the perspective of the viewer is stationary, but still allow a 360° range of vision) have been shown to be able to replicate some of the positive psychological effects of exposure to real nature (Chirico and Gaggioli, 2019; Yu et al., 2018), such as helping people reduce stress (Liszio and Masuch, 2018) or experiences of pain (Chirico et al., 2016; White et al., 2018). The effectiveness of virtual environments has further been confirmed in studies of urban environments, in which virtual images and soundscapes are perceived as comparable to the real environment (Maffei et al., 2016; Hong et al., 2019).

While the literature provides increasingly strong support for the effectiveness of static natural IVEs, more challenges are encountered in relation to *dynamic* IVEs (i.e., IVEs in which the perspective of the viewer moves while allowing a 360° range of vision, for example, a simulated walk in a natural environment). Previous studies have found some psychological benefits of exposure to dynamic IVEs administered either in sedentary conditions (Valtchanov et al., 2010) or in combination with physical movement (Plante et al., 2003, 2006). The head-mounted displays used in these studies, however, only allowed a 60° to 65° range of vision, thus not fully engaging the viewers' peripheral vision. To the best of our knowledge, only one study has used *dynamic* 360° IVEs to compare a simulated nature walk (both in combination and not in combination with actual physical movement) to an actual outdoor walk in the same environment (Calogiuri et al., 2018). The results from this study suggest that the technology might have the potential to elicit psychological responses similar to those experienced in real nature, as in fact the participants assigned equivalent levels of perceived environmental restorativeness in the IVE as in the real environment and spontaneously walked at the same pace in both conditions. However, the users reported a significant deterioration of their psychological state after exposure to the IVE, with a decrease in positive emotions (tranquility and positive affect) and an increase in negative emotions (fatigue and negative affect). Such dramatic psychological responses appeared to be primarily associated with the experience of a phenomenon known as *cyber sickness*.

The Impact of Cyber Sickness on the Effectiveness of Virtual Nature

Cyber sickness mimics the symptoms of motion sickness, inducing feelings of dizziness, nausea, and general discomfort (Smith, 2015), and can be viewed as a specific type of visually induced motion sickness (Kennedy et al., 2010). There has been an increase in reported cases of cyber sickness in recent years, which may relate to the fact that more technologically advanced displays, such as head-mounted displays, generally induce higher levels of cyber sickness (LaViola, 2000; Sharples et al., 2008). There are two prevailing theories regarding the cause of cyber sickness. The *sensory conflict theory* postulates that cyber sickness is caused by sensory conflict between visual, vestibular, and proprioceptive inputs (Reason and Brand, 1975). Another explanation to how cyber sickness may originate is provided by the *postural instability theory*, which states that long periods without postural control will cause cyber sickness (LaViola, 2000). The negative effects caused by cyber sickness is a concern in studies of virtual environments as it is likely to act as a competing factor to the potential benefits of exposure to virtual nature. For example, recent research suggests that cyber sickness is inversely related to presence and that reducing cyber sickness might improve presence (Weech et al., 2019). Cyber sickness may also compete with the environmental perceptions. According to Rachel and Stephen Kaplan's Attention-Restoration Theory, environments characterized by qualities of fascination, compatibility, extent, and feeling of being away have the potential to elicit cognitive restoration and positive affective responses (Kaplan, 1989, 1995). However, Calogiuri et al. (2018) compared affective responses after exposure to real and virtual natural environments and found that the real environment induced a more positive affective response compared to the virtual environment, despite the fact that the participants perceived the virtual environment as having restorative properties equivalent to those perceived in the real environment. Calogiuri et al. (2018) further demonstrated medium to high correlations between cyber sickness and participants' affective responses, which suggest that cyber sickness disrupted any potential positive effects related to the restorative value of the virtual environment. The discomfort caused by cyber sickness and its potential impact on affect and presence limit the application of VR in health promotion and research purposes, and highlight the need for scientific strategies to optimize virtual experiences. Interestingly, recent advances in handheld stabilizing devices specifically designed for 360° cameras provide a potential strategy. These stabilizing devices reduce camera oscillations, which might reduce levels of cyber sickness.

The Impact of Scene Oscillations on Cyber Sickness

It has been hypothesized that the presence of scene oscillations might play a central role in the generation of cyber sickness during exposure to dynamic IVEs. Oscillations, which include movements of the scene displayed in the head-mounted displays on the horizontal and/or vertical axis (also known as "pitch and yaw"), are an issue in the development of dynamic IVEs, especially those developed using 360° cameras. Such oscillations may be generated as a consequence of poor stabilization of the camera (e.g., general vibrations) as well as vertical movements associated with the locomotion of the camera operator. Previous provocation studies, i.e., participants were exposed to a stimulus that was expected to provoke a negative response, have investigated the effect of oscillations using head-mounted displays (Lo and So, 2001; Bonato et al., 2009). In these studies, they intentionally created computer-generated IVEs with severe levels of oscillations and found that an increase in oscillations increases levels of cyber sickness (Lo and So, 2001; Bonato et al., 2009). It is not clear how the presence of oscillations leads to increased levels of cyber sickness. However, it has been suggested that when the viewer experiences the scene moving in one direction, it causes a feeling of self-motion (i.e., vection) in the opposite direction (Lo and So, 2001). This sense of self-motion perceived by the visual sensory system might cause sensory conflict with input from the vestibular and proprioceptive systems, as these sensory systems would not perceive any motion in this situation, thus linking the sickness-inducing effect of oscillations to the sensory conflict theory. Although this is just a theory and researchers debate whether or not vection actually is related to cyber sickness (Keshavarz et al., 2015), the studies of Lo and So (2001), and Bonato (2009) have established that high levels of artificially generated oscillations have a severe impact on cyber sickness. However, it is still unknown whether this applies to more practical situations and, in particular, to what extent minimizing oscillations can reduce levels of cyber sickness in 360° videos that are not intentionally designed to provoke a negative response.

The Present Study

The purpose of the present study was to assess the extent to which improved camera stability, in dynamic 360° videos simulating a nature walk, could reduce cyber sickness and improve participants' sense of presence and psychophysiological responses.

> Our primary hypothesis was stated as follows:
> A 360° video simulating a nature walk with a high level of camera stability will be associated with less severe symptoms of cyber sickness compared to a less stable video.
>
> Our secondary hypotheses were stated as follows:
> 1.1. If a highly stable 360° video simulating a nature walk induces less cyber sickness, it will also be associated with higher levels of presence compared to a less stable video.
> 1.2. If a highly stable 360° video simulating a nature walk induces less cyber sickness, it will also be associated with a more positive psychophysiological response compared to a less stable video.

In addition, in relation to each hypothesis, we performed an exploratory correlation analysis investigating possible associations between the variables in order to evaluate possible pathways that can help explain the complex relation linking cyber sickness, environmental perceptions, and psychophysiological responses.

MATERIALS AND METHODS

This paper is structured in line with the CONSORT guidelines (Schulz et al., 2010).

Participants

Estimation of required sample size was based on total score on the simulator sickness questionnaire (SSQ) from a preliminary pilot study done in our laboratory. The smallest meaningful between-group difference in total SSQ score was set to 20, with a pooled standard deviation of 30. α-level and desired power was set to 0.05 and 80%, respectively. Based on this calculation, an approximate sample size of 50 was deemed appropriate. Participants were recruited by the first author among students and non-scientific employees at the Inland Norway University of Applied Sciences (Elverum), but also a few participants outside the University during the months of June and August–October. Inclusion criteria were as follows: being $\geq$18 years old, having normal or corrected-to-normal vision, having limited experience with VR (less than monthly use), and not having previous diagnosis of balance impairments. The final sample comprised 22 males and 28 females. Participants' background characteristics are presented in **Table 1**. All participants signed a written informed consent prior to the experiment. The study was approved by the Norwegian Center for research data (reference number: 60451) and conducted according to the declaration of Helsinki.

IVE Technology and Experimental Conditions

The IVEs used for the experiment consisted of two 10-min-long 360° videos showing a first-person walk along a path in a natural environment. The playback was made using Samsung S7, with Android 7.0, mounted on a Samsung Gear head-mounted display (Samsung Gear VR SM-R323). The environment contained a fairly straight paved trial in natural surroundings alongside a river in Elverum. In addition to natural elements such as trees, grass, and water, the environment also included some buildings and a football field. An actual walk of the same duration along the same path has previously been reported to improve participant's affect state, with significant reductions in fatigue and negative affect, but no changes in tranquility and positive affect (Calogiuri et al., 2018).

TABLE 1 | Baseline characteristics of the participants (n = 50).

	LS (n = 25)	HS (n = 25)
Male (n)	11	11
Female (n)	14	14
Variables	**M (SD)**	**M (SD)**
Age (years)	30.6 (11.6)	30.0 (11.3)
BMI (kg/m^2)	25.8 (3.5)	24.6 (3.1)
Weekly physical activity (METs)	54.8 (22.3)	59.6 (26.4)

LS = low stability video. HS = high stability video. BMI = body mass index.

The two videos showed the same nature walk and differed only in the extent to which they contained frequent scene oscillations of small magnitude. Both IVEs were recorded in the same location using the same 360° video camera (Samsung gear 360 smc200, 3840 × 1920 resolution at 30 frames per second), in pleasant weather conditions. Measures were taken to ensure that all elements except camera oscillations would be as similar as possible. This includes recording the scene segments at the same time of year with similar levels of "greenness," matching the lighting postproduction based on the subjective evaluation of the authors, matching start and end position of the videos, etc. The low-stability (LS) video was created using segments from a video used in a previous experiment (Calogiuri et al., 2018). To develop that video, a 360° camera was mounted on a modified Yelangu s60t mechanical handheld stabilizer and the video recorded was run through two software stabilizing programs as described in Calogiuri et al. (2018). This procedure was developed to minimize camera oscillations, but due to the oscillations associated with the camera operator locomotion as well as the mechanical nature of the stabilizer, oscillations of small magnitude still occurred along both the vertical and horizontal axis. In contrast, the high-stability (HS) video was recorded by mounting the 360° camera on an electronic gimbal handheld stabilizer (Feiyu Tech G360), which provided a high degree of stability, especially in the horizontal axis (pitch). The camera operator was also pushed along the path on a dolly to further minimize oscillations in the vertical axis (yaw). This procedure effectively eliminated pitch oscillations though, in order to align the camera positioning with the path, yaw oscillations of small magnitude still occurred sporadically (six times during the entire duration of the video). The two videos were similar in all aspects, but differed in both frequency and magnitude of oscillations.

Instruments

Cyber Sickness

The occurrence of cyber sickness was measured with a dichotomous question: "are you cyber sick," followed by a brief verbal explanation of the term, to which the participant responded either "yes" or "no" (Merhi et al., 2007; Munafo et al., 2017). The SSQ was used to measure the severity of the symptoms related to cyber sickness (Kennedy et al., 1993). As the name implies, the SSQ was designed to measure simulator sickness, but the questionnaire has seen widespread use in studies of cyber sickness as well (e.g., Draper et al., 2001; Merhi et al., 2007; Munafo et al., 2017). Participants were asked to rank, on a four-point Likert scale, the severity of 16 different symptoms such as "Headache" and "Increased salivation." Scoring and analysis of the SSQ data were performed according to the recommendations of Kennedy et al. (1993). The scale showed adequate internal consistency for the total score (α = 0.94).

Presence and Environmental Perceptions

To assess participants' sense of presence in the IVEs, we used a scale based on the approach of Nichols et al. (2000), which includes eight items related to presence in virtual environments. The items were formulated as statements as shown in **Table 2**, and participants were asked to rate their level of agreement

TABLE 2 | Items used to assess presence.

Short name	Item
Being there	In the computer-generated world, I had the sense of "being there"
Realism	I thought of the virtual environment as equal to the real environment
Sense of reality	The virtual world became more real or present to me compared to the real world. NB: by "real world," we mean the room where you were undergoing the test
Awareness	During the "virtual walk," I often thought of the other person(s) in the room with me
Other persons	It would have been more enjoyable to engage with the "virtual world" with no one else in the room
External noises	While I was doing the "virtual walk," I paid much attention to other noises around me in the room
Flatness	The virtual world appeared flat and missing in depth
Movements lag	The lag, delay or difference between my movements and the movements in the "virtual walk" were disturbing

to each statement on an 11-point Likert scale. Alongside the measure of presence, the extent to which the participants perceived the IVEs as having a potential for environmental restorativeness was assessed by administering the perceived restorativeness scale (Hartig et al., 2003). In the context of our study, this measure provided an indicator of the potential of the IVEs to elicit cognitive restoration. The scale consists of 16 items, rated on a 11-point Likert scale (0 = absolutely disagree, 10 = absolutely agree), which assess the subjective perception of four environmental qualities in line with Rachel and Stephen Kaplan's Attention-restoration theory (Kaplan, 1989, 1995): Being away, which refers to the extent to which the environment provides a feeling of "being away" from everyday demands and concerns (two items, e.g., "It was an escape experience"); Fascination, the environment's ability to capture the viewers' effortless attention (five items, e.g., "The setting has fascinating qualities"); Coherence, the extent to which the elements in an environment combines to a coherent whole (four items, e.g., "There is too much going on"); and Compatibility, which describes how well a place fits people's inclinations and interests (five items, e.g., "have a sense that I belong there"). The caption on top of the items explicitly stated "The following questions relate to the virtual environment." The scale showed adequate internal consistency (α = 0.74–0.86).

Psychophysiological Responses

The participants' psychophysiological responses to the different IVEs were evaluated in relation to enjoyment, pre-to-post changes of affect, and heart rate (HR). Enjoyment was assessed after exposure to the IVE using a single-item inquiring: "on a scale from 1 to 10, how enjoyable was the activity you engaged in?" This measure has been used in studies investigating participants' affective responses to green exercise, showing high correlation with measurements of perceived environmental restorativeness (Calogiuri et al., 2015, 2018). Participants' affect was assessed before (Pre) and after (Post) exposure to the IVE using the Physical activity affect scale (Lox et al., 2000). The scale consists of 12 items (e.g., "energetic," "calm," "miserable," and "tired") that, in line with Russel's circumplex model (Russell, 1980), are grouped in four components: Positive affect (positive valence, high activation), Tranquility (positive valence, low activation), Negative affect (negative valence, high activation), and Fatigue (negative valence, low activation). The scale showed, in general, adequate internal consistency for the different subscales (α = 0.68–0.87), though somewhat poor levels of internal consistency were found for Positive affect in the Pre assessment (α = 0.56) and Negative affect in both assessments (α = 0.56–0.56, in Pre and Post, respectively). Lastly, HR was recorded continuously over a 6-min period during exposure to the IVEs using a HR-monitor (Polar FT60M BLK WD) and extracted as beats per minute as a physiological indicator of stress (Allen et al., 2014; Duzmanska et al., 2018). It was decided to exclude the first and last couple of minutes of video exposure from the HR measurements to allow postural adaptation of HR in the beginning of the video, as the participants moved from a standing to a seated position, and due to concerns that the fact that the examiner reentered the experimental room at the end of the video would influence HR. Mean HR (HRmean), the mean of all individual measurements, and maximal HR (HRmax), the single highest value recorded, were automatically recorded by the HR monitor and used for further analyses.

Participants' Background Characteristics

This information was collected in order to establish a general indication of the health and fitness status of the participants, and included sex, age, body mass index (BMI), and physical activity habits. Sex and age were self-reported by the participants, while BMI was calculated [body weight (kg)/height $(m)^2$] based on assessments of height and body weight performed in the laboratory prior to participation in the experiment. The participant's physical activity levels were assessed using an adjusted version of the leisure time exercise questionnaire (Godin and Shephard, 1985), which was modified in the caption to include transportation physical activity (i.e., walking or biking to reach different destinations). This adjusted version of the leisure time exercise questionnaire was used in a previous study and was found to correlate with objective assessments of physical activity by accelerometer (Calogiuri et al., 2013).

Design and Procedure

The study was designed as a single-blinded experimental trial with two parallel groups. Participants were allocated to either one of the two experimental conditions with a 1:1 allocation ratio based on a predetermined sequence (i.e., the first participant was assigned to the LS IVE, the second to the HS IVE, the third to the LS IVE, and so on). This allocation procedure was chosen to ensure that an equal amount of experiments was carried out in each group in the same time period, as some participants were tested in June and some in August–October due to practical reasons. The allocation, which was determined by the first author, was stratified by sex to assure a balanced distribution of males and females in each group. This allocation was strictly based on the predetermined sequence, which was developed when the researchers were still unaware of the participants' order, and never modified to accommodate participants' preferences or characteristics. All participants were blinded to which condition they were allocated to and were unaware of the difference between the two IVEs. The experiment was performed in a controlled laboratory environment at Inland Norway University of Applied Sciences (Campus Elverum), with standardized temperature, ventilation, and lighting, and a high degree of sound insulation. The participants viewed the IVE while seated, and both videos lasted 10 min to approximate the exposure duration that give the largest effects on psychological outcomes according to the meta-analysis by Barton and Pretty (2010). No changes to methods were made after trial commencement.

The experimental procedures were performed as follows: (1) measurement of height and weight; (2) pre-exposure questionnaire, including physical activity affect scale and background information; (3) exposure to the IVEs, with continuous recording of HR from the third to the ninth minute of the IVE; and (4) post-exposure questionnaire, including SSQ, presence, perceived environmental restorativeness, physical activity affect scale, and enjoyment. In addition to the ones listed above, the study included additional measurements (i.e., a measure of future green exercise intention and assessments of postural stability during the first and last minute of video exposure), which are not presented in this paper.

Analyses

The data were preliminarily explored in order to examine the frequency distribution of the various variables as well as identify possible missing values and outliers. The assumption of normality was evaluated by a Shapiro–Wilk test, which revealed that none of the outcome variables were normally distributed. Hence, a Mann–Whitney *U* test was used to investigate possible differences between the two IVE conditions for the SSQ scores, the eight items of presence, the four components of perceived environmental restorativeness, the four components of affect (expressed as delta values: post-exposure - pre-exposure), enjoyment, and HR. Potential between condition differences for the dichotomous measure of cyber sickness were analyzed by a chi-square test. In order to establish possible pre-to-post changes in the four different components of affect, a Wilcoxon signed-rank test was also applied to each of the affect components (Positive affect, Tranquility, Negative affect, and Fatigue). Lastly, a Spearman's rank correlation coefficient (ρ) was used as an exploratory analysis to evaluate potential associations between cyber sickness, and presence, and all outcome variables. Because of the large number of between- and within-group comparisons, the level of significance was adjusted using the Benjamini–Hochberg procedure with a false discovery rate of 5%. Adjusted *p*-values are presented throughout the manuscript for between- and within-group comparisons. The correlation analysis was considered an exploratory analysis and, thus, the Benjamini–Hochberg procedure was not applied (Victor et al., 2010). All measurements were treated in accordance with standard procedures normally adopted for each instrument, and the overall statistical strategy was consistent with plans done prior to implementation of the study.

All outcome variables are presented as median (Mdn) and interquartile range (IQR). All statistical analyses were performed in IBM SPSS statistics 24 (IBM, New York, NY, United States). The significance level was set at $p < 0.05$.

RESULTS

The participants were generally considered active and healthy individuals with a mean (±standard deviation) age, height, weight, BMI, and modified leisure time exercise questionnaire score of 29.8 (±10.8) years, 173 (±10) cm, 76.1 (±14.9) kg, 25.2 (±3.3) kg/m^2, and 57.2 ± 24.3 units, respectively.

Three participants did not complete the full 10 min of video exposure due to high levels of cyber sickness. All three participants watched the LS video and discontinued after 3 min 56 s, 5 min 40 s, and 6 min 55 s. Data for all assessments were obtained for these participants and were included in the analysis (see flow diagram in **Figure 1**). Unfortunately, HR data were missing for two participants due to technical difficulties, and both of these participants were exposed to the HS condition.

Cyber Sickness

The dichotomous measure of cyber sickness revealed that 4 out of 25 participants (16%) in the HS condition and 12 out of 25 participants (46%) in the LS condition reported being sick. This effect was marginally not significantly different between the two conditions ($\chi^2 = 5.88$, adjusted $p = 0.055$). As shown in **Figure 2**, the Mann–Whitney *U* test on the total scores from the SSQ showed that participants in the HS condition reported significantly less severe symptoms of cyber sickness compared to participants in the LS condition (LS: Mdn = 33.66, IQR = 14.96–99.11; HS: Mdn = 18.70, IQR = 1.87–35.53, $U = 179.0$, adjusted $p = 0.039$).

Spearman's rank correlation showed no significant correlations among SSQ scores and any of the components of presence or perceived environmental restorativeness. On the other hand, the analysis revealed medium to high correlations between SSQ scores and enjoyment and all components of affect (**Table 3**). No significant associations were found among the SSQ scores and HR.

Presence and Environmental Perceptions

As shown in **Figure 3**, the sense of presence in the IVEs was similar in the two experimental conditions, with no significant between-condition differences for any of the eight items of presence (adjusted $p = 0.179–0.899$). Similarly, no significant differences between the two experimental conditions were found for the components of perceived environmental restorativeness (adjusted $p = 0.589–0.938$, **Figure 4**).

Spearman's rank correlation revealed significant correlations between some items of presence and perceived environmental restorativeness, the four components of affect, and enjoyment (**Table 4**) including medium correlations between being there and

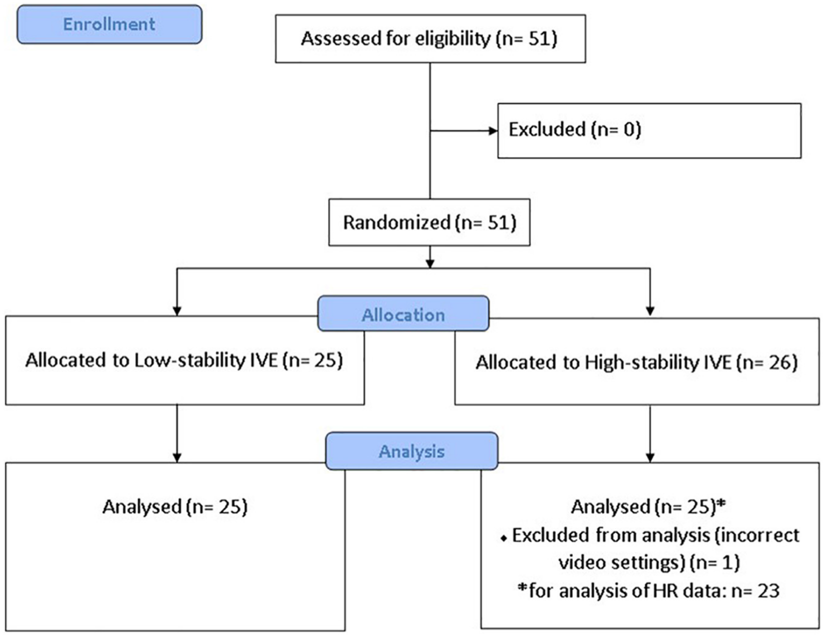


FIGURE 1 | Flow diagram showing participants enrolled, allocated to condition, and included in the analyses (Schulz et al., 2010).

three components of perceived environmental restorativeness and enjoyment, medium correlations between realism and one component of perceived environmental restorativeness and enjoyment, medium to high correlations between sense of reality and two components of perceived environmental restorativeness, a medium negative correlation between flatness and one component of perceived environmental restorativeness, and finally medium correlations between movement lag and the two negative components of the physical activity affect scale (**Table 4**). No significant correlations were found among the items of presence (**Table 4**).

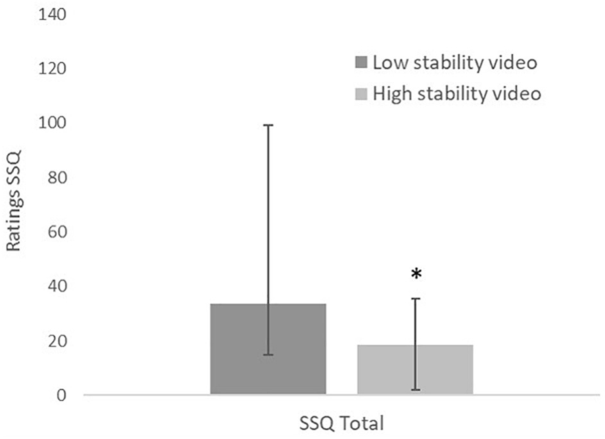


FIGURE 2 | Comparison of the severity of cyber sickness symptoms measured with the Simulator sickness questionnaire after exposure to a low- or high-stability 360° video. SSQ Total = Total score (n = 50; medians and IQRs). * = significant difference from low-stability video at the $p < 0.05$ level.

Psychophysiological Responses

The Wilcoxon signed-rank test showed that, after being exposed to the IVE, the participants in the LS condition had a significant deterioration of their affect state, with significant decrease in the ratings of Positive affect (Pre-exposure: Mdn = 3.67, IQR = 3.67–4.00; Post-exposure: Mdn = 3.33, IQR = 2.67–3.67; $Z = -2.735$, adjusted $p = 0.002$) and Tranquility (Pre-exposure: Mdn = 4.33, IQR = 4.00–4.67; Post-exposure: Mdn = 3.67, IQR = 2.67–4.33; $Z = -2.972$, adjusted $p = 0.021$) and a significant increase in the ratings of Negative affect (Pre-exposure: Mdn = 1.00, IQR = 1.00–1.33; Post-exposure: Mdn = 1.67, IQR = 1.00–3.00; $Z = -3.194$, adjusted $p = 0.014$). However, there was no significant change in ratings of Fatigue after the LS condition (Pre-exposure: Mdn = 1.67, IQR = 1.33–2.33; Post-exposure: Mdn = 2.00, IQR = 1.33–3.33; Z = -2.338, adjusted $p = 0.063$) as illustrated in **Table 5**. In contrast, no significant pre–post changes were observed in the HS condition for any of the components of affect (Positive affect, Pre-exposure: Mdn = 3.67, IQR = 3.00–4.00; Positive affect, Post-exposure: Mdn = 3.33, IQR = 3.00–4.00; Tranquility, Pre-exposure: Mdn = 4.33, IQR = 4.00–4.67; Tranquility, Post-exposure: Mdn = 4.00, IQR = 3.33–4.67; Negative affect, Pre-exposure: Mdn = 1.00, IQR = 1.00–1.67; Negative affect, Post-exposure: Mdn = 1.00, IQR = 1.00–1.67; Fatigue, Pre-exposure: Mdn = 2.00, IQR = 1.67–3.00; Fatigue, Post-exposure: Mdn = 1.67, IQR = 1.00–2.67; adjusted $p > 0.05$ for all comparisons). The Mann–Whitney U test of delta values for affect revealed significant differences between the two experimental conditions, with larger reductions of Positive

TABLE 3 | Spearman's rho correlation between total cyber sickness score (top row) and the items of presence[1], perceived environmental restorativeness[2] (fascination, being away, coherence, compatibility), affect[3] (positive affect, tranquility, negative affect, fatigue), enjoyment, HR, and background characteristics ($n = 50$).

	Total SSQ
Being there[1]	−0.14
Realism[1]	0.09
Sense of reality[1]	0.00
Awareness[1]	−0.04
Other people[1]	0.22
Noises[1]	0.19
Flatness[1]	0.02
Movement lag[1]	−0.15
Fascination[2]	−0.22
Being away[2]	−0.19
Coherence[2]	0.16
Compatibility[2]	−0.21
Positive affect[3] (Δ)	−0.39**
Tranquillity[3] (Δ)	−0.35*
Negative affect[3] (Δ)	0.50**
Fatigue[3] (Δ)	0.63**
Enjoyment	−0.48**
HRmean	0.11
HRmax	0.14
Sex	0.17
Age	0.04
BMI	−0.15
Weekly PA	−0.11

*BMI = body mass index. Weekly PA = weekly physical activity. Δ = delta values. *Correlation is significant at the $p < 0.05$ level. **Correlation is significant at the $p < 0.01$ level.*

affect ($U = 174.5$, adjusted $p = 0.031$) and larger increments of Negative affect ($U = 146.5$, adjusted $p = 0.006$) and Fatigue ($U = 171.0$, adjusted $p = 0.028$) after LS condition compared to HS. No significant difference between the two conditions was found for Tranquility ($U = 226.0$, adjusted $p = 0.196$). Similarly, the ratings of enjoyment after the HS condition (Mdn = 8.00, IQR = 6.00–9.00) were not significantly different compared to the LS condition (Mdn = 6.00, IQR = 5.00–7.00; $U = 211.0$, adjusted $p = 0.136$). No significant differences were found between the two experimental conditions for either average (LS: Mdn = 71.00, IQR = 64.00–77.00; HS: Mdn = 66.00, IQR = 62.00–77.00; $U = 241.5$, adjusted $p = 0.551$) or peak HR (LS: Mdn = 81.00, IQR = 72.00–91.00, $p = 0.342$; HS: Mdn = 76.00, IQR = 68.00–89.00; $U = 252.0$ adjusted $p = 0.584$).

DISCUSSION

The results of the present study demonstrate that the 360° video characterized by high camera stability induced significantly lower levels of cyber sickness compared to the 360° video characterized by low camera stability, which is in support of our main hypothesis. The lower levels of cyber sickness in the HS condition were not accompanied by a significant difference in presence, which contradicts our secondary hypothesis 1.1. For our last hypothesis (1.2), which postulated that a reduction in cyber sickness should be accompanied by an improved psychophysiological response, the results are partly in favor of the hypothesis as we found a more positive psychological response in the HS condition, but the physiological measures were similar between the two conditions. These results were obtained in two 360° videos that were perceived as having similar environmental characteristics as indicated by the similar values reported between the two conditions for the components of perceived environmental restorativeness. Furthermore, our exploratory correlation analysis revealed several possible pathways that can help explain the complex relation linking cyber sickness, environmental perceptions, and psychophysiological responses.

The total SSQ score was substantially lower after the HS condition compared to LS, which suggests that improving camera stability and thereby reducing camera oscillations reduce severity of cyber sickness symptoms in 360° videos. These results support the findings of previous provocation studies examining the impact of severe levels of oscillations on cyber sickness using a head-mounted display (Lo and So, 2001; Bonato et al., 2009). Lo and So (2001) found that a severe increase in either pitch, yaw, or roll increased symptom severity with no differences between axis in a head-mounted display with a limited field of view (48° horizontal, 36° vertical). Bonato et al. (2009) confirmed that severe levels of oscillations induce cyber sickness, and further revealed that oscillations along two different axes simultaneously increased symptom severity compared to single-axis oscillation in a head-mounted display with a 60° field of view. Our results are in line with the findings of Lo and So (2001) and Bonato et al. (2009) for 360° videos and further demonstrate that also low levels of oscillations influence cyber sickness. This notion is in line with the Sensory Conflict theory proposed by Reason and Brand (1975). As outlined in the introduction, it is believed that oscillations causes a sense of self-motion in the opposite direction of the oscillation, which causes a conflict between visual inputs and vestibular and proprioceptive inputs. In the present study, the HS condition produced less camera oscillation along all three axes, which may have reduced sensory conflict. This potential reduction in sensory conflict may explain the lower symptom severity after the HS condition. In contrast to symptom severity, the occurrence of cyber sickness was not significantly different between low and high stability. However, the effect was borderline significant even after applying the Benjamini–Hochberg procedure ($p = 0.055$), which suggests that scene stability may influence occurrence of cyber sickness and that the issue is worthy of further investigation.

The lower symptom severity (total SSQ score) and potentially less sensory conflict suggest that the HS condition should have induced higher levels of presence compared to LS, as a study by Slater et al. (1995) suggests that reduced sensory conflict may improve presence (Slater et al., 1995) and a recent review found an inverse relationship between presence and cyber sickness (Weech et al., 2019). This was not the case and participants reported similar levels of presence regardless of which video they had viewed. Early research in VR proposed the logical argument that lower levels of sensory conflict would lead to

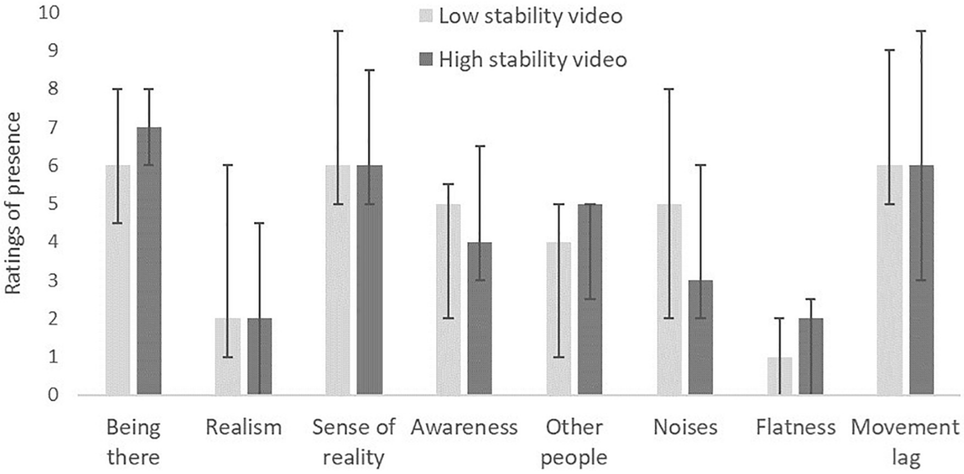


FIGURE 3 | Comparison of ratings of presence associated with exposure to a low- or high-stability 360° video (*n* = 50; medians and IQRs).

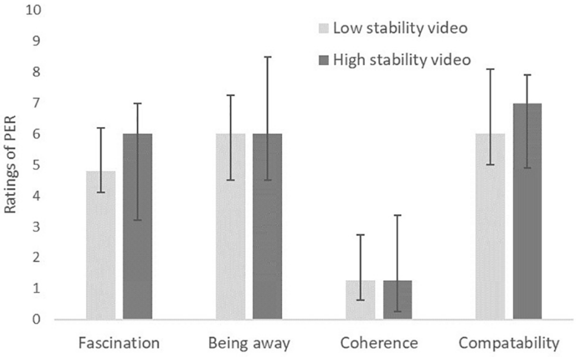


FIGURE 4 | Comparison of ratings of the four components of the perceived restorativeness scale (PER) associated with a low- or high-stability 360° video (*n* = 50; medians and IQRs).

higher levels of presence (Slater et al., 1995). This proposal is yet to be backed by rigorous scientific evidence, due to the challenge of directly measuring sensory conflict, but the idea has still carried on into more recent research (Weech et al., 2019). As stated above, we proposed the idea that the HS condition induced less sensory conflict compared to LS. These potentially lower levels of sensory conflict were not accompanied by higher levels of presence, which leads to one of two logical conclusions. Either lower levels of oscillations do not induce lower levels of sensory conflict or the idea that lower levels of sensory conflict increase presence is false. Unfortunately, the present study cannot make a definitive statement regarding this matter. However, our results definitively challenge the proposed relationship between cyber sickness and presence (Weech et al., 2019), as the between condition difference in cyber sickness was not accompanied by a difference in presence and there were no significant correlations between the two concepts. The lack of coherence with the conclusions by Weech et al. (2019) may have several explanations. Most importantly, Weech et al. (2019) acknowledges some limitations in the literature they reviewed: most of the literature had methodological limitations, such as limited sample size; most of the research identified supported an inverse relationship, but several papers also supported a positive relationship or no relationship; the review also identified several potential moderators of the relationship, such as sex, display factors, and context. In addition to the limitations in current research identified by Weech et al. (2019), it is also acknowledged that presence is a complex characteristic that is influenced by a multitude of factors, such as environmental interaction, synchrony of sensory stimuli, and fidelity of the virtual environment (Weech et al., 2019). Thus, it is possible that other aspects of the IVE, in addition to camera stability, must be improved in order to increase presence. Nevertheless, the present study does not support the proposed relationship between cyber sickness and presence and suggests that improved camera stability by itself does not result in higher levels of presence.

The fact that no differences were found between the HS and LS condition with respect to perceived environmental restorativeness is not surprising, as this measure is strongly dependent on the characteristics of the environments in which the 360° videos were filmed and should thus be interpreted as our efforts to reproduce highly comparable IVEs being successful. At the same time, this finding also suggests that, similarly to what was found for presence, the level of camera stabilization is unlikely to influence the viewers' perceptions of the virtual environment. Furthermore, the finding of the present study not only shows the paramount impact of camera stabilization in avoiding negative affective responses in the viewers of an IVE but also confirms the central role of cyber sickness in explaining such responses. It has to be stressed, however, that even though the HS condition was associated with significantly more positive affective responses than the LS condition, different from what we would expect from an *in vivo* situation, it was yet unable to induce significant improvements in the participants affect profile. In a previous study, we found in fact that an actual walk of the same duration in the same (real) environment where

TABLE 4 | Spearman's rho correlation between different components of presence (top row) and the components of perceived environmental restorativeness^1, affect^2, enjoyment, HR, and background characteristics (*n* = 50).

	Being there	Realism	Sense of reality	Awareness	Other persons	Noises	Flatness	Movement lag
Fascination^1	0.40**	0.34*	0.26	0.13	0.04	−0.06	−0.31*	−0.14
Being away^1	0.38**	0.26	0.46**	−0.17	−0.09	−0.10	−0.17	0.10
Coherence^1	−0.04	0.03	−0.04	0.19	−0.09	0.05	−0.05	0.23
Compatibility^1	0.36*	0.21	0.29*	−0.01	0.00	−0.09	−0.18	0.06
Positive affect^2 (Δ)	0.21	0.14	−0.10	−0.15	−0.03	−0.21	−0.12	−0.24
Tranquillity^2 (Δ)	0.06	0.21	−0.12	−0.11	−0.19	−0.13	0.25	−0.13
Negative affect^2 (Δ)	−0.07	−0.09	−0.06	0.12	0.07	0.04	−0.14	0.31*
Fatigue^2 (Δ)	−0.18	−0.16	−0.01	0.07	0.17	0.15	0.02	0.40**
Enjoyment	0.28*	0.30*	0.06	0.17	−0.09	0.17	−0.18	−0.19
HRmean	−0.09	0.20	−0.09	0.10	0.07	−0.08	0.13	−0.20
HRmax	−0.09	0.24	−0.09	0.09	0.09	−0.10	0.08	−0.21

*Δ = delta values. *Correlation is significant at the $p < 0.05$ level. **Correlation is significant at the $p < 0.01$ level.*

the 360° was filmed induced improvements in the participants' affect state, who reported a significant reduction of Fatigue and Negative affect after the walk as compared with before the walk (Calogiuri et al., 2018). This is in contrast with a previous study by Chirico and Gaggioli (2019), who found that the emotional responses to viewing a natural landscape *in vivo* or in form of IVE were not significantly different. In another study, Yu et al. (2018) compared participants' responses to viewing a natural vs. an urban setting in IVE and found some similarities to what would be expected *in vivo* (e.g., a reduction of negative emotions in the natural IVE as opposed to an increase in fatigue in the urban IVE). However, unlike trials *in vivo*, no difference between the two IVEs was observed with respect to physiological measurements (blood pressure, salivary α amylase, and HR variability). In the present study, the lack of influence of improved camera stability on presence (which remained somewhat limited) may also contribute to explain the inability of the virtual walk in the HS condition to provide psychophysiological outcomes similar to those expected *in vivo*. Presence is considered a key element of a successful IVE (Steuer, 1992) and research within various fields have linked an IVE's ability to induce feelings of presence to the ability to produce the desired effect of the specific IVE, e.g., within analgesia (Triberti et al., 2014) and treatment of anxiety and phobias (Ling et al., 2014; Botella et al., 2017). Since ratings of presence were similar in the HS and LS conditions, it was not surprising that the participants' psychophysiological responses were similar as well. Remarkably, and in line with our previous study (Calogiuri et al., 2018), the ratings of enjoyment and all components of the physical activity affect scale were moderately to highly correlated with total SSQ score, which emphasize the paramount role played by cyber sickness in modulating the viewers' affective responses to the IVE exposure. At the same time, significant medium correlations were also observed among enjoyment and two items of presence, namely, being there and realism. Based on the assumption that presence is a key element of an effective IVE, these findings suggest that the feeling of being there and realism were particularly important to the participants' rating of enjoyment. Similarly, three components of perceived environmental restorativeness were moderately to highly correlated with several items of presence, which suggest that improved feelings of presence are closely associated with the restorative value of nature IVEs.

TABLE 5 | Pre–post changes of the four components of affect.

	LS		HS	
	Mdn	**IQR**	**Mdn**	**IQR**
Positive affect				
Pre	3.67	3.67–4.00	3.67	3.00–4.00
Post	3.33**	2.67–3.67	3.33	3.00–4.00
Tranquility				
Pre	4.33	4.00–4.67	4.33	4.00–4.67
Post	3.67*	2.67–4.33	4.00	3.33–4.67
Negative affect				
Pre	1.00	1.00–1.33	1.00	1.00–1.67
Post	1.67*	1.00–3.00	1.00	1.00–1.67
Fatigue				
Pre	1.67	1.33–2.33	2.00	1.67–3.00
Post	2.00	1.33–3.33	1.67	1.00–2.67

*LS = low-stability video. HS = high-stability video. * = significant difference from pre-values at the $p < 0.05$ level. ** = significant difference from pre-values at the $p < 0.01$ level.*

It should be noted that there were considerable individual differences in the response to the IVEs presented in this study, especially for SSQ. This phenomenon is clearly illustrated by the size of IQRs and by the fact that three participants were unable to complete the 10 min of exposure to the LS condition due to high levels of cyber sickness, while others could view the same video without experiencing any symptoms of cyber sickness. Other studies have also reported large inter-individual differences in the extent to which different individuals respond to virtual environments in terms of susceptibility to cyber sickness (Akiduki et al., 2003; Curtis et al., 2015; Gavgani et al., 2017). These individual differences are not fully understood, but research suggests that genetics (Hromatka et al., 2015), sex (Munafo et al., 2017), visual acuity (Allen et al., 2016), and postural control (Munafo et al., 2017) may explain some of the inter-individual variability. In the present study, cyber sickness was not associated with sex, or any of the participants' background characteristics (age, BMI, and physical activity levels), which suggests that other factors caused the inter-individual variation. Further research that contributes to a better understanding of this phenomenon, and how it relates to the underlying causes of cyber sickness, is pivotal to shed more light on the issue of cyber sickness in relation to the application of IVE in green exercise research and practice, as well as and in the field of VR in general.

Strengths and Limitations

The primary strengths of this study relate to important characteristics of its design, such as blinding of participants and rigorous experimental procedure, which allowed strict control of most confounding factors such as expectations, carryover effects, temperature, noises, and lighting. A possible limitation was the fact that that the content of the IVEs was not exactly identical, as the videos were recorded at different times. Although measures were taken to make the content as similar as possible (see section "IVE Technology and Experimental Conditions"), some minor differences such as light conditions, ambient noises, placement of objects, and activities of other people passing by were unavoidable. These differences were considered minor and the impact on the outcome of the present study should be minimal, as corroborated by equivalent ratings of perceived environmental restorativeness in the two conditions. The sample size in the present study was calculated *a priori* for our main outcome (total SSQ score) and the statistical power should be satisfactory for this measure, but the sample size may still have been too small to obtain adequate power for the other measures included in this study. Generalizability of the findings might be limited, as our participants were healthy adults, and it is uncertain whether the findings apply to VR users with pre-recorded clinical conditions (e.g., severe sight deficiencies, infections of the vestibular system, or other health problems). The possibility of occurrence of type I error should also be considered for the correlation analysis given the relatively large amount of statistical tests performed. However, this analysis was meant to reveal potential associations to be considered for further investigation.

CONCLUSION

In the present study, we compared two different IVEs created by filming 360° videos with different stabilization techniques, leading to different amounts and frequency of small-magnitude oscillations. The findings show that a higher degree of scene stability in an IVE is paramount to reduce severity of cyber sickness symptoms, thus avoiding negative affective responses. Nevertheless, when comparing our findings to findings in studies of real nature, it is clear that even a highly stable IVE was ineffective in providing psychophysiological benefits equivalent to those expected *in vivo* (i.e., during a real nature walk). These findings not only demonstrate that technological advancements can improve the effectiveness of IVE in green exercise research and related areas but also show the complexity of the human–technology interaction and that more research and further technological advancement are needed before green exercise experiences can be sufficiently replicated in laboratory conditions.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. This study was registered in the Norwegian Centre for Research Data (reference number: 60451) and conducted in accordance with the Declaration of Helsinki. All patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SL and GC contributed to the study concept, study design, statistical analysis, and revision of the manuscript. SL conducted the experiments and drafted the manuscript. Both authors approved the final version of the manuscript.

FUNDING

This study was supported by the Inland Norway University of Applied Sciences.

ACKNOWLEDGMENTS

We thank Inland Norway University of Applied Sciences for funding this project and all participants who underwent the experiments. We also thank Lars-Christian Sørlie for his assistance recording the videos.

REFERENCES

Akiduki, H., Nishiike, S., Watanabe, H., Matsuoka, K., Kubo, T., and Takeda, N. (2003). Visual-vestibular conflict induced by virtual reality in humans. *Neurosci. Lett.* 340, 197–200. doi: 10.1016/s0304-3940(03)00098-3

Allen, A. P., Kennedy, P. J., Cryan, J. F., Dinan, T. G., and Clarke, G. (2014). Biological and psychological markers of stress in humans: focus on the trier social stress test. *Neurosci. Biobehav. Rev.* 38, 94–124. doi: 10.1016/j.neubiorev.2013.11.005

Allen, B., Hanley, T., Rokers, B., and Green, C. S. (2016). Visual 3D motion acuity predicts discomfort in 3D stereoscopic environments. *Entertain. Comput.* 13, 1–9. doi: 10.1016/j.entcom.2016.01.001

Barton, J., and Pretty, J. (2010). What is the best dose of nature and green exercise for improving mental health? a multi-study analysis. *Environ. Sci. Technol.* 44, 3947–3955. doi: 10.1021/es903183r

Bonato, F., Bubka, A., and Paumisano, S. (2009). Combined pitch and roll and cybersickness in a virtual environment. *Aviat. Space Environ. Med.* 80, 941–945. doi: 10.3357/Asem.2394.2009

Bosch, M. V. D., and Bird, W. (eds) (2018). *Nature and Public Health - the Role of Nature in Improving the Health of a Population*. Oxford: Oxford University Press.

Botella, C., Fernandez-Alvarez, J., Guillen, V., Garcia-Palacios, A., and Banos, R. (2017). Recent progress in virtual reality exposure therapy for phobias: a systematic review. *Curr. Psychiatry Rep.* 19:42. doi: 10.1007/s11920-017-0788-4

Bowler, D. E., Buyung-Ali, L. M., Knight, T. M., and Pullin, A. S. (2010). A systematic review of evidence for the added benefits to health of exposure to natural environments. *BMC Public Health* 10:456. doi: 10.1186/1471-2458-10-456

Calogiuri, G., and Chroni, S. (2014). The impact of the natural environment on the promotion of active living: an integrative systematic review. *BMC Public Health* 14:873. doi: 10.1186/1471-2458-14-873

Calogiuri, G., Litleskare, S., Fagerheim, K. A., Rydgren, T. L., Brambilla, E., and Thurston, M. (2018). Experiencing nature through immersive virtual environments: environmental perceptions, physical engagement, and affective responses during a simulated nature walk. *Front. Psychol.* 8:2321. doi: 10.3389/fpsyg.2017.02321

Calogiuri, G., Mikkila, S., and Weydahl, A. (2013). "Can promotion of outdoor activities impact people's vitamin d levels? in: *Proceedingsof the 2nd Electronic International Interdisciplinary Conference*, (Zilina).

Calogiuri, G., Nordtug, H., and Weydahl, A. (2015). The potential of using exercise in nature as an intervention to enhance exercise behavior: results from a pilot study. *Percept. Mot. Skills* 121, 350–370. doi: 10.2466/06.PMS.121c17x0

Chirico, A., and Gaggioli, A. (2019). When virtual feels real: comparing emotional responses and presence in virtual and natural environments. *Cyberpsychol. Behav. Soc. Netw.* 22, 220–226. doi: 10.1089/cyber.2018.0393

Chirico, A., Lucidi, F., De Laurentiis, M., Milanese, C., Napoli, A., and Giordano, A. (2016). Virtual reality in health system: beyond entertainment: a mini-review on the efficacy of VR during cancer treatment. *J. Cell Physiol.* 231, 275–287. doi: 10.1002/jcp.25117

Curtis, M. K., Dawson, K., Jackson, K., Litwin, L., Meusel, C., Dorneich, M. C., et al. (2015). "Mitigating visually induced motion sickness: a virtual hand-eye coordination task," in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, (Thousand Oaks, CA: Sage Publications), 1839–1843. doi: 10.1177/1541931215591397

Draper, M. H., Viirre, E. S., Furness, T. A., and Gawron, V. J. (2001). Effects of image scale and system time delay on simulator sickness within head-coupled virtual environments. *Hum. Factors* 43, 129–146. doi: 10.1518/001872001775992552

Duzmanska, N., Strojny, P., and Strojny, A. (2018). Can simulator sickness be avoided? A review on temporal aspects of simulator sickness. *Front. Psychol.* 9:2132. doi: 10.3389/fpsyg.2018.02132

Gavgani, A. M., Nesbitt, K. V., Blackmore, K. L., and Nalivaiko, E. (2017). Profiling subjective symptoms and autonomic changes associated with cybersickness. *Auton. Neurosci.* 203, 41–50. doi: 10.1016/j.autneu.2016.12.004

Godin, G., and Shephard, R. J. (1985). A simple method to assess exercise behavior in the community. *Can. J. Appl. Sport Sci.* 10, 141–146.

Hartig, T., Evans, G. W., Jamner, L. D., Davis, D. S., and Garling, T. (2003). Tracking restoration in natural and urban field settings. *J. Environ. Psychol.* 23, 109–123. doi: 10.1016/s0272-4944(02)00109-3

Hong, J. Y., Lam, B., Ong, Z. T., Ooi, K., Gan, W. S., Kang, J., et al. (2019). Quality assessment of acoustic environment reproduction methods for cinematic virtual reality in soundscape applications. *Build. Environ.* 149, 1–14. doi: 10.1016/j.buildenv.2018.12.004

Hromatka, B. S., Tung, J. Y., Kiefer, A. K., Do, C. B., Hinds, D. A., and Eriksson, N. (2015). Genetic variants associated with motion sickness point to roles for inner ear development, neurological processes and glucose homeostasis. *Hum Mol. Genet.* 24, 2700–2708. doi: 10.1093/hmg/ddv028

Hug, S., Hansmann, R., Monn, C., Krutli, P., and Seeland, K. (2008). Restorative effects of physical activity in forests and indoor settings. *Int. J. Fit.* 4, 25–37.

Kaplan, R. (1989). *The Experience of Nature: A Psychological Perspective*. Cambridge: Cambridge University Press.

Kaplan, S. (1995). The restorative benefits of nature - toward an integrative framework. *J. Environ. Psychol.* 15, 169–182. doi: 10.1016/0272-4944(95)90001-2

Kennedy, R. S., Drexler, J., and Kennedy, R. C. (2010). Research in visually induced motion sickness. *Appl. Ergon.* 41, 494–503. doi: 10.1016/j.apergo.2009.11.006

Kennedy, R. S., Lane, N. E., Berbaum, K. S., and Lilienthal, M. G. (1993). Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. *int. J. Aviat. Psychol.* 3, 203–220. doi: 10.1207/s15327108ijap0303_3

Keshavarz, B., Riecke, B. E., Hettinger, L. J., and Campos, J. L. (2015). Vection and visually induced motion sickness: how are they related? *Front. Psychol.* 6:472. doi: 10.3389/fpsyg.2015.00472

Lahart, I., Darcy, P., Gidlow, C., and Calogiuri, G. (2019). The effects of green exercise on physical and mental wellbeing: a systematic review. *Int. J. Environ. Res. Pub. Health* 16:E1352. doi: 10.3390/ijerph16081352

LaViola, J. J. Jr. (2000). A discussion of cybersickness in virtual environments. *ACM SIGCHI Bull* 32, 47–56. doi: 10.1145/333329.333344

Levi, D., and Kocher, S. (1999). Virtual nature: the future effects of information technology on our relationship to nature. *Environ. behav.* 31, 203–226. doi: 10.1177/00139169921972065

Ling, Y., Nefs, H. T., Morina, N., Heynderickx, I., and Brinkman, W. P. (2014). A meta-analysis on the relationship between self-reported presence and anxiety in virtual reality exposure therapy for anxiety disorders. *PLoS One* 9:e96144. doi: 10.1371/journal.pone.0096144

Liszio, S., and Masuch, M. (2018). "The relaxing effect of virtual nature: immersive technology provides relief in acute stress situations," in *Paper presented at the 23rd Annual CyberPsychology, CyberTherapy & Social Networking Conference*, Gatineau.

Lo, W. T., and So, R. H. Y. (2001). Cybersickness in the presence of scene rotational movements along different axes. *Appl. Ergon.* 32, 1–14. doi: 10.1016/S0003-6870(00)00059-4

Lox, C. L., Jackson, S., Tuholski, S. W., Wasley, D., and Treasure, D. C. (2000). Revisiting the measurement of exercise-induced feeling states: the physical activity affect scale (PAAS). *Meas. Phys. Educ. Exerc. Sci.* 4, 79–95.

Maffei, L., Masullo, M., Pascale, A., Ruggiero, G., and Romero, V. P. (2016). Immersive virtual reality in community planning: acoustic and visual congruence of simulated vs real world. *Sustain. Cities Soc.* 27, 338–345. doi: 10.1016/j.scs.2016.06.022

Mayer, F. S., Frantz, C. M., Bruehlman-Senecal, E., and Dolliver, K. (2009). Why is nature beneficial? The role of connectedness to nature. *Environ. Behav.* 41, 607–643. doi: 10.1177/0013916508319745

Merhi, O., Faugloire, E., Flanagan, M., and Stoffregen, T. A. (2007). Motion sickness, console video games, and head-mounted displays. *Hum. Fact.* 49, 920–934. doi: 10.1518/001872007X230262

Munafo, J., Diedrick, M., and Stoffregen, T. A. (2017). The virtual reality head-mounted display Oculus Rift induces motion sickness and is sexist in its effects. *Exp. Brain Res.* 235, 889–901. doi: 10.1007/s00221-016-4846-7

Nichols, S., Haldane, C., and Wilson, J. R. (2000). Measurement of presence and its consequences in virtual environments. *Int. J. Hum-Comput. Stud.* 52, 471–491. doi: 10.1006/ijhc.1999.0343

Plante, T. G., Aldridge, A., Su, D., Bogdan, R., Belo, M., and Kahn, K. (2003). Does virtual reality enhance the management of stress when paired with exercise? an exploratory study. *Int. J. Stress Manag.* 10:203. doi: 10.1037/1072-5245.10.3.203

Plante, T. G., Cage, G., Clements, S., and Stover, A. (2006). Psychological benefits of exercise paired with virtual reality: outdoor exercise energizes whereas indoor virtual exercise relaxes. *Int. J. Stress Manag.* 13, 108–117. doi: 10.1037/1072-5245.13.1.108

Reason, J. T., and Brand, J. J. (1975). *Motion Sickness*. Cambridge, MA: Academic Press.

Russell, J. A. (1980). A circumplex model of affect. *J. Personal. Soc. Psychol.* 39, 1161–1178. doi: 10.1037/h0077714

Schulz, K. F., Altman, D. G., Moher, D., and Consort Group. (2010). CONSORT 2010 statement: updated guidelines for reporting parallel group randomized trials. *Ann. Int. Med.* 152, 726–732. doi: 10.7326/0003-4819-152-11-201006010-00232

Sharples, S., Cobb, S., Moody, A., and Wilson, J. R. (2008). Virtual reality induced symptoms and effects (VRISE): comparison of head mounted display (HMD), desktop and projection display systems. *Displays* 29, 58–69. doi: 10.1016/j.displa.2007.09.005

Slater, M., Usoh, M., and Steed, A. (1995). *Taking Steps: The Influence of a Walking Technique on Presence in Virtual Reality*. New York, NY: ACM Transactions on Computer-Human Interaction, 201–219.

Smith, J. W. (2015). Immersive virtual environment technology to supplement environmental perception, preference and behavior research: a review with applications. *Int. J. Environ. Res. Pub. Health* 12, 11486–11505. doi: 10.3390/ijerph120911486

Steuer, J. (1992). Defining virtual reality - dimensions determining telepresence. *J. Commun.* 42, 73–93. doi: 10.1111/j.1460-2466.1992.tb00812.x

Triberti, S., Repetto, C., and Riva, G. (2014). Psychological factors influencing the effectiveness of virtual reality-based analgesia: a systematic review. *Cyberpsychol. Behav. Soc. Netw.* 17, 335–345. doi: 10.1089/cyber.2014.0054

Valtchanov, D., Barton, K. R., and Ellard, C. (2010). Restorative effects of virtual nature settings. *Cyberpsychol. Behav. Soc. Netw.* 13, 503–512. doi: 10.1089/cyber.2009.0308

Victor, A., Elsasser, A., Hommel, G., and Blettner, M. (2010). Judging a plethora of p-values: how to contend with the problem of multiple testing–part 10 of a series on evaluation of scientific publications. *Dtsch. Arztebl. Int.* 107, 50–56. doi: 10.3238/arztebl.2010.0050

Weech, S., Kenny, S., and Barnett-Cowan, M. (2019). Presence and cybersickness in virtual reality are negatively related: a review. *Front. Psychol.* 10:158. doi: 10.3389/fpsyg.2019.00158

White, M. P., Yeo, N. L., Vassiljev, P., Lundstedt, R., Wallergard, M., Albin, M., et al. (2018). A prescription for "nature" - the potential of using virtual nature in therapeutics. *Neuropsychiatr. Dis. Treat.* 14, 3001–3013. doi: 10.2147/Ndt.S179038

Yu, C. P., Lee, H. Y., and Luo, X. Y. (2018). The effect of virtual reality forest and urban environments on physiological and psychological responses. *Urban For. Urban Green.* 35, 106–114. doi: 10.1016/j.ufug.2018.08.013

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix: Paper III

Litleskare, S. (2021). The relationship between postural stability and cybersickness: It’s complicated – An experimental trial assessing practical implications of cybersickness etiology. *Physiology & Behavior*, *236*, 113422. https://doi.org/10.1016/j.physbeh.2021.113422

Physiology & Behavior 236 (2021) 113422

Contents lists available at ScienceDirect

Physiology & Behavior

journal homepage: www.elsevier.com/locate/physbeh

The relationship between postural stability and cybersickness: It's complicated – An experimental trial assessing practical implications of cybersickness etiology

Sigbjørn Litleskare

Department of Public Health and Sport Sciences, Inland Norway University of Applied Sciences, Terningen Arena, Hamarveien 112, 2406 Elverum, Norway

ARTICLE INFO

Keywords:
Virtual reality
Immersive virtual environments
Motion sickness
Visually induced motion sickness
Postural instability
Sensory conflict

ABSTRACT

Virtual reality (VR) is known to cause cybersickness, and studies report that deteriorations of postural stability coincides with the onset cybersickness. It is unclear whether these deteriorations are the cause or a consequence of cybersickness. Thus, it is also unclear whether measures of postural stability may either predict susceptibility (cause) or objectively measure (consequence) the malaise. To examine whether deteriorations of postural stability can either predict or objectively measure cybersickness, healthy active adults ($n = 50$) were exposed to one of two different 10 min 360° VR videos. Postural stability was assessed, using a force platform, before exposure with eyes open (baseline) and eyes closed, during the first and last minute of exposure, and approximately 10 min after exposure. The deterioration of postural stability from baseline to the first minute of exposure was larger in participants who reported cybersickness, compared to those who did not, for both total trace length ($p = 0.017$) and standard deviation velocity ($p = 0.008$). However, there was substantial individual variation and overlap between sick and well participants. Deteriorations of postural stability from baseline to the eyes closed condition did not differ between sick and well participants (trace length, $p = 0.270$; standard deviation velocity, $p = 0.112$). There was a significant correlation between the severity of cybersickness and the change of postural stability from the first to the last minute of VR exposure for trace length (r_s=0.32, $p = 0.027$), but not standard deviation velocity (r_s=0.20, $p = 0.187$). The deteriorations had returned to baseline levels 10 min after exposure. These findings suggest that deteriorations of postural stability was both a predictor and objective measure at a group level. However, the large individual variation, substantial overlap between sick and well participants, and the limited strength of correlations suggest that deterioration of postural stability has limited practical value as both a predictor and objective measure. These findings emphasize the complicated nature of the relationship between cybersickness and postural stability.

1. Introduction

The introduction of affordable head mounted displays (HMD's) has received a lot of attention and introduced the concept of virtual reality (VR) to the public [[5], [11]]. This technology has seen widespread use within several research areas as well [[6], [7], [17], [29]]. However, this technology is known to cause some discomfort, i.e. cybersickness. Cybersickness is a major issue in regards to the commercialization of modern VR technology and many considers cybersickness as the biggest threat to the success of VR. This malaise also influence and distort research findings in studies that aim to use VR as a research tool [[8], [16]]. Cybersickness is considered a type of visually induced motion sickness [23], which causes a wide array of symptoms, including nausea, dizziness, sweating and general discomfort. These symptoms are commonly evaluated by subjective means to quantify the severity of cybersickness [[24], [25]]. Unpleasant levels of cybersickness is a common finding in the literature and are reported to occur in as much as 100% of participants depending on the contents of the virtual environment and the circumstances of exposure [[30], [32], [33]]. Due to the impact of cybersickness on experiences in VR, studies have attempted to both explain the phenomenon and to find practical strategies to reduce its impact. Although some have successfully identified strategies to reduce the symptoms of the malaise [[16], [18], [28], [30]], the elusive origin of cybersickness is still unclear and a final solution does not seem imminent, and researchers are still looking to expand our understanding of the issue [[12], [18], [21], [31], [46]]. One way in which researchers

---

E-mail address: sigbjorn.litleskare@inn.no.

https://doi.org/10.1016/j.physbeh.2021.113422
Received 20 May 2020; Received in revised form 1 March 2021; Accepted 4 March 2021

have attempted to increase our understanding of cybersickness is by investigating the proposed relationship between postural stability (i.e. the ability to maintain an upright position) and cybersickness, as studies have demonstrated that the onset of cybersickness coincides with perturbations in postural stability [[4], [34], [51]]. This research is intriguing, as it may offer both insight in regards to cybersickness etiology and uncover practical solutions to either predict or objectively measure cybersickness.

1.1. Theories of cybersickness etiology

The etiology of cybersickness, and motion sickness in general, is unclear, but several theories has been proposed [28]. The two theories that has gained the most traction are the sensory conflict theory and the postural instability theory. The sensory conflict theory postulates that cybersickness is caused by a conflict between different sensory systems, and between experienced and expected stimuli based on past experiences [[37], [41], [42]]. During immersion in VR there is a conflict between visual, and vestibular and proprioceptive inputs. According to the sensory conflict theory, this sensory mismatch leads to an increase in symptoms of cybersickness. This theory is supported by the fact that patients with a dysfunctional vestibular system are particularly susceptible, while patients with a complete loss of vestibular functioning experience less cybersickness compared to healthy individuals [38]. Experimental research using VR systems also report that navigation modes and animations that may increase sensory conflict also increase symptoms of cybersickness [49]. The original formulation of this theory does not directly predict an association between cybersickness and postural stability. However, since perturbations of postural stability coincides with the onset of cybersickness [[4], [34], [51]], these perturbations may arise as a consequence of cybersickness and thereby sensory conflict. Thus, if deteriorations of postural stability follows the same trajectory as function of time during VR exposure as known cybersickness symptoms, it would suggest that the deterioration of postural stability is another symptom of cybersickness [[34], [36]]. This assumption has some intriguing practical applications, as deteriorations in postural stability could be used as an objective measure of cybersickness. The postural instability theory, on the other hand, postulates that situations associated with motion sickness are characterized by a period where patterns of movement control are reorganized to adapt to an unfamiliar stimulus. During this period, it is suggested that movement control is less efficient, which in turn leads to postural instability. The theory further postulates that this instability is a prerequisite for the development of cybersickness and that cybersickness will only occur in people who experience postural instability [[43], [48]]. In support of this theory, studies such as Villard et al. [50] have shown that deteriorations of postural stability precedes the onset of motion sickness when exposed to an oscillating virtual room in a projection-based system. Studies also report that individuals that exhibit low levels postural stability are more prone to motion sickness and that manipulation of stance width reduce both postural instability and motion sickness [[47], [48]]. If the postural instability theory is correct, measures of postural stability before the onset of cybersickness could predict the onset this malaise [43]. An accurate predictor of cybersickness onset would have useful practical applications, such as identifying susceptible people for exclusion or inclusion in studies of cybersickness and identify suitable VR-content for the individual user. Another interesting aspect related to the association between postural stability and cybersickness is the potential impact of individual differences in dependency of visual input to maintain postural stability . The results in some studies suggest that people that are more dependent on visual input to maintain postural stability are more likely to experience cybersickness [[27], [45]]. In accordance with these findings, the change in postural stability from an eyes open condition to an eyes closed condition could be used as a predictor of cybersickness.

1.2. Postural stability and cybersickness

Research that have examined the relationship between postural stability and cybersickness report limited or inconclusive findings. Unfortunately, few studies have employed an experimental set-up that allow evaluation of deteriorations of postural stability as a symptom of cybersickness. However, Murata [34] support the notion, while the results in other studies can be interpreted as evidence for postural stability as both a symptom and a predictor [[10], [32], [35]]. Several studies support the idea that perturbations in postural stability is a predictor of cybersickness, either by demonstrating that perturbations in postural stability precede the onset of cybersickness or by demonstrating that naturally unstable individuals are more susceptible to sickness [[4], [33], [40], [44]]. In contrast, the results in other studies indicate that postural stability is not a predictor of cybersickness [[2], [13], [14]], and some even indicate an inverse relationship and suggest that less stable individuals are less likely to experience sickness [[1], [15], [51]]. Similarly, studies that have included measures related to the participants' dependency on visual input to maintain postural stability report conflicting results as well [[27], [45], [47]]. In summary, the exact nature of the relationship is yet to be determined, and it is still unclear whether postural instability is the cause, a symptom or just an unrelated factor that happens to increase, or even decrease, when people are exposed to VR. Thus, it is also unclear whether measures of postural stability can be used as either a predictor or an objective measure of cybersickness.

1.3. Methodological considerations

In regards to methodological considerations, studies that report a significant relationship between postural stability and cybersickness have included several measures of postural stability, which inflates the probability of type I error, and measures that display significant associations in one study or condition fail to reach significance in other studies or conditions [[4], [33]]. In other words, the current research evidence demonstrate a lack of measures and/or methodology that consistently detects the proposed relationships between cybersickness and postural stability across studies and conditions, which suggests that studies of the relationship between postural stability and cybersickness should include more than one type of VR exposure to identify consistent measures. Furthermore, most studies that have examined the extent to which perturbations in postural stability can predict cybersickness have measured postural stability before exposure to VR [[4], [10], [12–14], [33], [35], [40], [44], [51]]. This approach has some advantages, but in line with the recommendations of Clifton and Palmisano [12] and Cobb [13], it may be required to measure postural stability during exposure to VR. This allows evaluation of the impact that VR exposure has on postural stability and its potential as a predictor of cybersickness. This approach has some additional advantages in relation to the sensory conflict theory, as it allows examination of correlations between cybersickness and decrements in postural stability as a function of exposure duration. Unfortunately, only a limited number of studies have measured postural stability during exposure to VR and evaluated the relation to cybersickness, and the results are inconclusive [[1], [15], [32]]. One commonality between these studies is a lack of comparison to a baseline measurement of postural stability [[1], [15], [32]]. According to the postural instability theory, it is required to measure the impact of VR on postural control, as the theory postulates that instability occurs as a result of exposure to a sickness inducing stimuli. Thus, measurements during VR exposure should be compared to a baseline measurement in order to evaluate whether postural instability has occurred as a result of VR exposure.

1.4. Purpose of the study

The purpose of the present study was to examine whether measures of postural stability is either a predictor or an objective measure of cybersickness across two different VR conditions. In line with the methodological considerations and the theoretical framework outlined above, there were formulated two hypotheses to evaluate whether perturbations of postural stability could predict cybersickness (H1 and H2), and one to evaluate whether perturbations of postural stability may be regarded as an objective measure of cybersickness (H3):

> H1. Participants that experience cybersickness will experience a significantly larger deterioration of postural stability immediately when exposed to VR than participants that do not experience cybersickness.
> H2. Participants that experience cybersickness are more dependent on visual input to maintain postural stability compared to participants that do not experience cybersickness.
> H3. Deterioration of postural stability during VR exposure will increase as a function of time and this increase will be correlated with the severity of cybersickness.

2. Materials and methods

2.1. Participants

The data for this study were collected in relation to a larger study investigating the impact of scene oscillations when viewing dynamic 360° videos [30]. The participants in this study were mainly recruited among students and non-scientific employees at the Inland Norway University of Applied Sciences (Elverum), but did also include a few participants outside the University. To be eligible for participation, the volunteers were required to meet the following criteria: ≥18 years old, normal or corrected to normal vision, limited experience with VR (less than monthly use) and not having a previous diagnosis of balance impairments [38]. The final sample comprised 50 participants (22 males and 28 females). All participants signed a written informed consent prior to the experiment. The study was approved by the Norwegian centre for research data (reference number: 60,451) and conducted according to the declaration of Helsinki

2.2. Design and procedures

The experimental procedures were designed as a pretest-posttest experimental trial with two parallel groups. The introduction section outlines the importance of including two different VR conditions although the data were to be analyzed collectively for both groups. The two experimental conditions consisted of two 360° videos of a nature walk with different levels of scene oscillations. These two videos have previously been shown to produce different levels of cybersickness, which signifies that the two videos represent two distinct VR experiences (total simulator sickness score of 33.7 vs 18.7; [30]). Both 360° videos were presented to participants using a HMD. The participants were allocated to one of the two experimental conditions, stratified by sex [[26], [33]], with a 1:1 allocation ratio based on a pre-determined sequence, and where not exposed to or informed of the video used in the other experimental condition. The experiment was performed in controlled laboratory conditions, and no changes to methods were made after trial commencement.

The participants met at the laboratory separately and were carefully explained the experimental procedures (Fig. 1). Firstly, participants' height, weight and physical activity levels were assessed, to be used as background information, before stepping onto the force platform (FP4, Hur labs Oy, Tampere, Finland). Postural stability was measured with eyes open (EO1), with eyes closed (EC) and during the first minute of VR exposure (VR1) in a standing position, with 60 s of rest between these three trials. The break between EC and VR1 was used to don the HMD. The participants were then seated, without removing the HMD, for eight more minutes of VR exposure. The opposite procedure was performed after the eighth minutes of VR exposure, as participants moved from a sitting to a standing posture without removing the HMD, before commencing a fourth measurement of postural stability (VR2). After VR2, all participants removed the HMD and completed the simulator sickness questionnaire (SSQ). The participants also completed additional questionnaires at baseline and after VR exposure which has been reported in a separate paper [30]. Lastly, a fifth measurement of postural stability, with eyes open, was performed before leaving the laboratory (EO2). The duration between VR2 and EO2 was not standardized, but the mean (± standard deviation; SD) duration is presented in the results section. The participant and the examiner where the only two people present in the laboratory.

2.3. VR-technology and experimental conditions

The two videos used for this study was recorded using the same 360° video camera (Samsung gear 360 smc200, 3840 × 1920 resolution and a refresh rate of 30 Hz) and showed a 10-minutes first-person walk along a path in a natural environment (Fig. 2). The two videos showed the same nature walk, but differed in both frequency and magnitude of oscillations; a low stability video and a high stability video. The low stability video was recorded with the camera mounted on a modified Yelangu s60t mechanical handheld stabilizer, while the high stability video was created by using an electronic gimbal handheld stabilizer (Feiyu Tech G360). The mechanical nature of the Yelangu s60t makes it less stable compared to the electronic stabilizer, and is particularly prone to oscillations caused by operator locomotion. The Samsung S7, with Android 7.0, mounted on a Samsung Gear HMD (Samsung Gear VR SM-R323) was used to present the videos to the participants.

2.4. Instruments and measurements

Postural stability – The participants' ability to maintain postural stability was assessed using a force platform (FP 4, Hur labs Oy, Tampere, Finland) and the associated software (HUR Labs Force Platform Software Suite). The platform was placed three meters in front of a blank wall, with a black circle placed at eye level (Fig. 2). EO1 (please refer Design and procedure) was used as a baseline measurement, which all consecutive measures were to be compared to in order to assess a potential impairment of postural stability. To address H1 we assessed the change of postural stability between EO1 and VR1, as a measure of the immediate impact of VR on postural stability. The difference between EO1 and EC was used as an indicator of the level of visual dependency on postural stability to address H2, and the change in postural stability between VR1 and VR2 was used to evaluate the change in postural stability as a result of continuous VR exposure to address H3. Lastly, the difference between EO1 and EO2 was partly used as an indicator of the after-effects of VR exposure, but more importantly as a safety measure to

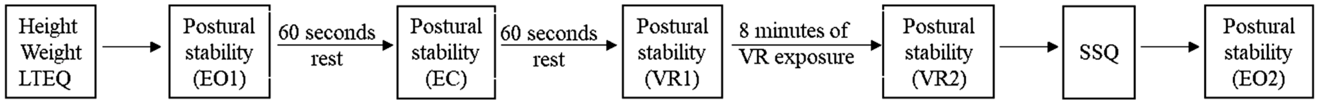


Fig. 1. Overview of experimental procedures. LTEQ = Leisure time exercise questionnaire. EO1 = baseline measurement of postural stability with eyes open. EC = measurement of postural stability with eyes closed. VR1 = measurement of postural stability during the first minute of VR exposure. VR2 = measurement of postural stability during the last (ninth) minute of VR exposure. EO2 = measurement of postural stability with eyes open after completing the post exposure questionnaire.

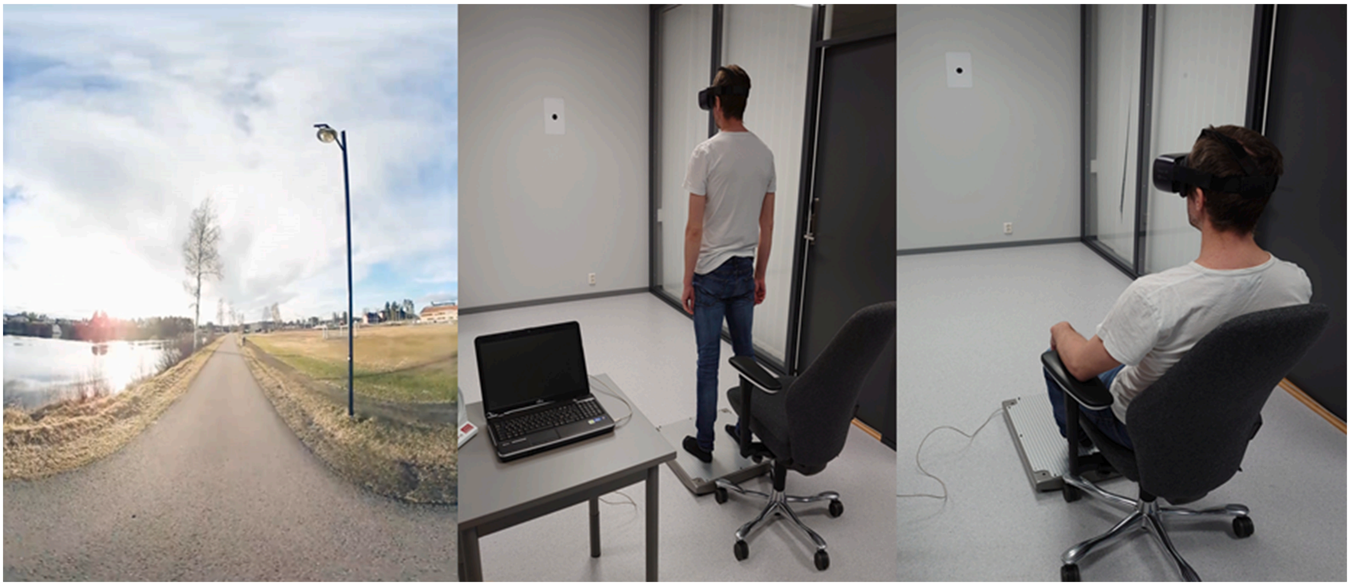


Fig. 2. Snapshot of the environment used in both VR conditions (left), and an overview of the laboratory environment and experimental setup while performing a measurement of postural stability (middle) and seated exposure to the VR environments (right).

ensure that participants did not leave the laboratory while experiencing severe levels of postural instability. During all conditions, participants were asked to remove their shoes and step onto the platform, placing the feet about a shoulder width apart and to look straight ahead. Postural stability was then assessed over a 60 s period and participants were asked to stand still with hands hanging effortlessly at their side during the full 60 s [22]. All trials were supervised to ensure that no unnecessary movements other than those required to maintain balance occurred. Total trace length (TL; mm) and standard deviation velocity (STDV; mm/s) of the center of pressure during the 60 s measuring periods were used for further analysis, as research suggests that these measures are reliable measures of postural stability [39]. TL represents the total distance traveled by the center of gravity, while STDV represents the velocity of corrective postural actions.

Cybersickness – Participants were categorized as either “sick” or “well” based on their response to the question “are you cybersick?” [[32], [33]]. The Simulator sickness questionnaire (SSQ) was used to measure the severity of cybersickness symptoms [24]. The SSQ consist of a checklist of 16 different symptoms (e.g. “Headache” and “Increased salivation”), and participants were asked to rank the severity of these symptoms on a 4-point Likert scale (0 = none, 1 = slight, 2 = moderate, 3 = severe). Scoring of the SSQ data were performed according to the recommendations of Kennedy et al., [24]. The scale showed adequate internal consistency for post exposure values for the total SSQ score (Chronbach’s $\alpha = 0.94$).

Demographics and background information – The participants’ height, weight, age, gender and physical activity levels were assessed and used to describe the study sample. The participants’ level of physical activity was assessed using a modified version of the leisure time exercise questionnaire [20] that includes active transportation (e.g. walking or biking as a mode of transportation). The adjusted version of LTEQ has been found to correlate with objective assessments of physical activity by accelerometer [9].

2.5. Analyses

The data were preliminary explored to examine frequency distributions and to identify potential missing values and outliers. Two outliers were identified for both TL and STDV at both VR1 and VR2, and a Shapiro-Wilk test [19] revealed that postural stability at two out of five time points (VR1 and VR2) and the SSQ data were not normally distributed. Thus, a Mann-Whitney U test was used to determine whether participants categorized as sick experienced lager deteriorations of TL and STDV at VR1 and with eyes closed, to address H1 and H2 respectively. To address H3, a Spearman’s rank correlation coefficient (ρ) was used to determine a potential association between the total SSQ score and the change of TL and STDV from VR1 to VR2. All measurements were performed according to standard procedures for each instrument and the statistical approach was not modified after commencement of the experimental procedures. The statistical analysis was performed in IBM SPSS statistics 25 (IBM., New york) and the level of significance was set at $p < 0.05$. Three participants did not complete the full 10 min of VR exposure due to high levels of cybersickness, and thus the values for VR2 are missing for these individuals. However, they completed the post exposure questionnaire immediately after termination of VR exposure, and they were included in all analyses not including measures at VR2.

3. Results

3.1. Sample characteristics

The mean (± SD) age, height, weight, BMI and modified LTEQ score of females were 29.5 (± 12.1) years, 166.5 (± 5.7) cm, 66.1 (± 9.8) kg, 23.9 (± 3.5) kg/m^2 and 55.8 (± 25.1) units, and in males 30.2 (± 9.2) years, 181.9 (± 6.7) cm, 88.8 (± 9.8) kg, 26.8 (± 2.1) kg/m^2 and 59.0 (± 23.7) units. Sixteen participants were categorized as “sick” and 34 as “well” based on their response to the dichotomous question regarding cybersickness. Twelve of the sick participants had seen the video with high levels of scene oscillations and four the video with low levels of scene oscillations.

3.2. Immediate impact of vr exposure on postural stability

The median (interquartile range; IQR) increase of TL from EO1 to VR1 was 405.0 (230.4–636.3) mm in well participants and 844.7 (451.6–1312.7) mm in sick participants (Fig. 3). The Mann-Whitney U test revealed that there was a significant difference between sick and well participants ($U = 157, p = 0.017$), showing that the sick group had a relatively larger impairment of TL after immediate VR exposure. A similar pattern emerged with STDV, as the median (IQR) increase in STDV from EO1 to VR1 was 3.2 (2.1–6.3) mm/s in well participants and

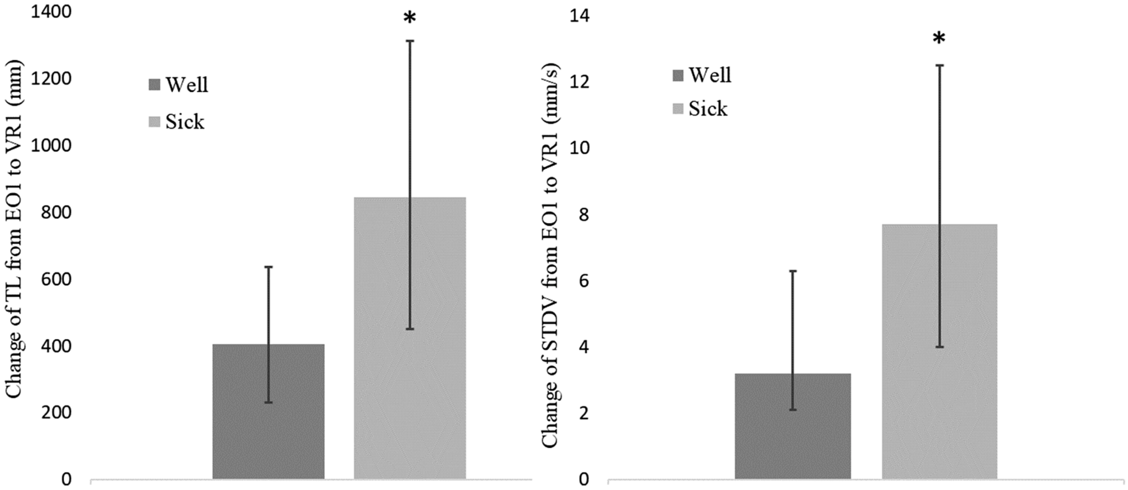


Fig. 3. The median (IQR) change in measures of postural stability from the baseline eyes open condition (EO1) to immediate exposure to VR (VR1) in both sick (n = 16) and well (n = 34) participants. TL = total trace length of center of pressure. STDV = standard deviation velocity of center of pressure. * = significant difference compared to well participants at the $p < 0.05$ level.

7.7 (4.0–12.5) mm/s in sick participants (Fig. 3). Again, a Mann-Whitney U test revealed that there was a significant difference between sick and well participants ($U = 145, p = 0.008$), showing that the sick group had a relatively larger impairment of STDV after immediate VR exposure. There was a large dispersion in both groups for both measures with individual values ranging from −101.2 to 7148.5 mm for TL in well participants and from −3.0 to 2104.3 mm in sick participants, and values ranging from −1.4 to 80.8 mm/s for STDV in well participants and from 0.2 to 18.8 mm/s in sick participants.

3.3. Dependency on visual input to maintain postural stability

The median (IQR) increase in TL from EO1 to EC was 340.3 (206.8–466.4) mm in well participants and 435.6 (257.0–816.1) mm in sick participants (Fig. 4). The observed difference between sick and well was not statistically significant ($U = 219, p = 0.270$). In regards to STDV, the median (IQR) increase in from EO1 to EC was 2.7 (1.5–4.1) mm/s in well participants and 3.6 (2.5–6.3) mm/s in sick participants (Fig. 4), with no significant difference between groups ($U = 196, p = 0.112$). The individual values for TL ranged from 95.4 to 985.2 mm in well participants and from −12.5 to 1866.2 mm in sick participants, and values ranging from 0.1 to 19.0 mm/s for STDV in well participants and from 0.5 to 6.4 mm/s in sick participants.

3.4. Association between postural stability during VR exposure and the severity of cybersickness

The Spearman rank correlation revealed a significant positive association between the total SSQ score and the change in TL from VR1 to VR2 for all participants combined ($r_s = 0.32$, $p = 0.027$, $n = 47$), showing that an increase in the severity of cybersickness symptoms was associated with an increase in the total distance traveled by the center of pressure. The correlation between total SSQ score and the change in STDV did not reach statistical significance ($r_s = 0.20, p = 0.187, n = 47$), showing that the severity of cybersickness was unrelated to the velocity of corrective postural actions.

3.5. After effects of VR exposure

Before performing the measurement of postural stability at EO2, participants spent an average (± SD) time of 9.9 (± 3.2) minutes completing the post exposure questionnaire. The median (IQR) change of TL from EO1 to EO2 was −393.9 (−603.4 to −263.1) mm in well participants and −387.6 (−547.9 to −118.0) mm in sick participants.

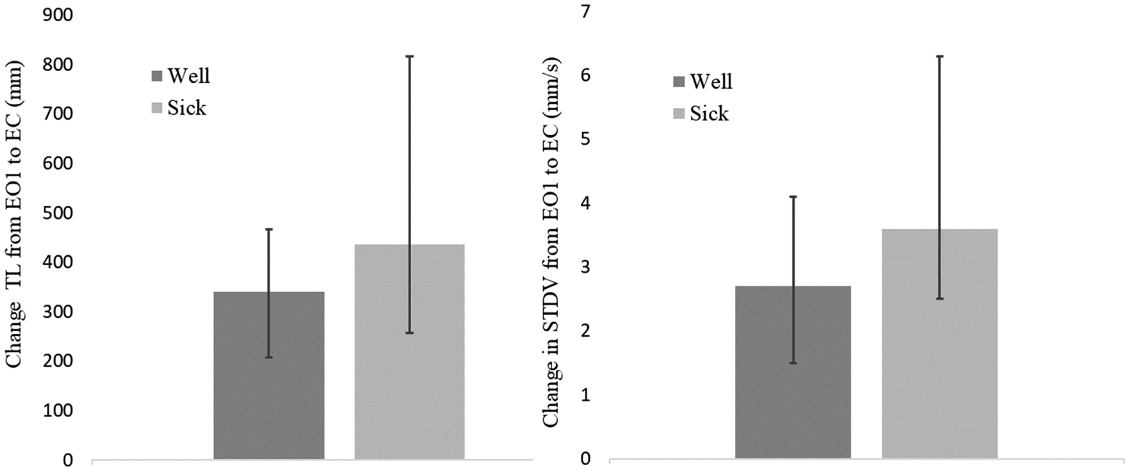


Fig. 4. The median (IQR) change in measures of postural stability from the baseline eyes open condition (EO1) to the eyes closed condition (EC) in both sick ($n = 16$) and well (n = 34) participants. TL = total trace length of center of pressure. STDV = standard deviation velocity of center of pressure. No significant difference between sick and well participants at the $p < 0.05$ level.

The Mann-Whitney U test revealed that there was not a significant difference between sick and well participants ($U = 210$, $p = 0.329$). Similarly, the median (IQR) change in STDV from EO1 to EO2 was 0.2 (−1.3 to 0.6) mm/s in well participants and −0.3 (−1.5 to 1.2) mm/s in sick participants, with no a significant difference between sick and well participants ($U = 244$, $p = 0.811$). The individual values ranged from −1055.9 to 7.2 mm for TL in well participants and from −973.6 to 154.0 mm in sick participants, and values ranging from −3.5 to 2.5 mm/s for STDV in well participants and from −3.1 to 4.2 mm/s in sick participants.

4. Discussion

The results demonstrated that participants who reported cybersickness experienced a larger deterioration of postural stability as a result of immediate exposure to VR compared to well participants, across two different VR conditions, but also showed that some participants experienced cybersickness without this deterioration. These results support our first hypothesis (H1). Furthermore, the results showed that participants reporting cybersickness were not more dependent on visual input to maintain postural stability, which contradicts our second hypothesis (H2). Our third hypothesis (H3) is supported by the fact that there was a significant correlation between the deterioration of TL as a function of time during VR exposure and the severity of cybersickness symptoms. Lastly, the deterioration of postural stability that some participants experienced during the experiment had returned to normal levels approximately 10 min after the VR exposure had ended.

4.1. Immediate impact of VR exposure on postural stability

Participants who experienced cybersickness exhibited a larger deterioration of postural stability at VR1 compared to well participants. Importantly, this finding was observed across two different VR conditions and across both of the measures of postural stability included in this study. Some deterioration was expected in both sick and well participants since the HMD effectively eliminates the vision of the external surroundings. The larger deterioration in sick participants can be explained by the postural instability theory [43]. According to this theory, the unfamiliar VR stimulus may have caused a reorganization of patterns of movement control in participants who experienced cybersickness. During this period of reorganization, the theory postulates that movement control is less efficient, leading to the observed perturbations of postural stability in the present study, which in turn caused the cybersickness in sick participants [[43], [48]]. Furthermore, it is reasonable to assume that the perturbations of postural stability occurred before the onset of cybersickness, as they were measured at during the first minute of VR exposure. Gavgani et al. (2018) have evidently shown that the onset of cybersickness can occur before the one minute mark in some participants during exposure to a severely provocative VR condition, but others have shown that the onset of cybersickness occurs after the one minute mark in less provocative conditions [1]. Assuming that the perturbations of postural stability in the present study occurred before the onset of cybersickness, argues in favor of the postural instability theory and against the hypothesis that perturbations may arise as a result of cybersickness. However, there was a large overlap in the size of the deterioration of postural stability at VR1 between sick and well participants, as indicated by the values for both IQR and range in both groups. This substantial overlap limits the usefulness of postural instability as a predictor of cybersickness, as individuals cannot be categorized as either susceptible or not susceptible to cybersickness based on the postural stability data, as previously suggested by other studies [[2], [13–15]]. The heterogeneity in our findings does not necessarily disprove the postural instability theory. It may be a case of each individual having their own threshold for how much postural deterioration they tolerate before developing cybersickness.

4.2. Dependency on visual input to maintain postural stability

There was no difference between sick and well participants in their dependency on visual input to maintain postural control, as indicated by a similar deterioration of postural stability with eyes closed in both sick and well participants. The idea that dependency of visual input would increase susceptibility to cybersickness is logically appealing, since the only sensory system involved in postural stability that is directly affected by the HMD is the visual component. This assumption is also supported by findings in previous research on visually induced motion sickness [[27], [45]]. However, the findings in previous research are equivocal, as others have rejected the notion by showing that there was not any difference in visual dependency between participants that did or did not experience sickness [47]. The present study adds to these conflicting reports and suggests that visual dependency, when measured as the change in postural sway from an eyes open condition to an eyes closed condition, cannot be used as a predictor of cybersickness. These results further suggest that the dependency of visual input to maintain postural stability is not related to the cause of cybersickness, whether it be postural instability or sensory conflict. However, it does not dismiss the possibility that visual acuity to certain elements during VR exposure is a predictor of susceptibility to cybersickness, as suggested by Allen et al. [3].

4.3. Association between postural stability during VR exposure and the severity of cybersickness

TL increased as a function of time from VR1 to VR2. Importantly, this increase was significantly and positively correlated with the total SSQ score, which show that the increase in the severity of known symptoms were associated with the increase in the total distance traveled by the center of pressure. In contrast to TL, the correlation between total SSQ score and the change in STDV did not reach statistical significance, showing that the severity of cybersickness was unrelated to the velocity of corrective postural actions. These results suggest that TL is a more sensitive indicator than STDV of the association between perturbations of postural stability and severity of cybersickness. It is well known that cybersickness symptoms increase as a function of exposure duration [[16], [34], [44]], and some have demonstrated that this is also true for perturbations of postural stability [[1], [32], [34]]. However, none of these studies have correlated the two variables to examine whether deteriorations of postural stability behaves similarly to known symptoms of cybersickness, which would indicate that postural stability is another symptom. The significant correlation between TL and total SSQ score in the present study show that the two variables are associated, but the limited strength of the association suggests that they do not behave similarly. This does not exclude the possibility that increased TL is a symptom of cybersickness, but it complicates a clear interpretation. This limitation may be explained by the fact that cybersickness severity is shown to develop linearly as a function of time [44], while limited evidence suggests that the total distance travelled by the center of pressure follows a slightly curve-linear trajectory [34]. The potential differences in the trajectory of these two variables would limit the strength of the association when assessed via correlation, which also limits the usefulness of TL as an objective measure of cybersickness symptoms. Furthermore, the lack of a precise measurement of the exact onset-time of cybersickness in the present study complicates a clear interpretation in favor of either the sensory conflict theory or the postural instability theory.

4.4. After effects of VR exposure

The measurement of postural stability at EO2 was performed, on average, approximately ten minutes after VR exposure. The results demonstrated that postural stability had returned to baseline values, at a group level, and that there was no difference between sick and well participants. None of the participants were considered at increased risk of injury or accidents at EO2. These findings support previous research, which have shown that postural stability returns to pre exposure values within 10 min after exit from VR [[13], [14]]. This shows that the level of postural perturbations observed in the present study quickly subsides to baseline values after the exposure, even in participants that experience cybersickness.

4.5. Strengths and limitations

The strengths of this study include the use of two different VR conditions to potentially identify a universal and consistent measure of the relationship between postural stability and cybersickness that can be used across different VR conditions. Additionally, measurements of postural stability were conducted during VR exposure and compared to baseline values to evaluate the impact of VR on postural stability. Unfortunately, the lack of a precise measurement of the exact onset-time of cybersickness and the lack of a continuous measurement of postural stability during VR exposure limits an evaluation of the temporal aspects of both cybersickness and postural stability, which complicates interpretations of our results to support either the sensory conflict theory or the postural instability theory.

5. Conclusion

The findings in the present study emphasize the complicated nature of the relationship between cybersickness and postural stability. On one hand, the study support the notion that deteriorations of postural stability can be regraded as both a predictor *and* an objective measure of cybersickness at a group level. On the other hand, the variability in the individual responses to VR exposure and the limited strength of the association between postural stability and cybersickness suggest that deterioration of postural stability has limited practical value as both a predictor and objective measure of cybersickness. These findings limits practical application of measurements of postural stability, and complicates interpretation of the findings as support for either the sensory conflict theory or the postural instability theory, as the findings argues both for and against both theories. These conclusions are not untimely in relation to previous research, but rather adds to the conflicting conclusions in different studies (e.g. [[4], [34], [51]]). In other words, *it's complicated*. However, the findings clearly demonstrated that individual differences in dependency on visual input to maintain postural stability did not predict the occurrence of cybersickness, and that perturbations of postural stability quickly returned to baseline levels after terminating VR exposure.

Funding

This research did not receive any specific grant funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

None.

Acknowledgments

The author thank Dr. Giovanna Calogiuri for her insights in the writing process.

References

[1] H. Akiduki, S. Nishiike, H. Watanabe, K. Matsuoka, T. Kubo, N. Takeda, Visual-vestibular conflict induced by virtual reality in humans, Neurosci. Lett. 340 (3) (2003) 197–200. Retrieved from, https://www.ncbi.nlm.nih.gov/pubmed/12672540.

[2] . . . H. Akizuki, A. Uno, K. Arai, S. Morioka, S. Ohyama, S. Nishiike, N. Takeda, Effects of immersion in virtual reality on postural control Neurosci. Lett. 379 (1) (2005) 23–26, https://doi.org/10.1016/j.neulet.2004.12.041.

[3] B. Allen, T. Hanley, B. Rokers, C.S. Green, Visual 3D motion acuity predicts discomfort in 3D stereoscopic environments, Entertain. Comput. 13 (2016) 1–9, https://doi.org/10.1016/j.entcom.2016.01.001.

[4] B. Arcioni, S. Palmisano, D. Apthorp, J. Kim, Postural stability predicts the likelihood of cybersickness in active HMD-based virtual reality, Displays 58 (2019) 3–11, https://doi.org/10.1016/j.displa.2018.07.001.

[5] Bajarin, T. (2019). The real significance Of AR, VR and mixed Reality. Retrieved from https://www.forbes.com/sites/timbajarin/2019/09/23/the-real-significance-of-ar-vr-and-mixed-reality/#709f05cc6d80.

[6] J.A. Bennett, C.P. Saunders, A virtual tour of the cell: impact of virtual reality on student learning and engagement in the STEM classroom, J. Microbiol. Biol. Educ. 20 (2) (2019), https://doi.org/10.1128/jmbe.v20i2.1658.

[7] C. Botella, J. Fernandez-Alvarez, V. Guillen, A. Garcia-Palacios, R. Banos, Recent progress in virtual reality exposure therapy for phobias: a systematic review, Curr. Psychiatry Rep. 19 (7) (2017) 42, https://doi.org/10.1007/s11920-017-0788-4.

[8] G. Calogiuri, S. Litleskare, K.A. Fagerheim, T.L. Rydgren, E. Brambilla, M. Thurston, Experiencing nature through immersive virtual environments: environmental perceptions, physical engagement, and affective responses during a simulated nature walk, Front. Psychol. 8 (2018), https://doi.org/10.3389/Fpsyg.2017.02321. Artn2321.

[9] G. Calogiuri, S. Mikkila, A. Weydahl, Can Promotion of outdoor activities impact people's vitamin D levels? Promising findings from a pilot study, in: Proceedings of the EIIC - The 2nd Electronic International Interdisciplinary Conference, 2013.

[10] J.R. Chardonnet, M.A. Mirzaei, F. Merienne, Features of the postural sway signal as indicators to estimate and predict visually induced motion sickness in virtual reality, Int. J. Hum. Comput. Interact. 33 (10) (2017) 771–785, https://doi.org/10.1080/10447318.2017.1286767.

[11] P. Cipresso, I.A.C. Giglioli, M.A. Raya, G Riva, The past, present, and future of virtual and augmented reality research: a network and cluster analysis of the literature, Front. Psychol. 9 (2018), https://doi.org/10.3389/fpsyg.2018.02086. ARTN2086.

[12] Clifton, J., & Palmisano, S. (2019). Effects of steering locomotion and teleporting on cybersickness and presence in HMD-based virtual reality. Virtual Real.. doi: 10.1007/s10055-019-00407-8.

[13] S.V.G Cobb, Measurement of postural stability before and after immersion in a virtual environment, Appl. Ergon. 30 (1) (1999) 47–57, https://doi.org/10.1016/S0003-6870(98)00038-6.

[14] S.V.G. Cobb, S.C Nichols, Static posture tests for the assessment of postural instability after virtual environment use, Brain Res. Bull. 47 (5) (1998) 459–464, https://doi.org/10.1016/S0361-9230(98)00104-X.

[15] M.S. Dennison, M D'Zmura, Cybersickness without the wobble: experimental results speak against postural instability theory, Appl. Ergon. 58 (2017) 215–223, https://doi.org/10.1016/j.apergo.2016.06.014.

[16] N. Duzmanska, P. Strojny, A. Strojny, Can simulator sickness be avoided? A review on temporal aspects of simulator sickness, Front. Psychol. 9 (2018), https://doi.org/10.3389/fpsyg.2018.02132. ARTN2132.

[17] A.S. Ferro, K. Nicholson, S. Koka, Innovative trends in implant dentistry training and education: a narrative review, J. Clin. Med. 8 (10) (2019), https://doi.org/10.3390/jcm8101618.

[18] A.M. Gavgani, K.V. Nesbitt, K.L. Blackmore, E. Nalivaiko, Profiling subjective symptoms and autonomic changes associated with cybersickness, Auton. Neurosci. 203 (2017) 41–50, https://doi.org/10.1016/j.autneu.2016.12.004.

[19] A. Ghasemi, S. Zahediasl, Normality tests for statistical analysis: a guide for non-statisticians, Int. J. Endocrinol. Metab. 10 (2) (2012) 486–489, https://doi.org/10.5812/ijem.3505.

[20] G. Godin, R., J. Shephard, A simple method to assess exercise behavior in the community, Canad. J. Appl. Sport Sci. 10 (3) (1985) 141–146.

[21] J. Guna, G. Gersak, I. Humar, J. Song, J. Drnovsek, M. Pogacnik, Influence of video content type on users' virtual reality sickness perception and physiological response. Future Generation Computer Systems-the, Int. J. Esci. 91 (2019) 263–276, https://doi.org/10.1016/j.future.2018.08.049.

[22] C.G. Horlings, M.G. Carpenter, U.M. Kung, F. Honegger, B. Wiederhold, J.H. Allum, Influence of virtual reality on postural stability during movements of quiet stance, Neurosci. Lett. 451 (3) (2009) 227–231, https://doi.org/10.1016/j.neulet.2008.12.057.

[23] R.S. Kennedy, J. Drexler, R.C. Kennedy, Research in visually induced motion sickness, Appl. Ergon. 41 (4) (2010) 494–503, https://doi.org/10.1016/j.apergo.2009.11.006.

[24] R.S. Kennedy, N. Lane E., K. Berbaum S., M. Lilienthal G., Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness, Int. J. Aviat. Psychol. 3 (3) (1993) 203–220.

[25] H.K. Kim, J. Park, Y. Choi, M. Choe, Virtual reality sickness questionnaire (VRSQ): motion sickness measurement index in a virtual reality environment, Appl. Ergon. 69 (2018) 66–73, https://doi.org/10.1016/j.apergo.2017.12.016.

[26] F. Koslucher, E. Haaland, T.A. Stoffregen, Sex differences in visual performance and postural sway precede sex differences in visually induced motion sickness, Exp. Brain Res. 234 (1) (2016) 313–322, https://doi.org/10.1007/s00221-015-4462-y.

[27] R. Laboissiere, J.C. Letievant, E. Ionescu, P.A. Barraud, M. Mazzuca, C. Cian, Relationship between spectral characteristics of spontaneous postural sway and motion sickness susceptibility, PLoS ONE 10 (12) (2015), e0144466, https://doi.org/10.1371/journal.pone.0144466.

[28] J., .J LaViola Jr, A discussion of cybersickness in virtual environments, ACM SIGCHI Bull. 32 (1) (2000) 47–56, https://doi.org/10.1145/333329.333344.

[29] Y. Ling, H.T. Nefs, N. Morina, I. Heynderickx, W.P. Brinkman, A meta-analysis on the relationship between self-reported presence and anxiety in virtual reality exposure therapy for anxiety disorders, PLoS ONE 9 (5) (2014) e96144, https://doi.org/10.1371/journal.pone.0096144.

[30] S. Litleskare, G. Calogiuri, Camera stabilization in 360 degrees videos and its impact on cyber sickness, environmental perceptions, and psychophysiological responses to a simulated nature walk: a single-blinded randomized trial, Front. Psychol. 10 (2019) 2436, https://doi.org/10.3389/fpsyg.2019.02436.

[31] M. Melo, J. Vasconcelos-Raposo, M. Bessa, Presence and cybersickness in immersive content: effects of content type, exposure time and gender, Comput. Graph. UK 71 (2018) 159–165, https://doi.org/10.1016/j.cag.2017.11.007.

[32] O. Merhi, E. Faugloire, M. Flanagan, T.A. Stoffregen, Motion sickness, console video games, and head-mounted displays, Hum. Factors 49 (5) (2007) 920–934, https://doi.org/10.1518/001872007X230262.

[33] J. Munafo, M. Diedrick, T.A. Stoffregen, The virtual reality head-mounted display Oculus Rift induces motion sickness and is sexist in its effects, Exp. Brain Res. 235 (3) (2017) 889–901, https://doi.org/10.1007/s00221-016-4846-7.

[34] A. Murata, Effects of duration of immersion in a virtual reality environment on postural stability, Int. J. Hum. Comput. Interact. 17 (4) (2004) 463–477, https://doi.org/10.1207/s15327590ijhc1704_2.

[35] . . . S. Nishiike, S. Okazaki, H. Watanabe, H. Akizuki, T. Imai, A. Uno, K. Kitahara, A. Horii, N. Takeda, H. Inohara, The effect of visual-vestibulosomatosensory conflict induced by virtual reality on postural stability in humans J. Med. Invest. 60 (2013) 236–239.

[36] C.M. Oman, A Heuristic Mathematical Model For the Dynamics of Sensory Conflict And motion Sickness, Acta Otolaryngologica, 1982, p. 44.

[37] C.M. Oman, Motion sickness: a synthesis and evaluation of the sensory conflict theory, Can. J. Physiol. Pharmacol. 68 (2) (1990) 294–303, https://doi.org/10.1139/y90-044.

[38] A.C. Paillard, G. Quarck, F. Paolino, P. Denise, M. Paolino, J.F. Golding, V. Ghulyan-Bedikian, Motion sickness susceptibility in healthy subjects and vestibular patients: effects of gender, age and trait-anxiety, J. Vestib. Res. 23 (4–5) (2013) 203–209, https://doi.org/10.3233/VES-130501.

[39] T. Paillard, F. Noe, Techniques and methods for testing the postural function in healthy and pathological subjects, Biomed. Res. Int. 2015 (2015), 891390, https://doi.org/10.1155/2015/891390.

[40] S. Palmisano, B. Arcioni, P.J. Stapley, Predicting vection and visually induced motion sickness based on spontaneous postural activity, Exp. Brain Res. 236 (1) (2018) 315–329, https://doi.org/10.1007/s00221-017-5130-1.

[41] J.T. Reason, Motion sickness adaptation: a neural mismatch model, J R Soc Med 71 (11) (1978) 819–829. Retrieved from, https://www.ncbi.nlm.nih.gov/pubmed/731645.

[42] J.T. Reason, J.J. Brand, Motion Sickness, Academic Press, Cambridge, MA, 1975.

[43] G.E. Riccio, T.A. Stoffregen, An ecological theory of motion sickness and postural instability, Ecol. Psychol. 3 (3) (1991) 195–240.

[44] D. Risi, S. Palmisano, Effects of postural stability, active control, exposure duration and repeated exposures on HMD induced cybersickness, Displays 60 (2019) 9–17, https://doi.org/10.1016/j.displa.2019.08.003.

[45] L.J. Smart Jr., T.A. Stoffregen, B.G Bardy, Visually induced motion sickness predicted by postural instability, Hum. Factors 44 (3) (2002) 451–465, https://doi.org/10.1518/0018720024497745.

[46] A. Somrak, I. Humar, M.S. Hossain, M.F. Alhamid, M.A. Hossain, J. Guna, Estimating VR Sickness and user experience using different HMD technologies: an evaluation study. Future Generation Computer Systems-the, Int. J. Esci. 94 (2019) 302–316, https://doi.org/10.1016/j.future.2018.11.041.

[47] T.A. Stoffregen, L.J. Smart, Postural instability precedes motion sickness, Brain Res. Bull. 47 (5) (1998) 437–448, https://doi.org/10.1016/S0361-9230(98)00102-6.

[48] T.A. Stoffregen, K. Yoshida, S. Villard, L. Scibora, B.G. Bardy, Stance width influences postural stability and motion sickness, Ecol. Psychol. 22 (3) (2010) 169–191, https://doi.org/10.1080/10407413.2010.496645. Pii 925052743.

[49] P. Veličković, M. Milovanović, Improvement of the interaction model aimed to reduce the negative effects of cybersickness in VR rehab applications, Sensors 21 (2) (2021) 321, https://doi.org/10.3390/s21020321.

[50] S.J. Villard, M.B. Flanagan, G.M. Albanese, T.A. Stoffregen, Postural instability and motion sickness in a virtual moving room, Hum. Factors 50 (2) (2008) 332–345.

[51] S. Weech, J.P. Varghese, M. Barnett-Cowan, Estimating the sensorimotor components of cybersickness, J. Neurophysiol. 120 (5) (2018) 2201–2217, https://doi.org/10.1152/jn.00477.2018.

Appendix: Paper IV

Litleskare, S., MacIntyre, T. E., & Calogiuri, G. (2020). Enable, Reconnect and Augment: A New ERA of Virtual Nature Research and Application. *Int J Environ Res Public Health*, *17*(5). https://doi.org/10.3390/ijerph17051738

International Journal of
Environmental Research and Public Health

Review

Enable, Reconnect and Augment: A New ERA of Virtual Nature Research and Application

Sigbjørn Litleskare [1,*], Tadhg E. MacIntyre [2] and Giovanna Calogiuri [1]

[1] Faculty of social and health sciences, Inland Norway University of Applied Sciences, 2406 Elverum, Norway; Giovanna.calogiuri@inn.no
[2] GO GREEN Initiative, Health Research Institute, University of Limerick, V94 T9PX Limerick, Ireland; Tadhg.macintrye@ul.ie
* Correspondence: sigbjorn.litleskare@inn.no; Tel.: +47-62430218

Received: 08 February 2020; Accepted: 2 March 2020; Published: 6 March 2020

Abstract: Being exposed to natural environments is associated with improved health and well-being, as these environments are believed to promote feelings of "being away" from everyday struggles, positive emotional reactions and stress reduction. Despite these positive effects, humanity is becoming increasingly more distanced from nature due to societal changes, such as increased urbanization and the reduced accessibility of natural environments. Technology is also partly to blame, as research suggests that people replace nature contact with increased screen time. In this cross-section between nature and technology, we find technological nature which is progressing towards a point where we may be capable of simulating exposure to real nature. Concerns have been raised regarding this technology, as it is feared it will replace real nature. However, research suggests that virtual nature may have a more positive impact on society than a mere replacement of real nature, and this review propose several areas where virtual nature may be a beneficial addition to actual nature (Enable), help people reconnect with the real natural world (Reconnect) and "boost" human-nature interactions (Augment). Based on the current research and theoretical framework, this review proposes guidelines for future research within these areas, with the aim of advancing the field by producing high quality research.

Keywords: virtual reality; technological nature; immersive virtual environments; nature; green exercise; nature based interventions; immersive virtual nature

---

1. Introduction

Human health is influenced by a wide range of factors, including the surrounding environment. Some environments may have a detrimental effect on human health, while others, such as natural environments, are believed to have a salutogenic effect. Research suggests that being exposed to natural environments (e.g., forests, parks and beaches) is associated with improved health and well-being [1–3]. For example, White et al. [3] reported positive associations between recreational nature contact in the last seven days and self-reported health and well-being in a sample consisting of almost 20,000 participants. Compared to no nature contact in the previous week, the likelihood of reporting good health or high levels of well-being became significantly greater when participants reported a total duration of nature contact of 120 min per week or more. The health impact of 120 min of nature contact was comparable to achieving the recommended levels of physical activity, living in a high versus low deprivation area or being employed in a high versus low social grade occupation, which signifies the importance of nature contact for public health [3].

Despite the positive effects associated with nature interactions, accumulating evidence suggests that opportunities for nature experiences are decreasing globally [4]. According to the United Nations

(UN), more than 55% of the world's population is currently living in urban environments, and the number is expected to increase to 68% by 2050 [5]. Furthermore, there are reports of a rapid loss of biodiversity and a degradation of the natural world [6] largely due to deforestation and unsustainable land use. In addition to reduced opportunities for nature contact, people are becoming less and less connected with the natural world, a trend that may influence a range of factors such as happiness, life satisfaction, as well as pro-environmental attitudes and behaviors [7,8]. All of this influences how humans perceive and interact with the natural world. In the UK, less than 40% of people visit natural environments during a regular week, of which only a small fraction consists of "active" visits [9]. Even in rural Norway, only 60% of adults engage in active visits in natural environment during a regular week [10]. These numbers are expected to decline even further in the coming years, as today's children spend less time outside compared to the previous generation [11,12]. Technology is believed to be part of this problem, as research suggests that many replace experiences in nature with increased screen time [12,13]. However, technology might also be part of the solution.

Human-nature interactions are usually associated with the outdoors, but modern technology has enabled people to bring nature experiences into their homes as well. This phenomenon is part of a concept that Peter Kahn defines as technological nature, i.e., technologies that in various ways mediate, augment and simulate our experience of the natural world [14]. The concept of technological nature has received increased attention in the research community. In particular, attention has been directed, often with some concerns, towards so-called virtual nature [15] and especially immersive virtual environments technology [16]. The combination of these two concepts has been defined as immersive virtual nature (IVN) [17], which combines visual and auditory stimuli to create an immersive nature experience. In 1999, when the commercial availability of IVN technology was seen as imminent, Levi and Kocher [15] investigated the potential impact of this technology on society. They found that while IVN may have the advantage of bringing nature to people, as well as increasing people's support for national natural reserves, this may come at the cost of a devaluation of local natural environments. Others have an even more cautious outlook on our future interactions with nature and fear that technological nature will be a replacement, and a downgrade, of authentic nature in a future where nature contact is severely limited [14]. Completely replacing authentic nature with virtual nature would have severe consequences, as virtual nature lacks the ability to provide important ecosystem services such as climate regulation and nutrient cycling. In spite of these gloomy outlooks on the future of the human species and the potential for interactions with nature, the present paper suggests that technological nature may be more than a mere replacement of real nature and argues that it may rather be part of the solution to increase human-nature interactions and improve public health. In particular, immersive virtual nature may (1) enable us to prolong the positive effects of nature-interactions when we have left the outdoor natural setting; (2) provide access to nature for individuals who may not be able to access it directly; (3) increase feelings of connectedness with the natural world and (4) elicit greater awareness of environmental issues and sustainability. The rapid technological development along with its increased accessibility (and economical affordability) might thus provide a series of opportunities to enhance human-nature interactions.

The purpose of this paper is to provide an overview of the possibilities and challenges of IVN, and offer guidelines for further research. More specifically, this paper will: (I) present an overview of Virtual Reality (VR) technology and IVN and present a general overview of issues associated with IVN technology, (II) discuss three major areas of possible applications or "levels" in which IVN can mediate humans' interactions with real nature: Enable, Reconnect and Augment (ERA), and (III) propose guidelines for further research based on existing evidence.

2. Possibilities and Challenges of Virtual Nature

2.1. Virtual Reality and Virtual Nature: Some Definitions

VR can, in short, be referred to as a computer-generated simulation of a three-dimensional image or environment that allows a certain degree of interaction, creating the illusion of reality (See Table 1 for a list of key terms). An important characteristic of VR is that it disconnects the viewer from the external (real) world, which allows the viewer to get immersed in the virtual world. Different types of VR exist, but the one that has gained the most interest in recent years is the type that is enabled by so-called head-mounted displays (HMD), commonly known as "VR masks" or "VR googles". The introduction of affordable HMDs is a major part of the recent mass appeal of VR technology. HMDs have the advantage of allowing 360° vision of the virtual world while eliminating the visual contact with the external environment. These devices are the basis of the so-called immersive virtual environment technology, which consists of a flow of synthetic sensory information that, through an HMD, provides a surrounding and continuous stream of stimuli, creating the illusory perception of being enclosed within and interacting with a real environment [16,18]. This type of technology is considered more immersive compared to other forms of virtual nature, such as digital images and videos, and is consequently likely to increase the viewers' sense of presence in the environment. Both immersion and presence are considered key elements of immersive virtual environments as outlined below.

Table 1. Definitions of the key terms and key concepts relating to immersive virtual nature.

Term	Definition	Source
Nature	Refers to "areas containing elements of living systems that include plants and non-human animals across a range of scales and degrees of human management—from a small urban park to "pristine wilderness."	[19] (pp. 121–122)
Green exercise	"Physical activities whilst at the same time being directly exposed to nature."	[20] (p. 7)
Nature-Based Interventions	"NBIs are programmes, activities or strategies that aim to engage people in nature–based experiences with the specific goal of achieving improved health and wellbeing."	[21] (p. 2)
Virtual Reality (VR)	"A medium composed of interactive computer simulation that senses the participant's position and actions and replaces or augments the feedback to one or more senses, giving the feeling of being mentally immersed or present in the simulation (a virtual world)."	[22] (p. 13)
Augmented Reality (AR)	AR "supplements the real world with virtual (computer-generated) objects that appear to coexist in the same space as the real world."	[23] (p. 34)
Immersion	"The extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding and vivid illusion of reality to the senses of a human participant"	[24] (p. 3)
Presence	''The (psychological) sense of being in the virtual environment."	[24] (p. 3)
Technological Nature	"Technologies that in various ways mediate, augment or simulate the natural world."	[14] (p. 37)
Immersive Virtual Nature (IVN)	Based on so-called immersive virtual environments technology, provides the illusory perception of being enclosed within a natural environment.	[17] (p. 280)

Immersion is solely related to technical aspects of the virtual environment, such as the frame rate, field of view and resolution of the display [25], and one can theoretically evaluate a system's level of immersion objectively. Presence, on the other hand, describes a person's subjective feeling of "being in the virtual environment" [24]. This concept relates to the psychological feeling of being transported from the physical location to the virtual location. Immersion and presence are distinct but interrelated concepts. It is believed that systems with a high level of immersion will increase the likelihood of inducing feelings of presence. Furthermore, presence is considered pivotal to the effectiveness of the virtual environment, as it relates to the virtual environment's ability to fulfill its purpose [26–28]. In the case of IVN, this translates into the ability of the IVN to elicit similar responses as interactions with real nature. A recent study provided support for this assumption, showing higher levels of stress reduction and positive affect in an underwater VR experience compared to a desktop counterpart [29].

Unfortunately, highly immersive virtual systems appear to have their limitations. For example, cyber sickness is a well-known side-effect of virtual environments. This malaise is a specific type of visually induced motion sickness [30] and may cause dizziness, nausea and general discomfort. The most prevalent explanation for cyber sickness suggest that the symptoms arise from a sensory conflict between visual, vestibular and proprioceptive signaling [31]. In other words, the visual input from the HMD does not match the input from the surroundings as perceived by vestibular and proprioceptive systems. Cyber sickness is reported to occur in as much as 100% of viewers depending on factors such as the contents of the virtual environment, exposure duration and technological fidelity [32–37]. Furthermore, recent research reports that cyber sickness and presence are inversely related, which suggests that cyber sickness may have a negative impact on the feeling of presence in virtual environments [38]. The issue of cyber sickness has recently become more relevant, as visual displays that are considered more immersive, such as HMDs, are more prone to induce high levels of cyber sickness [37]. This paradox must be solved in order to increase the usefulness of IVN, as the most advanced displays may be needed to provide a sufficient degree of presence. Luckily, researchers continue to identify factors that either increase or decrease the levels of cyber sickness, such as habituation, scene oscillation, movement lag and exposure time [34,39–41].

Combining IVN and physical activity, a combination that may be defined as virtual green exercise (i.e., physical activity in the presence of technological nature), introduces additional challenges, mainly associated with the issue of maintaining balance and, thus, exacerbating the sensory conflict leading to cyber sickness. In a study of virtual green exercise it was found that cyber sickness had a severe detrimental effect on participants’ emotional responses, which lead to a significant difference in participants’ emotional states after a bout of real green exercise compared to virtual green exercise [39]. Several participants also complained about the difficulties of maintaining balance and reported frustration because their movements did not sufficiently match the movements in the virtual environment [39]. Technology is advancing rapidly, and some of the challenges mentioned above might be addressed in the near future. In fact, a recent study has successfully reduced negative side-effects caused by cyber sickness by minimizing camera oscillations in 360° videos of green exercise [34].

2.2. Is Virtual Nature as Good as the Real Thing?

Emerging research on technological nature tentatively confirms that these interactions are more beneficial for health and well-being than an absence of human-nature interactions, but not as beneficial as genuine nature exposure [42–44] (see Figure 1). Findings from a range of studies suggest that virtual nature interactions produce some positive effects, but also show that virtual nature is unable to fully reproduce the effects of real nature [44–47]. Similar reports are found in studies comparing virtual to real green exercise. For example, a recent systematic review reported inconclusive evidence concerning the extent to which virtual green exercise can provide similar psychological or physiological health benefits as real green exercise [48]. The authors of the review warn, however, about limited research rigor in the individual studies, as well as a large variety of outcome measurements and the duration and mode of the physical activity interventions. It should also be noted that among the reviewed studies there was a large variation with respect to the technology used in the virtual nature conditions, with part of the studies using HMDs (only one of which as using a full 360° IVN), while other studies used non-immersive types of virtual nature (i.e., images or videos on a screen). This insight gives hope for the future of virtual nature, as it is expected that increased technological fidelity will improve both immersion and presence, which should improve the psychophysiological effects of virtual nature (see Figure 1). Recent studies adopting modern technology to create immersive nature experiences partly support this notion. For example, Chirico and Gaggiolo [49] created an IVN consisting of a static panoramic video of a natural landscape and successfully replicated some of the positive psychological responses recorded when the participants were exposed to the corresponding real landscape. Similarly, Yu et al. [50] found that exposure to an IVN was effective in eliciting psychological responses similar to those that would be expected in real nature. However the same IVN was unable to produce similar responses with respect to physiological measurements. Browning et al. [51], on the other hand, found a similar physiological response for IVN compared to a real natural environment, but also demonstrated a superior effect on mood levels for the real natural environment.

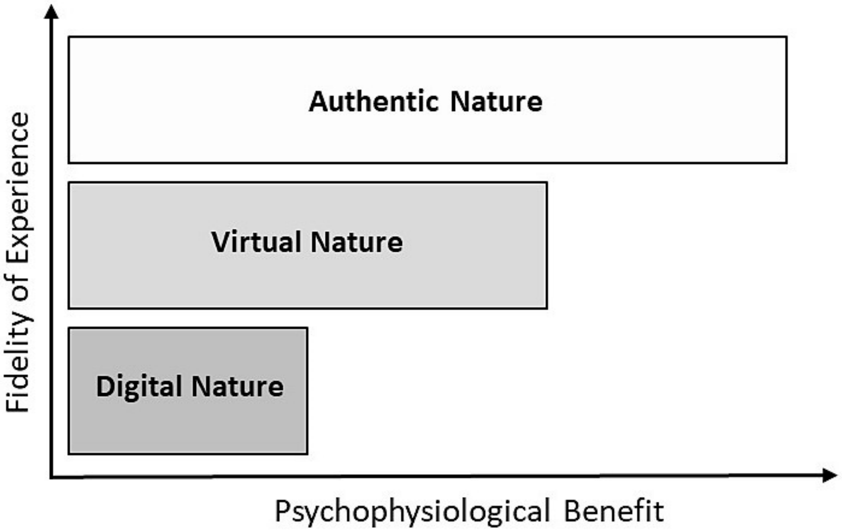


Figure 1. Predicted psychophysiological benefits from nature experiences at different levels of fidelity.

The aforementioned research suggests that IVN is currently not able to fully reproduce the whole range of psychophysiological responses that people experience in real nature. Further technological and scientific progress may allow the use of highly immersive IVNs to better recreate the fidelity of authentic experiences of nature. IVN may represent a valuable compromise when trying to balance people’s basic need to experience nature with the increasing distance between them and real natural environments, as well as balancing methodological rigor and life-like experiences in a research context. It is likely, however, that, no matter how much the technology improves, IVN will never fully replicate the holistic, multi-sensory and potentially elating experience of the real outdoors. The voice of one of the participants in our VR trials states the following in this regard: “Nature will always win for me. It is less stressful, you know where you are, you can stop and look, for example, at birds anytime.” ([39]; unpublished quote). Moreover, we should bear in mind Levi and Kocher’s warning: “the problem with virtual nature—like the problem with plastic trees—is that the value of nature is more than the experiential and recreational benefits it provides to people. Nature provides a variety of benefits beyond human’s immediate experience; nature exists and has value separate from human beings” [15] (p. 224). In addition, outdoor nature contact offers many additional benefits which to date cannot be incorporated in VR, such as, for example, enhanced immunity from exposure to microbiomes and phytoncides from trees (see [52]). Nevertheless, the opportunity that IVN can provide should not be overlooked, and these possibilities will now be reviewed.

3. Enable, Reconnect and Augment

3.1. Enable: Virtual Nature as a Supplement to Real Nature

Virtual nature may be used as a nature-based intervention for specific situations where exposure to real nature is difficult or inconvenient. Research has already identified several areas where IVN show particularly promising results and potential applications.

Palliative treatment in clinical settings–IVN has received a lot of attention in the field of clinical care, especially within palliative treatment. The interest in using VR technology as a tool for prevention and treatment of both mental and physiological health issues began in the 1990s [53,54]. Although some researchers have called for high quality studies to demonstrate the cost-effectiveness of VR in clinical settings, research within this field has consistently demonstrated that the use of VR technology is feasible and safe, and results in high patient satisfaction [55]. In a fact, a recent review by White et al. concludes that IVN is a useful tool to integrate with traditional treatment situations in which contact with real nature is not possible or unsafe, e.g., when the risk of injury outweighs the health-promoting effect of real nature [54]. White et al. [54] further reports that IVNs can be effectively applied in the following fields: pain management, neurological disorders, stroke rehabilitation, distraction and relaxation tools in cancer treatment, cognitive rehabilitation and mental health and well-being, including depression, anxiety, obesity, eating disorders and phobias.

Stress-management in the workplace–According to the European Agency for Safety and Health at Work [56], work-related stress is one of the biggest work-related health issues. Interestingly, a recent review of the literature highlights the stress-reducing effects of indoor nature exposure (indoor environments that contain real or representations of nature-based stimuli that engage a variety of senses), and emphasizes that the health benefits of indoor nature exposure occur by facilitating both the reduction of and recovery from stress [57]. IVN technology might further advance the field of nature in indoor settings by generating a more immersive and life-like experience. Although there is a general lack of research regarding the effectiveness of implementing IVNs in the workplace, some research has demonstrated that IVNs can induce stress reduction in experimental trials on healthy adults [50,58–60]. Moreover, exposure to IVN has been found to be a more effective tool to reduce anxiety levels and improve mood states when compared to images of nature presented on a traditional computer screen [29].

Mental health and cognitive development in school settings–Today's children spend a limited amount of time in contact with nature [11,12]. This is unfortunate as research demonstrates that nature contact has a positive impact on both physical and mental health in children and adolescents. For example, Mennis, Mason and Ambrus [61] showed that adolescents with immediate access to greenspaces within their living environment experienced reduced levels of psychological stress. Outdoor recreational activities have also been found to improve adolescents' self-esteem, well-being and perceived body image [62–64]. Nature interactions during childhood can also lead to a greater engagement in nature-based physical activity in adulthood [10,65], and can thus promote lifelong physical activity and improved physical and mental health. Although IVN may not provide all of the beneficial elements of interaction with real nature, it may still provide some benefits, especially with respect to cognitive restoration and enhanced psychological states [66]. There has also been increased interest in using VR as a supplement to children's school-based education [67]. In this regard IVNs may represent a useful tool to supplement interactions with real nature in schools with limited access to natural areas. VR provides safe environments for pupils and students to learn and gain skills, and IVN might be used to facilitate initial positive experiences of mastery that might reduce children's fear or insecurities when exploring the outdoors. Inspiration for this particular type of IVN may come from research within the field of nature advertisement and promotion, which provides useful recommendations for designing advertisements to promote green exercise participation in different groups of people [68]. These recommendations can be used to develop tailored IVNs that encourage children to visit real natural environments.

Nature experiences for astronauts in space-missions–In such conditions, IVN represents the only alternative for nature exposure. Space is an extreme environment for the human body and poses a serious threat to human health, as the lack of gravity leads to negative side effects such as muscular atrophy [69]. IVNs might help astronauts coping with the stress associated with this extreme environment as well as augment exercise routines in microgravity. This is an exciting line of research, with recent studies already trying to explore the potential use of psychological interventions to assist in the adaptation to and recovery from exposure to space and space-like environments [70].

3.2. Reconnect: Virtual Nature as a Strategy to Reconnect People to Nature

With the backdrop of land use change in the form of rapid urbanization as well as concerns regarding environmental sustainability, the concept of *nature connectedness* (i.e., an individual's' feeling of being emotionally connected to the natural world) has emerged as a key aspect of the human-nature relationship. Not only is nature connectedness an important component fostering sustainable behavior [8], but individuals with more positive attitudes towards nature were also found to spend more time in natural environments [10,71–73]. This may explain, at least in part, why nature connectedness has been linked with a range of health outcomes. For example, a recent meta-analysis showed that individuals who report higher levels of nature connectedness tend to experience higher levels of positive affect, vitality and life satisfaction compared to those less connected to nature [7]. People who report more positive feelings towards nature were also reported to be more likely to meet the minimum recommended levels of physical activity [10]. Exposure to and interaction with nature seems to be a key element to promote greater feelings of nature connectedness. Childhood experiences of nature, in particular, are known to be a strong predictor of positive feelings towards as well as more frequent interactions with nature as an adult [10,65]. Pupils attending schools with more opportunities for nature contact were found to be more empathetic and concerned for non-human life forms, as well as more aware of human-nature interdependence [74]. Nature experiences can also enhance nature connectedness in adult populations. For example, a tree-planting program was found to enhance participants' feelings of connectedness with nature, which in turn led to increased engagement in pro-environmental behaviors [75]. Simpler forms of human-nature interactions might lead to similar outcomes. For instance, in a series of experiments by Mayer et al. [76], it was found that a single 10-min walk in a pleasant natural environment can lead to enhanced nature connectedness in college students.

Limited research suggests that exposure to virtual nature may have a similar effect, although scientific research in this field is extremely scarce. Mayer [76] found that participants' sense of connectedness to nature was improved after watching short videos of pleasant natural environments, with patterns that were similar, although with a smaller effect-size, to an actual walk in real nature. Moreover, connectedness to nature and time spent outdoors are related [10,71–73]. Thus, by triggering a greater feeling of nature connectedness, virtual nature may be used as an instrument to re-connect people with nature in a broader sense, persuading them to visit real natural environments, although, to the best of the authors' knowledge, no study to date has investigated this hypothesis. However, motivational theories are already in place to support the idea. For instance, Calogiuri and Chroni [77] have proposed a model based on the Theory of Planned Behavior [78], which describes that exposure to and experiences in natural environments can influence people's attitudes towards nature-based physical activity and their future intention and behavior. Positive experiences associated with IVNs might serve as a type of positive reinforcement that can enhance people's attitudes towards nature-based activities. Research that aims to promote nature-based physical activity has indeed emphasized the importance of presenting natural environments that are considered highly restorative, in line with the Attention-Restoration Theory by Rachel and Stephen Kaplan [68].

3.3. Augment: Virtual Nature to Boost the Benefits of Human-Nature Interaction

The effectiveness of virtual nature can go beyond facilitating interactions with simulated nature (Enable) or even helping people reconnect with the real natural world (Reconnect). Virtual nature may offer the possibility to "boost" human-nature interactions (Augment), leading to more restorative experiences as well as enhanced knowledge and engagement. This can be accomplished by the inclusion of virtual elements such as markers to follow pre-set journeys, interactive information-points for learning experiences, guided instructions for meditation, etc. All of these (and many more) components can, rather than simply expose passive viewers to sceneries of nature, trigger and direct users' attention as well as encourage them to interact with the virtual world and engage in reflections. By using these techniques, virtual nature can maximize restorative experiences. Virtual nature experiences may be designed in a way that users may not only enjoy a pleasant walk in nature, but could also, for example, learn about biodiversity, its importance and how it can be protected (see also [21]).

It should be noted that these possibilities are not a specific prerogative of IVN, as they also apply to other forms of non-immersive virtual nature. Non-immersive virtual reality or 'mixed reality' might be used for the same purposes and have the advantage of being easily integrated into people's everyday routines. This includes, for example, mobile apps and augmented reality (AR). AR technology, in particular, has been emerging as a valuable supplement to traditional education tools [79] as well as to engaging visitors to touristic locations, including natural parks [80]. More specifically, AR applications have been shown to engage its users in natural environments as well as teach them about environmental issues such as water quality and biodiversity to a greater extent than other educational tools do [81,82].

On the other hand, given IVN's potential to provide more immersive experiences and more life-like perceptions, as well as its greater effectiveness in eliciting psycho-cognitive restoration as compared to non-immersive virtual nature [29] and other virtual experiences [66], IVN may have the advantage of engaging users' attention to a greater extent and may lead to more intense emotional responses. By disconnecting the viewer from the external (real) world and creating a limited and controllable (virtual) environment, IVN provides particularly favorable conditions in which nature-savoring (i.e., a person's ability to attend to, appreciate and enhance the positive experience of being in contact with nature; [83]) can be triggered and trained. Special IVN-based programs can be designed to elicit and train users' nature-savoring, an ability they can later apply in the presence of real nature, maximizing the psychological benefits of the human-nature interaction. Thus, nature-based interventions can not only provide an opportunity for the experience of nature but can in addition provide specific learning on psycho-social skills or sustainability which can optimize future human nature interactions [21].

Regarding how virtual nature can boost users' nature experiences, gamification is another important concept. Gamification is defined as "the use of game design elements in non-game contexts" [84] (p. 2) and has the purpose to motivate and increase user engagement. While gamification has been predominantly applied in business, marketing and corporate management, its use is also increasing in the field of education [85] and health promotion [86]. Gamification might be included within virtual nature systems to, for example, enhance users' compliance with psychological training programs (e.g., by adding rewards or competition elements) as well as enhance their engagement in educational processes (e.g., through quizzes).

4. Future Perspectives for Research on (or Involving) Virtual Nature

This section will discuss the potential of IVN as a nature-based intervention in addition to evaluating the methodological challenges and providing specific recommendations for researchers in this field. Researchers within areas such as environmental psychology and public health have an interest in understanding how natural environments affect human emotions, cognition, behaviors and health. Such an understanding may have several uses, including designing outdoor or indoor environments that induce stress recovery and helping policy makers and planners take informed decisions about regulations related to planning and re-naturing public spaces [87]. This research can also help in understanding the psychophysiological mechanisms underlying human-nature interactions, as well as engagement in pro-environmental behaviors and sustainable lifestyles. However, examining how people respond to natural environments, as compared with other indoor or outdoor environments, is a difficult task. Conducting rigorous research requires that possible confounders are eliminated or controlled for; this can be accomplished by conducting experimental trials in standardized environmental conditions (laboratory-based studies) and by performing appropriate randomization and blinding procedures, which is often challenging or even impossible to accomplish in natural settings. Thus, in this context, VR technology might be particularly useful. Despite being a young research area, there are several known factors that should be considered when conducting studies using IVN, and more can be deduced from theoretical frameworks. Based on these factors, the following sections will present a generic methodology to consider when planning and conducting research with IVNs based on 360° 2D images/videos to be presented using HMDs.

4.1. General Considerations

4.1.1. Study Design

A recent systematic review of the literature [48] found that studies of green exercise, including virtual green exercise, are often characterized by a high risk of bias due to (I) inadequate/unclear randomization procedures; (II) a lack of blinding of both participants and assessors to the experimental conditions; (III) inadequate washout periods in trials with crossover design; (IV) and potential contamination in control conditions. Furthermore, most trials had insufficient statistical power, and the scarcity of preregistered trials limited the possibility of ruling out selective reporting. Thus, it is recommended that future research on (or involving) IVN be conducted according to general guidelines for randomized controlled trials [88]. Accordingly, performing appropriate randomization procedures, as well as the blinding of participants and possibly also the examiner, is paramount to reduce risks of bias in the assessments and analyses.

When planning trials with a crossover design, it is important to consider that the carry-over effect is a real concern in studies involving IVNs. This may relate especially to negative emotional and physical responses associated with cyber sickness. A review by Duzmanska [40] indicated that symptoms of cyber sickness may last up to 4 h depending on the severity of the symptoms and the duration of exposure. Thus, it is recommended that trials with a crossover design avoid administering multiple IVN exposures within the same day.

The characteristics of the control and/or comparison conditions also require careful evaluation. Some studies have used “true control conditions” such as sitting quietly staring at a blank wall (e.g., [51]). This may, however, be problematic. Whitehead [89] recommends using an “active control” condition, in general, to sufficiently control for a potential placebo effect. This may be particularly important when the IVN intervention involves physical activity, which can induce psychological benefits in itself [90]. Furthermore, the true control condition may elicit feelings of boredom, which may in turn lead to negative emotional states. For example, in a summary of 11 studies, Wilson et al. [91] reported that sitting alone in a room doing nothing was perceived as non-enjoyable, to the point that in one of the reported studies many preferred to administer mild electric shocks to themselves. Many studies involving IVN or other forms of virtual nature have rather opted for comparison conditions that retained some similarity with the treatment condition, e.g., exposure to virtual urban environments [2,48,92].

4.1.2. Theory-Based Approaches

Theory-led investigations of virtual nature may be useful for advancing our understanding of the mechanisms underlying benefits to health from nature contact. A multiplicity of possible mechanisms have been proposed, but the majority of these assume direct rather than indirect (e.g., virtual) nature contact [4,21,52]. A recent review has attempted to explain the benefits and risks of human-nature interactions by accounting for dose-response relations, exposure (referring to the amount of contact that an individual or population has with nature), experience (includes interaction and dose), and natural features [4]. More generally, contemporary conceptual frameworks [4,42] can help generate additional testable hypotheses beyond the traditional approaches of the Stress-Reduction Theory [93] and Attention-Restoration Theory [94].

4.1.3. Natural Typologies

The presence, distribution and diversity of natural features in the environment, whether of a virtual or authentic nature, have to be considered [95,96]. Features of nature that potentially influence mental health include the size of the environment (total area), its composition (proportions of different types of natural elements) and spatial configuration (e.g., degrees of fragmentation and connectivity with other green spaces) [95,96]. Other relevant natural attributes may include the tree canopy density, vegetation structure, species composition or biodiversity across a range of different settings or typologies. These typologies include public green spaces, peri-urban nature reserves, wilderness and pastoral landscapes [97]. Preferences for different typologies should be considered in developing IVN stimuli. As Depledge et al. [98] suggested, "we are ignorant of how subtle changes in these features, or the removal of certain sensory effects from an environment ("de-integration"), are perceived by simulation users and what effects these may have on performance, engagement and, indeed, well-being" (p. 4463). VR can provide a laboratory to dissect at least some of the stimuli we receive from being outdoors in nature and to aid the evaluation of their relative contribution to well-being.

4.1.4. Reporting Findings

The systematic review by Lahart et al. [48] calls for enhanced standards in reporting green exercise (and virtual green exercise) studies. In line with such a call, the authors of this review encourage researchers who perform IVN studies to report their findings in compliance with internationally recognized guidelines (e.g., CONSORT statement). In particular, Lahart et al. [48] encourage researchers to provide clear information regarding randomization procedures and methodological transparency and rigor via the preregistration of study designs and statistical plans, as well as by making data openly accessible.

In addition to these general recommendations, it is recommended that researchers report details of the IVN technology used in their studies (brand and model of devices, hardware and processing techniques), as well as detailed information on how the IVNs were developed, as research suggests that the generalization between devices may be limited [99,100]. Information about the participants' characteristics, especially in relation to possible confounding variables (see Section 4.2.3), should also be clearly stated when reporting findings.

4.2. Specific Considerations

4.2.1. Duration of the IVN Exposure

The exposure duration should be carefully evaluated, as this might influence both the effect size of the psychophysiological responses to virtual nature and influence the risk of cyber sickness. Shorter bouts (e.g., 5 min) of nature experiences have been associated with the largest effect sizes on self-esteem and total mood, while benefits on biological indicators of stress (e.g., blood pressure) would peak at 10 min of exposure [62]. On the other hand, in IVN studies it is important to take into consideration the possible impact of the IVN exposure on cyber sickness. In this regard, a review by Duzmanska et al. [40] shows that cyber sickness symptoms generally increase with time, at least until a certain threshold (~75 min). This means, for specific studies, that there may be a trade-off between the optimal exposure duration to induce the desired effect and the optimal exposure duration to minimize the impact of cyber sickness. In these cases, it may be crucial to conduct a pilot study in advance to identify the ideal compromise.

4.2.2. Choosing the Appropriate Type of IVN

Different types of IVN exist, which differ in the way they are created as well as in their resemblance with real nature. One way to create IVN is to use photorealistic representations using video-game development technology. This type of IVN can achieve relatively high levels of realism, and has been found to elicit psychological and cognitive restoration [60,101]. To the best of our knowledge, however, this technology has not yet been applied to dynamic 360° systems. Another way to create IVN is to use special 360° cameras. This alternative has become increasingly popular as commercial 360° cameras are becoming more affordable and of a higher quality (higher resolution, better in-built stabilization option, greater possibility to edit images and videos in post-production, etc.), making it relatively easy to create IVNs based on existing locations. This technique allows the creation of different types of IVN, each coming with advantages and disadvantages. 360° images may be considered as not being very life-like, as they does not display any moving objects (e.g., leaves moving in the wind or waves rolling). On the other hand, the lack of movement makes 360° images less likely to induce sensory conflict, and thus less likely to induce cyber sickness [31]. Some studies have applied this technique (see e.g., [50]) and show that 360° nature images were able to elicit some of the expected benefits of nature exposure. Static 360° videos are similar to the 360° image, but they also displays the movement of objects, which may make the IVN more 'life-like'. This technique has also been applied in previous studies (see e.g., [49]), finding that static 360° videos can induce psychological responses similar to those experienced when exposed to real nature. Dynamic 360° videos (i.e., 360° videos in which the viewer perspective moves in the virtual space) may provide the advantage of recreating the feeling of exploring a natural environment and can be administered in combination with physical activity, which is shown to improve the users' feelings of presence [38], but these videos also have some issues. In particular, they are more prone to inducing cyber sickness, which can have a negative impact on the restorative benefits of the IVN exposure [39]. In this regard, the stability of the sceneries in dynamic 360° videos seems to be crucial for avoiding cyber sickness [34,102,103]. Improved stability can be achieved by using external or in-built stabilizers in combination with a dolly or a hoverboard [34], and available computer software can further reduce vibrations and oscillations in 360° videos. Research also suggests that the posture of the viewer should match the perspective in the virtual environment, i.e., seated participants experience lower levels of presence compared to standing participants when exposed to an environment where you would typically be walking [33]. To further reduce sensory conflict and optimize the potential of dynamic 360° videos, it is important that the pace of the user matches that of their virtual avatar [39]. This can be achieved either by externally controlling the users' pace (e.g., making them walk on a treadmill at a predetermined speed that corresponds to the speed in the video) or connecting the locomotion device (e.g., a manually driven treadmill or a cycle-ergometer) to the IVN system so that the user can determine the pace. Both options come with advantages and disadvantages, e.g., externally controlling the users' pace may allow for a better standardization in experimental trials, but allowing the users to determine their own pace may increase the sense of presence.

4.2.3. Control of Confounders

In general, it is recommended that studies involving IVN be conducted in standard environmental conditions, in order to control for general environmental confounders such as temperature, humidity, lighting, etc. More specifically, the literature on VR and IVN has provided evidence on a variety of user-related as well as technology-related factors that influence the way people experience and respond to IVN exposure. In studies involving IVN, it is thus recommended that the researchers control for as many of these possible confounders as possible (e.g., by considering them when outlining the eligibility criteria or by including them as covariates in the statistical analysis), or at least take into consideration the possible impact that they may have on the study outcomes. Some of the key factors are reviewed below.

Individual Characteristics

To assess the effects of virtual nature it is important to evaluate how these effects are moderated according to individual differences. Sex has been found to influence both cyber sickness and presence in virtual environments, with men tending to experience lower levels of cyber sickness and higher levels of presence [38]. Studies have identified other factors that may impact cyber sickness, such as genetics [104], habituation [40], visual acuity [32] and postural control [105].

An individual's habitual physical activity levels have been recently found to influence the extent to which a person is able to correctly estimate the visual speed of their avatar in a non-immersive virtual environment [106]. In particular, as compared with people with more running experience, people with lower levels of weekly physical activity were found to underestimate the visual speed relative to their actual running speed more often. Noticeably, the underestimation of visual speed was dependent on the actual speed (i.e., it was larger at higher speeds). This could be explained by the fact that individuals who regularly engage in physical training show better functions related to visual skills [107–109]. Although this phenomenon has been, to the best of our knowledge, shown only in non-immersive virtual environments, it is likely that similar patterns could also be observed in immersive virtual environments, such as dynamic IVNs. In this regard, some participants may experience a feeling of mismatch between the actual walking/running/cycling speed on an ergometer and the speed in the IVN, even though the speeds are designed to match, potentially leading to a reduced sense of presence and increased levels of cyber sickness.

Personality has also been suggested as a factor that can influence how individuals experience and respond to virtual environments. While it is established that individuals' personality influences the way they perceive and respond to different environments, recent studies have also found similar patterns when individuals are exposed to IVNs (e.g., [110]). It has been proposed that presence might play an important role in explaining the relationship between personality and the inter-individual differences in VR experiences. However, this relationship was found to be largely dependent on the instruments used to assess both personality and presence [111]. One individual factor that should be considered is nature connectedness, which can easily be examined with standardised instruments (e.g., NR6; [112]). As outlined above, nature connectedness influences people's inclinations towards nature, and this may extend to virtual nature. Similarly, it may be useful to assess other psychological factors which have been subject to recent study in the broader green exercise literature. For example, Flowers et al. [113] validated a tool to assess beliefs about green exercise which can help account for placebo effects.

Novelty and habituation may also influence the results in studies of IVN. Habituation reduces the impact of cyber sickness [40], which suggests that participants who are familiar with VR may perceive IVN as a more positive experience. On the other hand, recent research reports that the novelty effect also influences the results in studies on virtual and augmented reality [114,115], which suggests that participants who are unfamiliar with the technology might view the experience as positive based on the novelty of the technology alone. Although a study of IVN by Browning et al. [51] concluded that the novelty effect did not influence the results in studies of virtual nature, it may be too soon to make a definite conclusion regarding this matter. Demographic factors including age and being a 'digital native' should also be considered depending on the goal of the study and the target sample.

Characteristics of the IVN

With respect to recommendations regarding appropriate technology in IVN trials, Rebenitsch and Owen [99] provide an exhaustive list of display characteristics that may influence the users' experiences, and particularly cyber sickness. In general, high-resolution IVN systems would be preferable, as qualitative reports indicate that a low resolution or sharpness of the image can be associated with discomforts during the exposure [39]. The frame rate and latency are also shown to influence both cyber sickness and presence [38]. In addition to display characteristics, the quality of the sound also needs to be cautiously considered. Previous research shows that the sounds and acoustics in both real and virtual environments have a prominent impact on people's experiences. The results from a pilot study by Annerstedt et al. [116] showed that virtual nature with sounds was effective in eliciting stress-reducing effects, while the effect was absent in virtual nature without sounds. Research on soundscapes has demonstrated that auditory input can influence both psychological and physiological measures of health and well-being [117–119]. Soundscape refers to acoustic environments as perceived by people, in context, and evidence is accumulating to support the proposition that urban soundscapes contribute to the environmental quality of urban areas in the same way that microclimatic data does [120]. There are different techniques for creating sounds in IVN, and some have been proven to create more realistic experiences as compared to others (for an overview on this issue, see [121]). This accumulating evidence suggests that the type and quality of the soundscape is important to consider when creating IVNs.

5. Limitations

The main limitation of this review is the narrative nature of the paper, as well as the fact that some aspects that relate to IVN are only discussed briefly. However, a full systematic review and detailed description of all aspects related to IVN is a monumental task and beyond the scope of this paper. The focus of this review was to give an overview of key areas related to the creation and implementation of IVNs. In addition, because VR, IVN and related research areas are still in their infancy, it is expected that there are still several unknowns in the process of successfully implementing IVNs both in research and in real-life situations.

6. Summary and Conclusions

Nature experiences in their various forms will continue to provide a pathway to enhanced well-being and health, and the contribution of technological nature, and specifically IVN, has yet to be fully elucidated. This paper suggested several uses for IVN. Some uses are backed by substantial research, while other uses still await solid confirmation or disconfirmation. Nevertheless, the diminishing access to authentic nature in urban settings should be a driver for further exploration of IVNs' ability to enable, reconnect and augment human-nature experiences. IVN as a research area, and the technology it involves, are still in its infancy, which suggests that there is an untapped potential that might be uncovered in the future. To tap into this potential, researchers and manufacturers must identify strategies to deliver highly immersive experiences with high levels of presence, while at the same time avoiding the issue of cyber sickness. In this regard, specific recommendations for the next wave of research have been provided. Caution is advised, though, as concerns have been raised regarding the risk of replacing real nature with virtual nature, and thus accelerating the disconnection from the natural world. The long-term effects of using IVN are also unknown; it is possible that the positive effects identified by short-term studies will diminish in the long term.

Author Contributions: Conceptualization, S.L., T.E.M. and G.C.; writing—original draft preparation S.L.; writing—review and editing, S.L., T.E.M. and G.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bosch, M.V.D.; Bird, W. *Nature and Public Health—The Role of Nature in Improving the Health of a Population*, 1st ed.; Oxford University Press: Oxford, UK, 2018; p. 338.
2. Bowler, D.E.; Buyung-Ali, L.M. A systematic review of evidence for the added benefits to health of exposure to natural environments. *BMC Public Health* **2010**, *10*, 456.
3. White, M.P.; Alcock, I.; Grellier, J.; Wheeler, B.W.; Hartig, T.; Warber, S.L.; Bone, A.; Depledge, M.H.; Fleming, L.E. Spending at least 120 min a week in nature is associated with good health and wellbeing. *Sci. Rep.* **2019**, *9*, 7730.
4. Bratman, G.N.; Anderson, C.B.; Berman, M.G.; Cochran, B.; de Vries, S.; Flanders, J.; Folke, C.; Frumkin, H.; Gross, J.J.; Hartig, T.; et al. Nature and mental health: An ecosystem service perspective. *Sci. Adv.* **2019**, *5*, eaax0903.
5. UN. *World Urbanization Prospects: The 2018 Revision [Key Facts]*; New York, NY, USA, 2018.
6. IPBES. *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*; Bonn, Germany, 2019.

7. Capaldi, C.A.; Dopko, R.L.; Zelenski, J.M. The relationship between nature connectedness and happiness: A meta-analysis. *Front. Psychol.* **2014**, *5*, 976.
8. Geng, L.; Xu, J.; Lijuan, Y.; Wenjun, Z.; Kexin, Z. Connections with nature and environmental behaviors. *PLoS ONE* **2015**, *10*, e0127247.
9. White, M.P.; Elliott, L.R.; Taylor, T.; Wheeler, B.W.; Spencer, A.; Bone, A.; Depledge, M.H.; Fleming, L.E. Recreational physical activity in natural environments and implications for health: A population based cross-sectional study in England. *Prev. Med.* **2016**, *91*, 383–388.
10. Calogiuri, G.; Patil, G.G.; Aamodt, G. Is Green Exercise for All? A Descriptive Study of Green Exercise Habits and Promoting Factors in Adult Norwegians. *Int. J. Environ. Res. Public Health* **2016**, *13*, 1165.
11. Balci, S.; Ahi, B. Mind the gap! Differences between parents' childhood games and their children's game preferences. *Contemp. Issues Early Child.* **2017**, *18*, 434–442.
12. Clements, R. An Investigation of the Status of Outdoor Play. *Contemp. Issues Early Child.* **2004**, *5*, 68–80.
13. Larson, L.R.; Szczytko, R.; Bowers, E.P.; Stephens, L.E.; Stevenson, K.T.; Floyd, M.F. Outdoor Time, Screen Time, and Connection to Nature: Troubling Trends among Rural Youth? *Environ. Behav.* **2019**, *51*, 966–991.
14. Kahn, P.H.; Severson, R.L.; Ruckert, J.H. The Human Relation With Nature and Technological Nature. *Curr. Dir. Psychol. Sci.* **2009**, *18*, 37–42.
15. Levi, D.; Kocher, S. Virtual nature—The future effects of information technology on our relationship to nature. *Environ. Behav.* **1999**, *31*, 203–226.
16. Smith, J.W. Immersive Virtual Environment Technology to Supplement Environmental Perception, Preference and Behavior Research: A Review with Applications. *Int. J. Environ. Res. Public Health* 2015, **12** 11486–11505.
17. Calogiuri, G.; Litleskare, S.; MacIntyre, T.E. Future-thinking through technological nature: Connecting or disconnecting. In *Physical Activity in Natural Settings: Green and Blue Exercise*; Donnelly, A.A., MacIntyre, T.E., Eds.; Routledge: New York, NY, USA, 2019; pp. 279–298.
18. Loomis, J.M.; Blascovich, J.J.; Beall, A.C. Immersive virtual environment technology as a basic research tool in psychology. *Behav. Res. Methods Instrum. Comput.* **1999**, *31*, 557–564.
19. Bratman, G.N.; Hamilton, J.P.; Daily, G.C. The impacts of nature experience on human cognitive function and mental health. *Year Ecol. Conserv. Biol.* **2012**, *1249*, 118–136.
20. Pretty, J.N.; Griffin, M.; Sellens, M.; Pretty, C. *Green Exercise: Complementary Roles of Nature, Exercise and Diet in Physical and Emotional Well-Being and Implications for Public Health Policy*; University of Essex: Colchester, UK, 2003.
21. Shanahan, D.F.; Astell-Burt, T.; Barber, E.A.; Brymer, E.; Cox, D.T.C.; Dean, J.; Depledge, M.; Fuller, R.A.; Hartig, T.; Irvine, K.N.. Nature-Based Interventions for Improving Health and Wellbeing: The Purpose, the People and the Outcomes. *Sports* **2019**, *7*, 141.
22. Sherman, W.R.; Craig, A.B. *Understanding Virtual Reality. Interface, Application, and Design*; Barsky. B.A., Ed.; Morgan Kaufmann Publishers: San Fransisco, CA, USA, 2003.
23. Azuma, R.; Baillot, Y.; Behringer, R.; Feiner, S.; Julier, S.; MacIntyre, B. Recent advances in augmented reality. *IEEE Comput. Graph. Appl.* **2001**, *21*, 34–47.
24. Slater, M.; Wilbur, S. A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments. *Presence Teleoper. Virtual Environ.* **1997**, *6*, 603–616.
25. Bowman, D.A., McMahan, R.P. Virtual reality: How much immersion is enough? *Computer* **2007**, *40*, 36–43.
26. Botella, C.; Fernández-Álvarez, J.; Guillén, V.; Garciá-Palacios, A.; Baños, R. Recent Progress in Virtual Reality Exposure Therapy for Phobias: A Systematic Review. *Curr. Psychiatry Rep.* **2017**, *19*, 42.
27. Steuer, J. Defining Virtual Reality—Dimensions Determining Telepresence. *J. Commun.* **1992**, *42*, 73–93.
28. Triberti, S.; Repetto, C.; Riva, G. Psychological factors influencing the effectiveness of virtual reality-based analgesia: A systematic review. *Cyberpsychol. Behav. Soc. Netw.* **2014**, *17*, 335–45.
29. Liszio, S.; Graf, L.; Masuch, M. The Relaxing Effect of Virtual Nature: Immersive Technology Provides Relief in Acute Stress Situations. *Annu. Rev. Cyberther. Telemed.* **2018**, *16*, 87–93.
30. Kennedy, R.S.; Drexler, J.; Kennedy, R.C. Research in visually induced motion sickness. *Appl. Ergon.* **2010**, *41*, 494–503.
31. Reason, J.T.; Brand, J.J. *Motion Sickness*; Academic Press: Cambridge, MA, USA, 1975.

32. Allen, B.; Hanley, T.; Rokers, B.; Grees, C.S. Visual 3D motion acuity predicts discomfort in 3D stereoscopic environments. *Entertain. Comput.* **2016**, *13*, 1–9.
33. Clifton, J.; Palmisano, S. Effects of steering locomotion and teleporting on cybersickness and presence in HMD-based virtual reality. *Virtual Real.* **2019**, doi:10.1007/s10055-019-00407-8.
34. Litleskare, S.; Calogiuri, G. Camera Stabilization in 360 degrees Videos and Its Impact on Cyber Sickness, Environmental Perceptions, and Psychophysiological Responses to a Simulated Nature Walk: A Single-Blinded Randomized Trial. *Front. Psychol.* **2019**, *10*, 2436.
35. Merhi, O.; Faugloire, E.; Flanagan, M.; Stoffregen, T. Motion sickness, console video games, and head-mounted displays. *Hum. Factors* **2007**, *49*, 920–934.
36. Murata, A. Effects of duration of immersion in a virtual reality environment on postural stability. *Int. J. Hum. Comput. Interact.* **2004**, *17*, 463–477.
37. Sharples, S.; Cobb, S.; Moody, A.; Wilson, J.R. Virtual reality induced symptoms and effects (VRISE): Comparison of head mounted display (HMD), desktop and projection display systems. *Displays* **2008**, *29*, 58–69.
38. Weech, S.; Kenny, S.; Barnett-Cowan, M. Presence and Cybersickness in Virtual Reality Are Negatively Related: A Review. *Front. Psychol.* **2019**, *10*, 158.
39. Calogiuri, G.; Litleskare, S.; Fagerheim, K.A.; Rydgren, T.L.; Brambilla, E.; Thurston, M. Experiencing Nature through Immersive Virtual Environments: Environmental Perceptions, Physical Engagement, and Affective Responses during a Simulated Nature Walk. *Front. Psychol.* **2018**, *8*, 2321.
40. Duzmanska, N.; Strojny, P.; Strojny, A. Can Simulator Sickness Be Avoided? A Review on Temporal Aspects of Simulator Sickness. *Front. Psychol.***2018**, *9*, 2132.
41. Gavgani, A.M.; Nesbitt, K.V.; Blackmore, K.L.; Nalivaiko, E. Profiling subjective symptoms and autonomic changes associated with cybersickness. *Auton. Neurosci.* **2017**, *203*, 41–50.
42. Frumkin, H.; Bratman, G.N.; Breslow, S.J.; Cochran, B.; Kahn, P.H.; Lawler, J.J.; Levin, P.S.; Tandon, P.S.; Varanasi, U.; Wolf, K.L; et al. Nature Contact and Human Health: A Research Agenda. *Environ. Health Perspect.* **2017**, *125*, 075001.
43. Olafsdottir, G.; Cloke, P.; Vogele, C. Place, green exercise and stress: An exploration of lived experience and restorative effects. *Health Place* **2017**, *46*, 358–365.
44. Plante, T.G.; Cage, G.; Clements, S.; Stover, A. Psychological benefits of exercise paired with virtual reality: Outdoor exercise energizes whereas indoor virtual exercise relaxes. *Int. J. Stress Manag.* **2006**, *13*, 108–117.
45. Fuegen, K.; Breitenbecher, K.H. Walking and Being Outdoors in Nature Increase Positive Affect and Energy. *Ecopsychology* **2018**, *10*, 14–25.
46. Gatersleben, B.; Andrews, M. When walking in nature is not restorative-the role of prospect and refuge. *Health Place* **2013**, *20*, 91–101.
47. Kjellgren, A.; Buhrkall, H. A comparison of the restorative effect of a natural environment with that of a simulated natural environment. *J. Environ.Psychol.* **2010**, *30*, 464–472.
48. Lahart, I.; Darcy, P.; Gidlow, C.; Calogiuri, G. The Effects of Green Exercise on Physical and Mental Wellbeing: A Systematic Review. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1352.
49. Chirico, A.; Gaggioli, A. When Virtual Feels Real: Comparing Emotional Responses and Presence in Virtual and Natural Environments. *Cyberpsychol. Behav. Soc. Netw.* **2019**, *22*, 220–226.
50. Yu, C.P.; Lee, H.Y.; Luo, X.Y. The effect of virtual reality forest and urban environments on physiological and psychological responses. *Urban For. Urban Green.* **2018**, *35*, 106–114.
51. Browning, M.H.E.M.; Mimnaugh, K.et al. Can Simulated Nature Support Mental Health? Comparing Short, Single-Doses of 360-Degree Nature Videos in Virtual Reality with the Outdoors. *Front. Psychol.* **2019**, doi:10.3389/fpsyg.2019.02667.
52. Kuo, M. How might contact with nature promote human health? Promising mechanisms and a possible central pathway. *Front. Psychol.* **2015**, *6*, 1093.
53. Chirico, A.; Lucidi, F.; De Laurentiis, M.; Milanese, C.; Napoli, A.; Giordano, A. Virtual Reality in Health System: Beyond Entertainment. A Mini-Review on the Efficacy of VR During Cancer Treatment. *J. Cell. Physiol.* **2016**, *231*, 275–287.
54. White, M.P.; Yeo, N. L; Vassiljev, P.; Lundstedt, R.; Wallergård, M.; Albin, M.; Lõhmus, M. A prescription for "nature"—the potential of using virtual nature in therapeutics. *Neuropsychiatr. Dis. Treat.* **2018**, *14*, 3001–3013.

55. Dascal, J.; Reid, M.; IsHak, W.W.; Spiegel,B.; Recacho,J.; Rosen,B.; Danovitch, I. Virtual Reality and Medical Inpatients: A Systematic Review of Randomized, Controlled Trials. *Innov. Clin. Neurosci.* **2017**, *14*, 14–21.
56. European Agency for Safety and Health at Work. *Psychosocial Risks and Stress at Work*; Bilbao, Spain, 2018. Avaible online: https://osha.europa.eu/en/themes/psychosocial-risks-and-stress (Assesd on 25 February 2020).
57. McSweeney, J.; Rainham, D.G.C.; Johnson, S.A.; Sherry, S,B.; Singelton, J. Indoor nature exposure (INE): A health-promotion framework. *Health Promot. Int.* **2015**, *30*, 126–139.
58. Hedblom, M.; Gunnarsson, B.; Iravani, B.; Knez, I.; Schaefer, M; Thorsson, P.; Lundstrom, J.N. Reduction of physiological stress by urban green space in a multisensory virtual experiment. *Sci. Rep.* **2019**, *9*, 1–11.
59. Plante, T.G.; Frazier, S.; Tittle, A.; Babula, M.; Ferlic, E.; Riggs, E. Does virtual reality enhance the psychological benefits of exercise? *J. Hum. Mov. Stud.* **2003**, *45*, 485–507.
60. Valtchanov, D.; Barton, K.R.; Ellard, C. Restorative Effects of Virtual Nature Settings. *Cyberpsychol. Behav. Soc. Netw.* **2010**, *13*, 503–512.
61. Mennis, J.; Mason, M.; Ambrus, A. Urban greenspace is associated with reduced psychological stress among adolescents: A Geographic Ecological Momentary Assessment (GEMA) analysis of activity space. *Landsc. Urban Plan.* **2018**, *174*, 1–9.
62. Barton, J.; Bragg, R.; Pretty, J.; Roberts, J.; Wood, C. The Wilderness Expedition: An Effective Life Course Intervention to Improve Young People’s Well-Being and Connectedness to Nature. *J. Exp. Educ.* **2016**, *39*, 59–72.
63. Swami, V.; Barron, D.; Furnham, A. Exposure to natural environments, and photographs of natural environments, promotes more positive body image. *Body Image* **2018**, *24*, 82–94.
64. Wood, C.; Sandercock, G.R.; Barton, J. Interactions between physical activity and the environment to improve adolescent self-esteem: A randomised controlled trial. *Int. J. Environ. Health* **2014**, *7*, 144–155.
65. Thompson, C.W.; Aspinall, P.; Montarzino, A. The childhood factor—Adult visits to green places and the significance of childhood experience. *Environ. Behav.* **2008**, *40*, 111–143.
66. Chung, K.; Lee, D.; Park, J.Y. Involuntary Attention Restoration During Exposure to Mobile-Based 360 degrees Virtual Nature in Healthy Adults With Different Levels of Restorative Experience: Event-Related Potential Study. *J. Med. Internet Res.* **2018**, *20*, e11152.
67. Parsons, T.D.; Riva, G.; Parsons, S.; Mantovani, F.; Newbutt, N.; Lin, L.; Venturini, E.; Hall, T. Virtual Reality in Pediatric Psychology. *Pediatrics* **2017**, *140*, S86–S91.
68. Gavarkovs, A.G. Nature-based physical activity advertising: Recommendations based on attention restoration theory and psychoevolutionary Theory. *WURJ Health Nat. Sci.* **2016**, *6*, doi:10.5206/wurjhns.2015-16.4.
69. Demontis, G.C.; Germani, M.M.; Caiani, E.G.; Barravecchia, I.; Passino, C.; Angeloni, D. Human Pathophysiological Adaptations to the Space Environment. *Front. Physiol.* **2017**, *8*, 547.
70. Guillot, A.; Debarnot, U. Benefits of Motor Imagery for Human Space Flight: A Brief Review of Current Knowledge and Future Applications. *Front. Physiol.* **2019**, *10*, 396.
71. Beery, T.H. Nordic in nature: Friluftsliv and environmental connectedness. *Environ. Educ. Res.* **2013**, *19*, 94–117.
72. Nisbet, E.K.; Zelenski, J.M.; Murphy, S.A. The Nature Relatedness Scale Linking Individuals’ Connection With Nature to Environmental Concern and Behavior. *Environ. Behav.* **2009**, *41*, 715–740.
73. Pyky, R.; Neuvonen, M.; Kangas, K.; Ojala, A.; Lanki, T.; Borodulin, K.; Tyrvainen, L. Individual and environmental factors associated with green exercise in urban and suburban areas. *Health Place* **2019**, *55*, 20–28.
74. Giusti, M.; Barthel, S.; Marcus, L. Nature Routines and Affinity with the Biosphere: A Case Study of Preschool Children in Stockholm. *Child. Youth Environ.* **2014**, *24*, 16–42.
75. Whitburn, J.; Linklater, W.L.; Milfont, T.L. Exposure to Urban Nature and Tree Planting Are Related to Pro-Environmental Behavior via Connection to Nature, the Use of Nature for Psychological Restoration, and Environmental Attitudes. *Environ. Behav.* **2018**, *51*, 787–810.
76. Mayer, F.S.; Frantz, C.M.; Bruehlman-Senecal, E.; Dolliver, K. Why Is Nature Beneficial? The Role of Connectedness to Nature. *Environ. Behav.* **2009**, *41*, 607–643.
77. Calogiuri, G.; Chroni, S. The impact of the natural environment on the promotion of active living: An integrative systematic review. *BMC Public Health* **2014**, *14*, 873.

78. Ajzen, I. The Theory of Planned Behavior. *Organ. Behav. Hum. Decis. Process.* **1991**, *50*, 179–211.
79. Kesim, M.; Ozarslan, Y. Augmented reality in education: Current technologies and the potential for education. *Procedia Soc. Behav. Sci.***2012**, *47*, 297–302.
80. Kounavis, C.D.; Kasimati, A.E.; Zamani, E.D. Enhancing the Tourism Experience through Mobile Augmented Reality. *Int. J. Eng. Bus. Manag.* **2012**, *4*, 10.
81. Kamarainen, A.M.; Metcalf, F.; Grotzer, T.; Browne, A.; Mazzuca, D.; Tutwiler, M. S.; Dede, C. EcoMOBILE: Integrating augmented reality and probeware with environmental education field trips. *Comput. Educ.* **2013**, *68*, 545–556.
82. Ryokai, K.; Agogino, A. Off the paved paths: Exploring nature with a mobile augmented reality learning tool. *Int. J. Mob. Hum. Comput. Interact.* **2013**, *5*, 21–49.
83. Bryant, F.B.; Veroff, J. *Savoring: A New Model of Positive Experience*; Psychology Press: New York, NY, USA, 2017.
84. Deterding, S.; Dixon, D.; Khaled, R.; Nacke, L. From Game Design Elements to Gamefulness: Defining Gamification. In Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments, Tampere, Finland, 29–30 September 2011; ACM, New York, NY, USA: 2011.
85. Dicheva, D.; Dichev, C.; Agre, G.; Angelova, G. Gamification in Education: A Systematic Mapping Study. *Educ. Technol. Soc.* **2015**, *18*, 75–88.
86. Edwards, E.A.; Lumsden, J.; Rivas, C.; Steed, L.; Edwards, L.A.; Thiyagarajan, A.; Sohanpal, R.; Caton, H.; Griffits, C.J.; Munafo, M.R.; et al. Gamification for health promotion: Systematic review of behaviour change techniques in smartphone apps. *BMJ Open* **2016**, *6*, e012447.
87. MacIntyre, T.E.; Gidlow, C.; Baronian, M.; Nieuwen-huijsen, M.; Collier, M.; Gritzka, S.; Warrington, G. Nature-based solutions and interventions in cities: a look ahead. In *Physical Activity in Natural Settings: Green and Blue Exercise*; Donnelly, A.A., MacIntyre, T.E., Eds.; Routledge: New York, NY, USA, 2019; pp. 335–348.
88. Chalmers, T.C.; Smith, H.; Blackburn, B.; Silverman, B.; Schroeder, B.; Reitman, D.; Ambroz, A. A method for assessing the quality of a randomized control trial. *Control Clin. Trials* **1981**, *2*, 31–49.
89. Whitehead, W.E. Control groups appropriate for behavioral interventions. *Gastroenterology* **2004**, *126*, S159–S163.
90. Ekkekakis, P.; Parfitt, G.; Petruzzello, S.J. The Pleasure and Displeasure People Feel When they Exercise at Different Intensities Decennial Update and Progress towards a Tripartite Rationale for Exercise Intensity Prescription. *Sports Med.* **2011**, *41*, 641–671.
91. Wilson, T.D.; Reinhard, D.A.; Westgate, E.C.; Gilbert, D.T.; Ellerbeck, N.; Hahn, C.; Brown, C.L.; Shaked, A . Just think: The challenges of the disengaged mind. *Science* **2014**, *345*, 75–77.
92. Anderson, A.P.; Mayer, M.D.; Fellows, A.M.; Cowan, D.R.; Hegel, M.T.; Buckey, J.C. Relaxation with Immersive Natural Scenes Presented Using Virtual Reality. *Aerosp. Med. Hum. Perform.* **2017**, *88*, 520–526.
93. Ulrich, R.S. Aesthetic and affective response to natural environment. In *Behavior and the Natural Environment*; Altman, E. Wohlwill, J.F., Eds.; Springer: New York, NY, USA, 1983; pp. 85–125.
94. Kaplan, S. The Restorative Benefits of Nature—Toward an Integrative Framework. *J. Environ. Psychol.* **1995**, *15*, 169–182.
95. Han, K.T. Responses to six major terrestrial biomes in terms of scenic beauty, preference, and restorativeness. *Environ. Behav.* **2007**, *39*, 529–556.
96. van Esch, E.; Minjock, R.; Colarelli, S.M.; Hirsch, S. Office window views: View features trump nature in predicting employee well-being. *J. Environ. Psychol.* **2019**, *64*, 56–64.
97. Keniger, L.E.; Gaston, K.J.; Irvine, K.N.; Fuller, R.A. What are the Benefits of Interacting with Nature? *Int. J. Environ. Res. Public Health* **2013**, *10*, 913–935.
98. Depledge, M.H.; Stone, R.J.; Bird, W.J. Can Natural and Virtual Environments Be Used To Promote Improved Human Health and Wellbeing? *Environ. Sci. Technol.* **2011**, *45*, 4660–4665.
99. Rebenitsch, L.; Owen, C. Review on cybersickness in applications and visual displays. *Virtual Real.* **2016**, *20*, 101–125.
100. Somrak, A.; Humar, I.; Hossain, M.S.; Alhamid, M.F.; Hossain, M.A.; Guna, J. Estimating VR Sickness and user experience using different HMD technologies: An evaluation study. *Future Gener. Comput. Syst. Int. J. Esci.* **2019**, *94*, 302–316.
101. Blum, J.; Rockstroh, C.; Goritz, A.S. Heart Rate Variability Biofeedback Based on Slow-Paced Breathing With Immersive Virtual Reality Nature Scenery. *Front. Psychol.* **2019**, *10*, 2172.

102. Bonato, F.; Bubka, A.; Paumisano, S. Combined Pitch and Roll and Cybersickness in a Virtual Environment. *Aviat. Space Environ. Med.* **2009**, *80*, 941–945.
103. Lo, W.T.; So, R.H. Cybersickness in the presence of scene rotational movements along different axes. *Appl. Ergon.* **2001**, *32*, 1–14.
104. Hromatka, B.S.; Tung, J.Y.; Kiefer, A.K. ; Do, C.B. ; Hinds, D.A. ; Eriksson, N . Genetic variants associated with motion sickness point to roles for inner ear development, neurological processes and glucose homeostasis. *Hum. Mol. Genet.* **2015**, *24*, 2700–2708.
105. Munafo, J.; Diedrick, M.; Stoffregen, T.A. The virtual reality head-mounted display Oculus Rift induces motion sickness and is sexist in its effects. *Exp. Brain Res.* **2017**, *235*, 889–901.
106. Caramenti, M.; Lafortuna, C.L.; Mugellini, E.; Khaled, O.A.; Bresciani, J.P. Dubois, A. Regular physical activity modulates perceived visual speed when running in treadmill-mediated virtual environments. *PLoS ONE* **2019**, *14*, e0219017.
107. Ishigaki, H.; Miyao, M. Differences in Dynamic Visual-Acuity between Athletes and Nonathletes. *Percept. Mot. Skills* **1993**, *77*, 835–839.
108. Christenson, G.N.; Winkelstein, A.M. Visual skills of athletes versus nonathletes: Development of a sports vision testing battery. *J. Am. Optom. Assoc.* **1988**, *59*, 666–675.
109. Savelsbergh, G.J.P.; Williams, A.M. ; Van Der Kamp, J. Ward, P. Visual search, anticipation and expertise in soccer goalkeepers. *J. Sports Sci.* **2002**, *20*, 279–287.
110. Senese, V.P.; Pascale, A.; Maffei, L.; Cioffi, F.; Sergi, I.; Gnisci, A.; Masullo, M. The Influence of Personality Traits on the Measure of Restorativeness in an Urban Park: A Multisensory Immersive Virtual Reality Study. In *Neural Approaches to Dynamics of Signal Exchanges*; Esposito, A., Faundez-Zanuy, M.; Morabito, F.C.; Pasero, E., Eds.; Springer: Singapore, 2020.
111. Kober, S.E.; Neuper, C. Personality and Presence in Virtual Reality: Does Their Relationship Depend on the Used Presence Measure? *Int. J. Hum. Comput. Interact.* **2013**, *29*, 13–25.
112. Nisbet, E.K.; Zelenski, J.M. The NR-6: A new brief measure of nature relatedness. *Front. Psychol.* **2013**, *4*, 813.
113. Flowers, E.P.; Freeman, P.; Gladwell, V.F. The Development of Three Questionnaires to Assess Beliefs about Green Exercise. *Int. J. Environ. Res. Public Health* **2017**, *14*, 1172.
114. Hopp, T.; Gangadharbatla, N. Novelty Effects in Augmented Reality Advertising Environments: The Influence of Exposure Time and Self-Efficacy. *J. Curr. Issues Res. Advert.* **2016**, *37*, 113–130.
115. Merchant, Z.; Goetz, E.T.; Cifuentes, L.; Keeney-Kennicutt, W.; Davis, T.J. Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-analysis. *Comput. Educ.* **2014**, *70*, 29–40.
116. Annerstedt, M.; Jonsson, P.; Wallergård, M.; Johansson, G.; Karlson, B.; Grahn, P.; Hansen, Å.M.; Wahrborg, P. Inducing physiological stress recovery with sounds of nature in a virtual reality forest—Results from a pilot study. *Physiol. Behav.* **2013**, *118*, 240–250.
117. Cassina, L.; Fredianelli, L.; Menichini, I.; Chiari, C.; Licitra, G. Audio-Visual Preferences and Tranquillity Ratings in Urban Areas. *Environments* **2018**, *5*, 1.
118. Aletta, F.; Oberman, T.; Kang, J. Associations between Positive Health-Related Effects and Soundscapes Perceptual Constructs: A Systematic Review. *Int. J. Environ. Res. Public Health* **2018**, *15*, 2392.
119. Erfanian, M.; Mitchell, A.J.; Kang, J.; Aletta, F. The Psychophysiological Implications of Soundscape: A Systematic Review of Empirical Literature and a Research Agenda. *Int. J. Environ. Res. Public Health* **2019**, *16*, 3533.
120. Jeon, J.Y.; Lee, P.J.; You, J.; Kang, J. Perceptual assessment of quality of urban soundscapes with combined noise sources and water sounds. *J. Acoust. Soc. Am.* **2010**, *127*, 1357–66.
121. Hong, J.Y.; Lam, B.; Ong, Z-T.; Ooi, K.; Gan, W-S.; Kang, J.; Feng, J.; Tan, S-T. Quality assessment of acoustic environment reproduction methods for cinematic virtual reality in soundscape applications. *Build. Environ.* **2019**, *149*, 1–14.

Appendix: Paper V

Litleskare, S., Fröhlich, F., Flaten, O. E., Haile, A., Johnsen, S. Å. K., & Calogiuri, G. Taking real steps in virtual nature: A randomized blinded trial. *Virtual reality*. https://doi.org/10.1007/s10055-022-00670-2

Virtual Reality
https://doi.org/10.1007/s10055-022-00670-2

ORIGINAL ARTICLE

Taking real steps in virtual nature: a randomized blinded trial

Sigbjørn Litleskare[1] · **Fred Fröhlich**[2] · **Ole Einar Flaten**[2] · **Amelia Haile**[1] · **Svein Åge Kjøs Johnsen**[3] · **Giovanna Calogiuri**[1,4]

Received: 22 December 2021 / Accepted: 8 June 2022

Abstract
Studies show that green exercise (i.e., physical activity in the presence of nature) can provide the synergistic psychophysiological benefits of both physical exercise and nature exposure. The present study aimed to investigate the extent to which virtual green exercise may extend these benefits to people that are unable to engage in active visits to natural environments, as well as to promote enhanced exercise behavior. After watching a video validated to elicit sadness, participants either performed a treadmill walk while exposed to one of two virtual conditions, which were created using different techniques (360° video or 3D model), or walked on a treadmill while facing a blank wall (control). Quantitative and qualitative data were collected in relation to three overarching themes: "Experience," "Physical engagement" and "Psychophysiological recovery." Compared to control, greater enjoyment was found in the 3D model, while lower walking speed was found in the 360° video. No significant differences among conditions were found with respect to heart rate, perceived exertion, or changes in blood pressure and affect. The analysis of qualitative data provided further understanding on the participants' perceptions and experiences. These findings indicate that 3D model-based virtual green exercise can provide some additional benefits compared to indoor exercise, while 360° video-based virtual green exercise may result in lower physical engagement.

Keywords Green exercise · Virtual reality · Immersive virtual environments · Virtual green exercise · Mixed-methods

1 Introduction

1.1 The salutogenic effects of nature and green exercise

Research has shown that exposure to natural environments is important for human health and well-being. A recent study estimated that individuals who spend at least 120 min in contact with nature during a regular week achieve significant improvements of health and well-being (White et al. 2019). In this regard, green exercise (any physical activity in presence of nature; Pretty et al. 2003) is considered particularly beneficial, as one may combine the benefits of nature exposure with the benefits of physical activity. Compared to physical activity taking place indoors or urban settings, green exercise can provide more positive effects on indicators of exercise experience, physical engagement and psychophysiological recovery, for example: higher levels of enjoyment (Focht 2009), reduced sense of perceived exertion (Calogiuri et al. 2015; Harte and Eifert 1995), increased exercise intensity (Mieras et al. 2014), reduced blood pressure (Pretty et al. 2005), cognitive restoration (Kajosaari and Pasanen 2021), and improved mood or affect state (Calogiuri et al. 2015; Focht 2009; Hartig et al. 2003; Lacharité-Lemieux et al. 2015). There is still some debate regarding the underlaying mechanisms for the additional benefits of green exercise, but the recent theoretical framework by Rogerson et al. (2019) suggest that the psychological benefits associated with nature exposure (e.g., reduced mental-fatigue) interact with the physiological effects of exercise (e.g., reduced cortisol levels), eliciting additional health benefits

---

✉ Sigbjørn Litleskare
sigbjorn.litleskare@inn.no

[1] Department of Public Health and Sport Sciences, Inland Norway University of Applied Sciences, Elverum, Norway

[2] Game School–Department of Game Development, Inland Norway University of Applied Sciences, Hamar, Norway

[3] Department of Psychology, Inland Norway University of Applied Sciences, Lillehammer, Norway

[4] Department of Nursing and Health Sciences, Centre for Health and Technology, University of South-Eastern Norway, Drammen, Norway

compared to when these two stimuli occur independently (Rogerson et al. 2019). According to this framework, such psychological and physiological benefits support health by intertwining with behavioral factors, so that the resulting psychophysiological benefits shape exercise behavior, for example leading to higher exercise intensity (Mieras et al. 2014) and encouraging long-term exercise participation (Calogiuri and Chroni 2014). Unfortunately, because of a variety of reasons, including poor accessibility to safe and physical activity-supportive natural environments, challenging weather conditions, and individual barriers such as poor health, many people may not have the possibility to regularly engage in green exercise. For instance, a English study found that only about 20% of the population engaged in green exercise sessions of at least 30 min at least once during a regular week (White et al. 2016), while a Norwegian study found that about half of the population engaged in green exercise for at least one hour during a regular week (Calogiuri et al. 2016).

1.2 Virtual green exercise

Virtual green exercise is defined as physical activity while being exposed to virtual representations of nature (Litleskare et al. 2020). Virtual green exercise aims to extend the benefits of nature exposure and green exercise to people that are unable to engage in active visits to real nature, such as residents in health care facilities or people with limited accessibility to natural environments, as well as to promote health through enhanced physical activity and nature exposure (Litleskare et al. 2020). For this reason, virtual green exercise received increased attention within healthcare (White et al. 2018). A recent integrative analysis by Calogiuri et al. (2021) proposed that virtual green exercise may provide health benefits in line with the framework proposed by Rogerson et al. (2019). In particular, by adding the element of nature exposure, virtual green exercise could deliver psychophysiological (e.g., cognitive restoration, mood enhancement and stress relief) and behavioral (e.g., enhanced exercise output) benefits above and beyond indoor exercise. The integrative analysis by Calogiuri et al. (2021), however, highlighted that, to date, the evidence regarding health benefits of virtual green exercise is still in its infancy. Accordingly, a recent systematic analysis by Lahart et al. (2019) found no evidence of consistent psychological or physiological benefits of virtual green exercise compared to indoor exercise. This review, however, emphasized the fact that studies in this field was associated with a high risk of bias, and called for more rigorous experimental trials on this topic.

1.3 The issue of immersion and cybersickness

In the context of virtual green exercise, different types of technology have been used to create virtual representations of natural environments, including computer screens (see, e.g., Akers et al. 2012; Mayer et al. 2009; Pretty et al. 2005; White et al. 2015) and head-mounted displays (HMD; see, e.g., Alkahtani et al. 2019; Calogiuri et al. 2018; Chan et al. 2021). By enclosing the user within the virtual environment and replacing the sensory input from the real surroundings with sensory input from the virtual environment (Slater et al. 1995), HMDs are believed to be a more efficient tool compared to other displays, as they can provide higher levels of immersion (Joseph et al. 2020; Litleskare et al. 2020). Immersion is defined as a technology's capability of delivering an inclusive, extensive, surrounding, and vivid illusion of reality to the senses of a human participant (Slater and Wilbur 1997). Higher levels of immersion are believed to improve the VR experience as it contributes to increased levels of presence, i.e., the subjective feeling of being within the virtual environment (Slater and Wilbur 1997), ideally to such a degree that the virtual environment feels more real than the actual surroundings. Presence is considered a key element for the success of a virtual natural environment (Litleskare et al. 2020). In support of these assumptions, studies show that exposures to virtual representations of nature through HMDs can provides greater relaxation and stress relief compared to non-immersive technologies (Knaust et al. 2021; Liszio et al. 2018).

Unfortunately, highly immersive displays are also more prone to cybersickness (Chang et al. 2020; Guna et al. 2019; LaViola 2000; Sharples et al. 2008; Yildirim 2020). Cybersickness is considered a specific type of motion sickness and is known to cause symptoms such as dizziness, nausea and general discomfort (Kennedy et al. 2010; Smith 2015). The etiology of cybersickness is still unclear, but the two most prominent theories suggest that it is caused by either sensory conflict (Oman 1990; Reason 1978) or postural instability (Riccio and Stoffregen 1991) during VR immersion. Cybersickness may have a severe negative impact on experiences in VR and hamper the users' feelings of presence (Weech et al. 2019) as well as distort research findings (Calogiuri et al. 2018). Recent research provides some insight into how to alleviate the issue of cybersickness. Synchronizing the treadmill speed with the optical flow (Chang et al. 2020; Saredakis et al. 2020) and minimizing scene oscillations (Litleskare and Calogiuri 2019) has been shown to reduce the severity of cybersickness.

1.4 Challenges associated with virtual green exercise

The use of HMDs in studies of green exercise is considered a challenging endeavor, due to increased risk of inducing cybersickness in dynamic VR content, as well as the challenge of maintaining upright balance during virtual exercise (Joseph et al. 2020; Litleskare et al. 2020). To the best of the authors' knowledge, only three published studies have been conducted on the effects of a dynamic virtual green exercise simulation using a HMD with a full field of view (Alkahtani et al. 2019; Calogiuri et al. 2018; Chan et al. 2021). Calogiuri et al. (2018) compared a real green exercise bout with a virtual homologue while simultaneously walking on a manually driven treadmill. While participants rated the two environments with equal levels of environmental restorativeness and spontaneously walked at the same pace in both conditions, the experience was severely influenced by cybersickness, which was associated with a decrement of participants' affect and an increased sense of effort compared to the real green exercise bout (Calogiuri et al. 2018). Alkahtani et al. (2019) compared two high-intensity interval cycling sessions, with and without exposure to a video montage of natural scenes. The study found no significant differences between the two sessions for mood, thought there was some indication of greater psychological distress in the virtual green exercise condition (Alkahtani et al. 2019), possibly related to cybersickness. Chan et al. (2021) examined changes in mood, nature connectedness, and heart-rate variability in both young adults and elderly exposed to a virtual natural environment or a virtual urban environment, which they could navigate using a "walk in place" system. In this case, this study found that, compared with the virtual urban walk, virtual green exercise provided greater psychophysiological benefits.

1.5 The impact of developmental techniques on virtual green exercise experiences

While the existing literature provides mixed findings regarding the possibility to use HMDs for virtual green exercise purposes, these mixed findings also suggest that the characteristics of hardware, software, mode of locomotion etc. are important to overcome the issue of cybersickness and enhance the overall user's experience. In particular, the technique used to develop the VR scenery is emerging as an important factor influencing the experience. Mostly, two types of VR scenarios are uses for simulation nature experiences; 360° videos created using 360° cameras, or computer-generated virtual environments developed through three-dimensional (3D) modelling. The VR sceneries used in Calogiuri et al. (2018) and Alkahtani et al. (2019) consisted of 360° videos. As this technique reproduces photographic representations of actual environments, it can allow the creation of highly realistic virtual nature sceneries. On the other hand, a recent review have highlighted challenges associated with VR scenaries created using this technique, especially in relation to cybersickness (Saredakis et al. 2020). In recent years, 3D models based on video game development techniques have emerged as an alternative to 360° videos when creating representations of natural elements and landscapes. Advances within this field allow for creation of 3D models containing representations of nature that can achieve high levels of realism. Studies using this type of VR sceneries in the context of virtual green exercise have reported positive psychophysiological responses as demonstrated by Chan et al. (2021). However, to the best of the authors' knowledge, only two studies have directly compared 360° videos with matching (or similar) 3D models. Nukarinen et al. (2020), compared physiological and psychological responses associated with exposure to a static 360° video of a forest versus a matching 3D model, with a third experimental condition in the real natural environment being also included. While no direct differences were found between the two VR conditions for any of the tested parameters, the study found a significant greater reduction in negative affect in the real nature condition as compared with the 360° video exposure, while such difference was not observed for the 3D model. Yeo et al. (2020) compared psychological responses associated with exposure to a static 360° video versus a 3D model, both showing a sequence of underwater tropical coral reef scenes. The findings of this study indicated equivalent effects of both VR sceneries for all psychological parameters included except for positive affect, which showed greater improvements in the 3D model as compared with the 360° video. In conclusion, although some evidence suggests that a sedentary exposure to a 3D model may elicit more positive affective responses than those elicited by 360° videos (Nukarinen et al. 2020; Yeo et al. 2020), such evidence is limited.

1.6 The present study

The purpose of the present study was two-fold. Firstly, the study examined the participants' perceptions and experiences associated with two virtual green exercise experiences created using different techniques (i.e., 360° video and 3D modeling) as compared to treadmill walking without VR exposure. Secondly, the study investigated the extent to which the two virtual green exercise conditions could elicit greater physical engagement and psychophysiological recovery compared to treadmill walking without VR exposure. By collecting and analyzing quantitative and qualitative information, the study was set to provide both statistical evidence in the context of a blinded experiment and in-depth understanding of the participants perceptions and experience.

2 Materials and methods

This paper is structured in line with the CONSORT guidelines and the trial was pre-registered at ISRCTN (trial ID: ISRCTN14275608).

2.1 Trial design

The study was designed as a double-blinded experimental trial with three parallel groups (Fig. 3) to reduce the impact of carry-over- and expectancy effects (Litleskare et al. 2020). The parallel group design is generally the recommended design for this type of VR study (Joseph et al. 2020; Litleskare et al. 2020). Participants were randomly assigned (picked from a hat) to one of the three experimental conditions. To minimize the expectancy effect in both the participants and the examiner, the randomization was performed after the baseline- and pre-exposure assessments (Fig. 1), meaning the participants and the examiner were blinded to the allocated condition during assessments at baseline and pre exposure, but not post exposure. The experiment was performed at a Sport Physiology Laboratory with standardized temperature (18 °C), ventilation, and lighting, and a high degree of sound insulation. No changes to methods were made after trial commencement.

2.2 Participants

Estimation of required sample size was performed using the G*Power software, based on expected effect size for negative affect, which previous research has found to be a sensitive measure for detecting impacts of virtual nature (Frost et al. 2022; Yeo et al. 2020). The expected effect size was set as medium ($f = 0.25$), as previous research suggests that the typical effect of real green exercise on negative affect is equivalent of a medium effect size or larger (Lahart et al. 2019). Alpha was set to 0.05 and power was set to 90%. The optimal sample size was estimated to be 54 participants. Six additional participants were recruited to account for possible missing data. Participants ($n = 60$) were recruited via announcements on Facebook, the university's official webpage, and by word of mouth. All participants were required to be 18 years or older, have normal or corrected to normal sight and without any diagnose of balance impairments. The study was approved by the Regional Ethics Committee for Medical and Health Research (ref. number 134663) and was performed according to the Declaration of Helsinki. The participants were informed about the purpose of the study and associated benefits and risks, before they gave their written consent to participate.

2.3 Experimental conditions and VR technology

Three conditions were tested: (i) 360° video exposure; (ii) 3D model exposure; and (iii) control condition (walking on treadmill while facing blank wall). The two VR conditions (360° video and 3D model) reproduced the same environment, i.e., a walk by a river (Fig. 1). Previous research has shown that an actual walk along this path, in the same season and similar weather conditions, elicited positive emotional responses (Calogiuri et al. 2018). Participants viewed a 2′50’’ film clip that is validated to elicit the feeling of sadness prior to exposure to one of the three experimental conditions (Rottenberg et al. 2007). The purpose of this film clip was to reduce individual variation in affect prior to the experimental conditions and to invoke a state were the restorative potential of virtual green exercise may transpire. In all conditions, the participants walked on a manually driven treadmill (Woodway curve, Woodway Inc., USA) for 10 min at self-selected speeds (the participants were instructed to walk at a comfortable pace and to hold on to the hand-rails of the treadmill to maintain balance) while wearing the HMD or facing the blank wall. The manual

Fig. 1 Snapshot from the 360° video (left) and the 3D model (right)

treadmill allowed participants to walk at a self-selected speed to increase ecological validity (Focht 2009), and to assess their behavioral response to the different experimental conditions and the corresponding psychophysiological effects. The exposure duration of 10 min was chosen to comply with the minimum time to elicit positive psychological outcomes of real green exercise (Meredith et al. 2020). The walking speed in both VR-conditions was synchronized with the speed of the manually driven treadmill by using a USB output from the treadmill to obtain the necessary data. Synchronizing the treadmill speed with the optical flow of the playback should reduce cybersickness (Chang et al. 2020; Saredakis et al. 2020). The playback was made via a HTC Vive Pro HMD (resolution of 2880 × 1600; refresh rate of 90 Hz) connected to a computer (Intel(R) i7-8700 k processor, 16 gigabytes of RAM, NVIDIA Geforce RTX 2080 graphics card), and Sony WH-1000X M3 noise canceling headphones (Sony Corporation, Tokyo, Japan). There was no VR control condition, as research shows that there is no difference between virtual control conditions and real control conditions (Yin et al. 2018).

The 360° video was developed using a GoPro Fusion 360° camera with a built-in stabilizer (5228 × 2624, resolution, 30 frames per second; GoPro, San Mateo, California, USA). Following the approach by Litleskare and Calogiuri (2019), the camera operator was moving along the path on a hover board (AAG, MADD gear electric, Victoria, USA) to improve the stability of the recording which should reduce cybersickness severity (Litleskare and Calogiuri 2019). The video was then run through a post-production editing process. First, the video was edited in the GoPro Fusion Studio (GoPro Inc., California, USA) to apply the Full Stabilization filter, which locks the orientation of the camera on the horizon. The edited video was imported to Adobe Premiere Pro (Adobe Systems, California, USA) to adjust the colors for a more realistic look compared to the slightly over-saturated raw video clip. The 3D model was created using photogrammetry techniques and assembled for real time playback in Unreal Engine 4.22 (Epic Games, Cary, North Carolina, USA). A high-resolution digital terrain model obtained from hoydedata.no served as the basis to accurately recreate the general landscape, elevation, and horizon. The path and immediate surroundings were scanned with a drone in 4 K resolution (Phantom 4 Pro UAV, DJI, Shenzhen, China). The 3D model was reconstructed from the aerial drone photographs with the photogrammetry software RealityCapture (Capturing Reality, Bratislava, Slovakia). The photogrammetry data was optimized for real time playback, and the retopologizing and UV mapping was done using the software 3D Coat version 4.8 (Pilgway, Kiev, Ukraine). Other objects like lamps and trash bins were reconstructed with photo references using the digital content creation application Maya (Autodesk, San Rafael, California, USA). Bushes and grass models are based on purchased presets from SpeedTree (Interactive Data Visualization Inc., Lexington, South Carolina, USA). The optimized 3D assets were imported into Unreal Engine where a lighting model was created to match the geolocation. Due to performance issues, some minor elements from the real location were not recreated in the 3D model (e.g., grass/foliage by the river, see Fig. 1). A surround microphone that captures sound in four channels simultaneously was used to record sounds along the path (Zoom H2, Zoom Corporation, Chiyoda-ku, Japan). This soundtrack was used for both the 360° video and the 3D model played back in full surround sound based on spatial audio and the users head movement.

To adhere to current recommendations regarding descriptions of the specific elements present in the environment (Browning et al. 2020a, b), two videos of our prototype environments were uploaded to YouTube (https://www.youtube.com/watch?v=hK3vzKaHDao and https://www.youtube.com/watch?v=8VKzMnU9Tno). Although the content of the environments is representative of the final version, the experimental setting, procedures, and conditions are not.

2.4 Instruments

2.4.1 Experience

Enjoyment – The participants level of enjoyment was assessed after the experimental condition using the following inquiry: "on a scale from 1 to 10, how enjoyable was the activity you engaged in?" This measure has previously been used in studies examining affective responses to green exercise (Calogiuri et al. 2015, 2018).

Perceived environmental restorativeness – The perceived restorativeness scale (PRS; Hartig et al. 1997; 2003) was used as a measure of (virtual) environmental qualities that may lead to psychological restoration. This scale consists of 16 items assessing the subjective perception of four environmental qualities in line with the Attention-restoration theory (R. Kaplan 1989; S. Kaplan 1995): fascination, the environments ability to capture the viewers' effortless attention (five items, e.g., "The setting has fascinating qualities"); being away, the environments ability to provide a feeling of "being away" from everyday demands and concerns (two items, e.g., "It was an escape experience"); coherence, the extent to which the elements in an environment is perceived as a coherent whole (four items, e.g., "There is too much going on"); and, compatibility, the extent to which the environment is compatible with the participants inclinations and interests (five items, e.g., "have a sense that I belong there"). The internal consistency for the different components were adequate for fascination ($\alpha = 0.87$), coherence ($\alpha = 0.78$) and compatibility ($\alpha = 0.78$), but somewhat poor for being away ($\alpha = 0.66$).

Cybersickness – The severity of cybersickness symptoms were assessed by the simulator sickness questionnaire (Kennedy et al. 1993) after the three conditions. The questionnaire was originally developed to measure simulator sickness, but has been extensively used in studies of cybersickness as well (Chang et al. 2020). Participants were asked to rank the severity of 16 different symptoms on a 4-point Likert scale. The total score of these symptoms was calculated according to the recommendations of Kennedy et al. (Kennedy et al. 1993). The scale showed adequate internal consistency for the total SSQ score ($\alpha = 0.75$).

Presence – The assessment of the participants' sense of presence in the two virtual environments was based on the approach of Nichols et al. (Nichols et al. 2000), but slightly modified to fit the purpose of this study. The participants were asked to rate the level of agreement to eight statements related to the presence in virtual environments, using a 11-point Likert scale, as previously used in Litleskare and Calogiuri (Litleskare and Calogiuri 2019).

2.5 Physical engagement

Walking speed – The walking speed was recorded during the full 10 min of the experimental conditions by the built-in treadmill computer. The average walking speed used for further analysis.

Heart rate – Heart rate (HR) was recorded continuously during the treadmill walk via a HR-monitor (Garmin Forerunner 310XT, Garmin International Inc., Olathe, Kansas, USA) and extracted as beats per minute. The mean of all individual measurements was automatically recorded by the HR-monitor and used for further analyses.

Perceived exertion – Participants reported their ratings of perceived exertion (RPE) immediately after completing the experimental condition using the 20-point version of the Borg scale with verbal cues (Borg 1982). The scale consists of values ranging from 6–20 with a corresponding description of the level of exertion (e.g., 11 = fairly light).

2.6 Psychophysiological recovery

Affect – Participants' affect was assessed at baseline (i.e., before the stress-elicitation), pre-, and post-exposure to the experimental conditions using the physical activity affect scale (PAAS; Lox et al. 2000). The scale consists of 12 items (e.g., "energetic", "calm", "miserable", and "tired") that are grouped in four components according to Russel's circumplex model of affect (Russell 1980): positive affect (positive valence, high activation), tranquility (positive valence, low activation), negative affect (negative valence, high activation), and fatigue (negative valence, low activation). The scale showed adequate internal consistency for most of the components at most time points ($\alpha = 0.65$–0.80); however, poor levels of internal consistency were found for positive affect at baseline ($\alpha = 0.39$) and pre ($\alpha = 0.57$).

Blood pressure – The Watch BP Office Target semi-automatic blood pressure kit (Microlife, Taipei, Taiwan) was used to measure blood pressure at four different time points; after five minutes of sedentary time at baseline; at 5 min after viewing the film clip designed to elicit sadness; at 5 and 15 min after completing the experimental condition, as a previous study has shown that blood pressure was significantly lower 15 min after exercise in a projection-based virtual green exercise trial (Duncan et al. 2014).

2.7 Participants' background characteristics

Information regarding the participants' sex, age, body mass index (BMI), physical activity habits, and connectedness to nature was collected and used as background characteristics to describe the participant's health status, levels of physical activity, and inclinations toward nature. Sex, age, and height were self-reported by the participants (due to Covid-19 restrictions), while weight was measured using a Seca 877 (SECA GmbH, Hamburg, Germany). The participant's physical activity levels were assessed using a version of the leisure time exercise questionnaire (LTEQ; Godin and Shephard 1985) modified to include transportation physical activity (i.e., walking or biking as a means of transportation). This adjusted version of LTEQ correlates well with assessments of physical activity by accelerometer (Calogiuri et al. 2013). The participants baseline level of nature connectedness was assessed by a version of the connectedness to nature scale (CNS) modified to measure state (Mayer et al. 2009).

2.8 Qualitative information

As little is known about how people perceive and respond to virtual green exercise, in addition to the quantitative data described above, qualitative information was collected among the participants who underwent one of the two VR conditions. This allowed to capture possible themes not dominated by a priori categories, as well as to gain a more nuanced understanding of the quantitative findings. The qualitative information was collected in form of written essays guided by open-ended questions, which were presented to the participants after completing the VR conditions and subsequent quantitative assessments. In order to facilitate the integration of the quantitative and qualitative findings, the questions were developed based on the overarching themes of the quantitative assessments- a question was developed for each of the quantitative variables in such way that the participants could elaborate further on the responses provided in the questionnaire. Questions were phrased to allow for negative, positive as well as neutral viewpoints, for example: “What emotions are you experiencing right now, after having completed the virtual walk?” and “When you answered the question about how “enjoyable” the activity was, what determined where on the scale you put your mark?”.

2.9 Procedures

An overview of the experimental procedures is presented in Fig. 2. After meeting at the laboratory, the participants remained seated for 5 min while completing the baseline questionnaire, which included the LTEQ, CNS, and PAAS. After completing the questionnaire, a baseline measurement of blood pressure was taken and the participants subsequently watched the film clip validated to elicit feelings of sadness (Rottenberg et al. 2007). The participants then remained seated for 5 min while completing the pre-exposure PAAS assessment, after which the pre-exposure measurement of blood pressure was taken. Next, the participants were randomly allocated to one of the three conditions, by picking a number from a hat, and the participant received the information corresponding to that condition only. Participants were briefly familiarized with the treadmill and the HMD before performing the allocated condition. After completion of the treadmill walk, the post-exposure questionnaire was administered, which consisted of RPE, PAAS, enjoyment, SSQ, presence, PRS, and the open ended questions (the three latter were administered only to the participants in the two VR-conditions). Blood pressure was measured 5 and 15 min after completion of the treadmill walk. Lastly, the participants were weighed and reported their height to the closest centimeter. All measurements were performed according to standard procedures for each instrument. The questionnaires included additional questions regarding future green exercise intention and nature connectedness that are not presented in this paper.

2.10 Analyses

To analyze the quantitative findings, one-way ANOVA with post hoc analysis was used to assess possible effects of “condition” (360° video, 3D model and control) on enjoyment, SSQ, and walking speed. An ANCOVA with post hoc analysis was used to analyze possible effects of “condition” on HR and RPE, while correcting for walking speed. An independent-samples Student’s t-test was used to analyze potential differences between the two VR conditions for PER and presence. A mixed between-within subjects ANOVA with post hoc analysis was used to test for possible effects of “time” (baseline, pre exposure, post exposure) and “time by condition” interaction on the different components of PAAS and blood pressure. All post hoc analyses were performed applying a Bonferroni’s correction of alpha. The statistical approach was in accordance with the strategy set prior to experiments. The results are presented as means and standard deviation (M ± SD). The level of significance was set at $p < 0.05$. The statistical analyses were performed in SPSS version 25 (IBM corp., New York, USA).

The purpose of the qualitative analysis to extend and deepen the understanding of the quantitative findings. The qualitative data were analyzed thematically, with an coding frame being defined a priori based on the main domains of the quantitative instrument (i.e., experience, physical engagement, and psychological recovery) and the psychological constructs contained within each of these overarching themes (e.g., enjoyment, perceived exertion, and changes in psychological states). Reiterative reading and recoding of the data led to refinement and extension of the coding frame. In this way, the themes that emerged from the analysis were

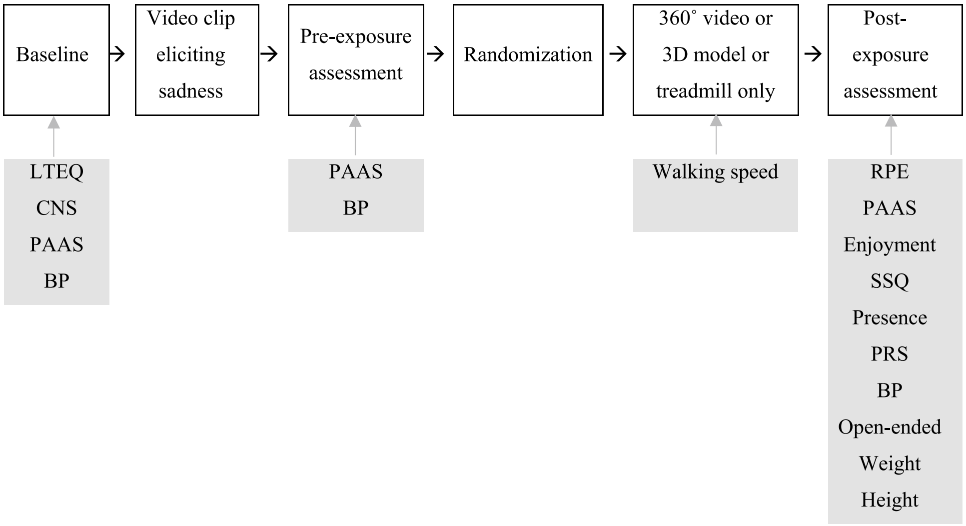


Fig. 2 Overview of experimental procedures (LTEQ = leisure time exercise questionnaire; CNS = Connectedness to nature scale; PAAS = physical activity affect scale; BP = blood pressure; RPE = rating of perceived exertion; SSQ = simulator sickness questionnaire; PRS = perceived restorativeness scale)

substantively grounded in the data, while being informed by the domains of the quantitative instrument, which served the purpose of facilitating the following integration between quantitative and qualitative findings. To be noted that, although the qualitative analysis was *informed* by the quantitative constructs, the emerged themes are independent of the quantitative findings. A first draft of the analysis was performed by one author (GC), which was then further developed in collaboration with another author (SÅKJ). A third author (AH) acted as a "critical friend."

In the Results chapter, for each overarching theme (experience, physical engagement, and psychological recovery), the quantitative and qualitative findings are presented separately and independently from each other—i.e., first the outcomes of the statistical analysis are presented, followed by the themes emerged from the qualitative analysis, without any integration between the two strands. The integrated discussion of the quantitative and qualitative findings is eventually presented in the Discussion chapter, with emphasis on the similarities and differences of these two approaches. The quantitative findings shall be seen as having most weight, especially with respect to providing statistical evidence of the effectiveness of the VR conditions as compared with treadmill walking alone as well as possible differences between the two types of VR (360° video vs. 3D model). Although the qualitative findings shall be seen as secondary, they are important to enhance and extend the understanding of the quantitative findings, especially with respect to the participants' perceptions and experiences.

3 Results

Study enrolment and allocation are presented in Fig. 3. The participants in this study were considered healthy and active individuals with fairly high levels of connectedness to nature (Table 1).

3.1 Experience

The mean values of enjoyment were 6.9 ± 2.4 in the 360° video, 8.3 ± 1.9 in the 3D model, and 5.9 ± 2.6 in control. The one-way ANOVA revealed a significant effect of condition on enjoyment ($F(2,57) = 5.357$, $p = 0.007$, $\eta p = 0.158$),

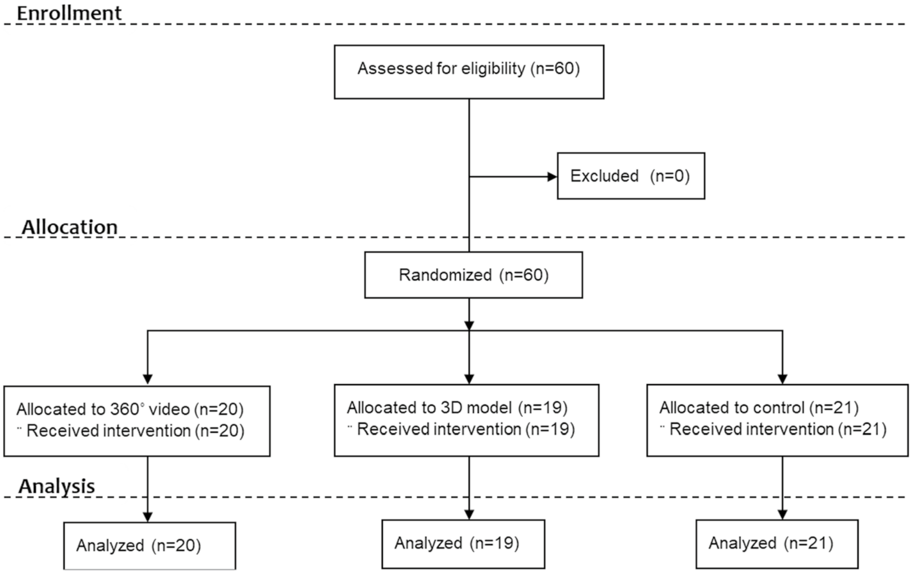


Fig. 3 Flow diagram showing the number of participants enrolled, allocated to experimental conditions and included in the analysis

Table 1 Gender distribution, age, body mass index (BMI), levels of physical activity (LTEQ—leisure time exercise questionnaire) and levels of nature connectedness (CNS—connectedness to nature scale) for all participants in each experimental condition

	360° video ($n = 20$)	3D model ($n = 19$)	Control (n = 21)
Males/females (*n*)	12/8	9/10	11/10
Age (years)	31.2 ± 13.7	31.6 ± 15.3	27.1 ± 7.3
BMI (kg/m^2)	24.8 ± 3.8	24.8 ± 4.0	25.0 ± 2.6
LTEQ	58.6 ± 22.9	54.9 ± 24.9	57.1 ± 28.3
CNS	3.9 ± 0.7	4.0 ± 0.7	4.0 ± 0.6

Means ± standard deviation

with post hoc analysis demonstrating that the 3D model was perceived as more enjoyable compared to control ($p=0.006$). No significant differences were found between 360° video and control ($p=0.533$) or between 360° video and 3D model ($p=0.189$). Overall, satisfactory ratings were observed for all the PRS components (Fig. 4). No significant differences between the two VR conditions were found for any of the PRS components (fascination: $t(37)=-−81$, $p=0.078$; being away: $t(37)=-−91$, $p=0.064$; coherence: $t(37)=0.34$, $p=0.733$; compatibility: $t(37)=-1.64$, $p=0.110$). The SSQ score was 25.2 ± 15.6 in the 360° video, 21.1 ± 15.0 in the 3D model, and 16.2 ± 14.7 in control, indicating relatively low levels of cybersickness. The ANOVA showed no significant differences among conditions in relation to SSQ score ($F(2,57)=1.801$, $p=0.174$, $\eta p=0.059$). Rather high levels of presence, especially in relation to "being there" and "sense of reality", were found in both VR conditions, though rather high ratings for "flatness" and "movement lag" were also reported (Fig. 5). The t-test showed no significant differences between the 360° video and the 3D model for any of the eight items of presence ($p>0.05$ for all eight items), but there was a tendency for the item "being there" in favor of the 3d model ($t(37)=-−1.85$, $p=0.072$).

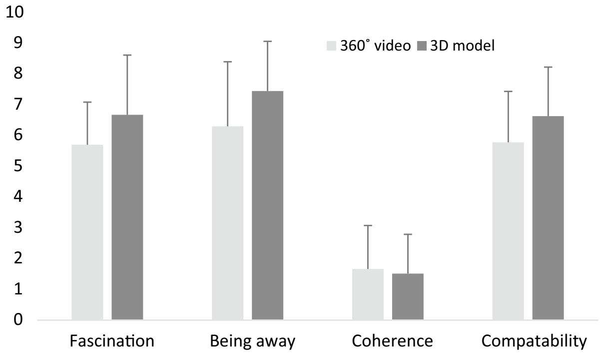


Fig. 4 Ratings of the four components of the perceived restorativeness scale in the 360° video and the 3D model (M ± SD). NB: Low values of "coherence" indicate high perceived coherence

In relation to the overarching theme "2.4", for each of the quantitative domains that initially informed the analysis, two sub-themes emerged: "excitement versus. boredom" and "break the routine" (enjoyment); "appreciating the naturalistic scenario" and "familiarity with the place" (environmental qualities); "dizziness negatively affecting the experience" and "challenges with postural stability" (cybersickness); "feeling Immersed" and "not like real nature" (presence).

It appeared that most of the participants enjoyed the experience, which was recurrently labelled as "fun," "exciting", or "interesting". However, in both VR conditions, a few participants described the virtual walk as little stimulating ("A little boring", "There was little going on"), while some participants appeared to be more excited by the novelty of the technology. This was especially the case among participants who never had tried VR before (e.g., "It was fun to try something new"; "The technology was fascinating"), but also by one who had previous familiarity with VR:

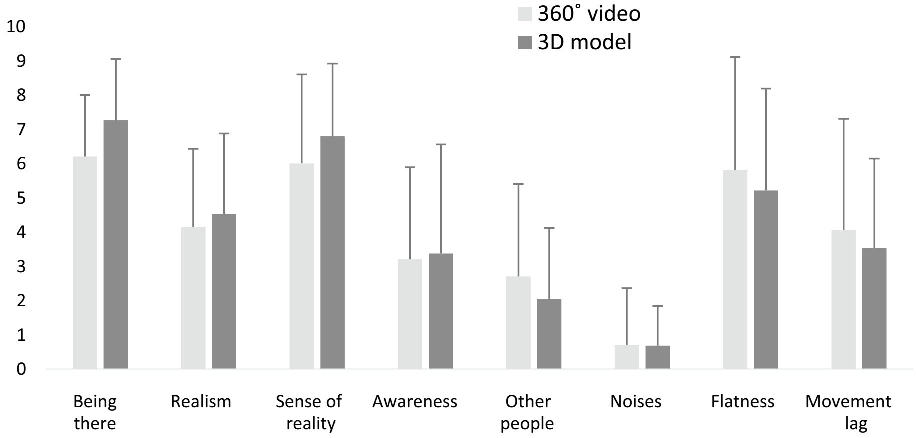
"VR is something I have tried before, and being able to actually move over longer distances while it happens in VR was a new and exciting experience… the simulation itself was not very impressive, but the movement aspect made the VR experience new and exciting." (Man, 32 years, 360° video).

Some participants stated that the virtual walk gave them an opportunity to "disconnect" from daily routines in such a manner that was remarkably similar to what is associated with experiences in real nature. A few participants (all in the 3D model condition) described experiences that are indicative of a flow-like state:

"For a few minutes I almost forgot where I was and just focused on walking and did not think about anything else." (Woman, 36 years, 3D model).

Although some participants found the virtual environment rather plain and little stimulating, several participants made explicit references to the fact that the environment

Fig. 5 Ratings of presence in the 360° video and the 3D model (M ± SD)



(and most recurrently, the *nature* elements) triggered their curiosity, as exemplified by these quotations:

"There was little to look at. I felt like there was nothing I could focus on, as opposed to being in a forest where one can see new trees/animals/lakes around every corner" (Man, 22 years, 360° video).

"What caught my attention during the walk were the trees, the buildings, but also the river that flowed slowly past" (Woman, 24 years, 3D model).

The nature elements in the virtual environments were also recurrently associated with liking the setting (e.g., "The weather, the birds' singing and the river's rushing sound. Green grass and leaves [made the experience enjoyable for me]"), as opposed to elements of the built environment (e.g., "The less traffic noise the more pleasant"; "It was not very fascinating due to the large football pitches"). Several participants reported to have enjoyed the fact that the VR settings gave them an opportunity to experience a day of spring/summer and nice weather ("… it was nice to walk in daylight, now that it is dark early in the afternoon").

Many participants also mentioned the fact that they were familiar with the place, which was associated with pleasant feelings of safety ("It was a safe and friendly environment") and attachment with the place ("I felt a sense of belonging").

"I 'walked' in a familiar environment where I often find myself and it was interesting to see it this way… I was in a place where I often visit and with which I have good relationships… The [virtual] environment attracted my attention because I have often visited that place myself, and quickly recognized myself there … I felt a sense of belonging because I often visit the virtual environment even in real life." (Man, 22 years, 360° video).

Some participants (all in the 360° video condition) experienced dizziness during the VR experience. In most cases, the feelings of dizziness appeared relatively mild and/or temporary, though for two participants it was more severe:

"[I felt] a little uncomfortable… was a bit dazed and a bit dizzy during the walk and the last minutes I was just looking forward to be finished." (Woman, 26 years, 360° video).

A few participants, in both the VR conditions, reported some challenges in relation to postural stability. It should be noted, however, that while the two participants in the 3D model condition appeared to have experienced relatively mild and/or temporary challenges, the experience of the one participant in the 360° video condition was more severe:

"I held on pretty tight with my hands [on the handrails] and certainly could not have managed to walk without holding myself … may have felt a little discomfort with my sight … during the [first half of the walk] it was easier to walk than the [last half]." (Woman, 20 years, 360° video).

About one third of the participants (and slightly more frequently in the 3D model condition), described experiences indicative of very high levels of presence, with several reporting that they felt disconnected from the real place (i.e., the laboratory room) and, in some cases, even appeared to be completely present in the virtual environment:

"I felt like I was out in the virtual environment and focused on it, so I did not know what was happening in the room… It was fascinating how real it was … so I felt like I was walking for real." (Man, 22 years, 360° video).

The most frequently reported factors contributing to reduced feeling of being in nature were poor graphics, feelings of mismatch between one's movements and those of their virtual selves', and poor soundscape or presence of external noises (e.g., the noise from the treadmill). A few participants mentioned the lack of a virtual body, or that they experienced some discomfort in relation to the equipment (e.g., the weight of the headset). Several participants complained that the virtual world appeared visibly artificial (e.g., "It was so clear it was not real"), and some also noticed the lack of sensorial elements typically associated with experiences in real natural environments, such as feeling smells and the wind blowing (e.g., "It was … not something I would do again as I like to feel the smell and wind of nature when I walk"), but also the absence of other people:

"The only thing I might have missed a bit in the virtual environment was more activity from people and/or animals, as I felt quite alone… the virtual environment seemed a bit cold and lonely" (Man, 36 years, 3D model).

3.2 Physical engagement

The mean walking speed was 6.6 ± 1.4 km/h in the 360° video, 7.7 ± 1.5 km/h in the 3D model, and 8.3 km/h ± 1.8 in control. The one-way ANOVA revealed an effect of condition on walking speed (F(2,57) = 6.694, $p = 0.002$, ηp = 0.190), with the post hoc analysis showing a significantly lower walking speed in the 360° video condition compared to control ($p = 0.02$), and a potential trend compared to the 3D model ($p = 0.064$). No statistically significant differences were found between the 3D model and control ($p = 0.762$). The ANCOVA found no differences among conditions for HR (98.4 ± 17.4 beats/min in the 360° video, 112.6 ± 16.6 beats/min in the 3D model and 121.8 beats/min ± 23.8 in control; (F(2,56) = 2.345, p = 0.110, ηp = 0.08) or RPE (9.9 ± 3.0 in the 360° video, 11.2 ± 2.2 in the 3D model and 10.5 ± 2.5 in control; F(2,56) = 1.284, $p = 0.285$, ηp = 0.04) when adjusting for walking speed. Three themes emerged with respect to the overarching theme "2.4.1": "challenges with walking on treadmill," "appreciating the possibility of self-pacing," and "feeling the exercise." Some participants, all in the 360° video condition, experienced some challenges with balance and walking on the treadmill, something that may have forced the participants to walk at a slower pace (e.g., "It was difficult to increase the speed").

"I held on rather strongly with my arms [on the handrails] and certainly could not manage to walk without holding myself. I felt like I worked-out more with my arms than my legs in the end … the [first part] was easier to walk than the [second part]" (Woman, 20 years, 360° video).

On the other hand, the possibility of self-pacing appeared to be appreciated by other participants, who perceived it as something that allowed them to have control of the experience and enjoy the surroundings:

"I liked that one could walk at the pace one wanted, and it was a big plus. I'm used to VR experiences that just move at a set rhythm." (Man, 29 years, 360° video).

"… as I could adjust my pace it was possible to look around" (Woman, 67 years, 3D model).

Some participants, all in the 3D model condition, reported to have experienced moderate levels of physical exertion:

"It feels a bit like I've been out for a little walk" (Woman, 29 years, 3D model).

"I feel in my body that I walked" (Man, 25 years, 3D model).

3.3 Psychophysiological recovery

Figure 6 shows the ratings (M ± SD) for all the components of affect in the different assessment points and different experimental conditions. The mixed between-within subjects ANOVA revealed a significant effect of "time" on all the components of affect: positive affect (F(2,114) = 56,71, $p < 0.001$, ηp = 0.499), tranquility (F(2,114) = 18,79, $p < 0.001$, ηp = 0.248), negative affect (F(2,114) = 15,69, $p < 0.001$, ηp = 0.216), and fatigue (F(2,114) = 18,45, $p < 0.001$, ηp = 0.245). However, no significant "time by condition" interaction was found for any of the components of affect (positive affect: F(2,56) = 2.376, $p = 0.102$, ηp = 0.018; tranquility: F(2,56) = 0,736, $p = 0.483$, ηp = 0.023; negative affect: F(2,56) = 1.399, $p = 0.255$, ηp = 0.017; fatigue F(2,56) = 2.178, $p = 0.123$, ηp = 0.015). A post hoc analysis showed that pre-exposure values were significantly lower compared to both baseline and post exposure for positive affect (baseline vs. pre: $p < 0.001$; pre vs. post: $p < 0.001$) and tranquility (baseline vs. pre: $p < 0.001$; pre vs. post: $p < 0.001$). A reversed pattern emerged for negative affect, as pre values were significantly higher compared to both baseline and post (baseline vs. pre: $p = 0.001$; pre vs. post: $p < 0.001$). The results for fatigue followed a slightly different pattern, with significantly lower values in post exposure compared with pre and baseline (post vs. baseline: $p < 0.001$; post vs. pre: $p < 0.001$), indicating a reduction in feelings of fatigue throughout the three assessment time-points. In regards

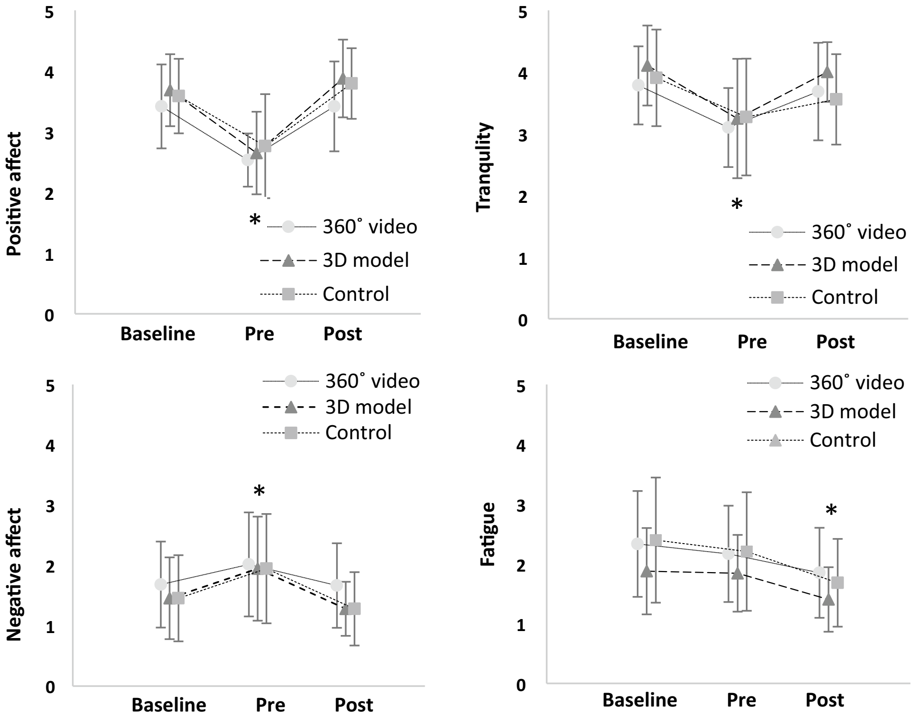


Fig. 6 Ratings (M ± SD) of the four components of the physical activity affect scale in the 360° video, 3D model and control (means and standard deviations). Pre-values were significantly different from baseline and post for positive affect (top left), tranquility (top right) and negative affect (bottom left), while post-values were significantly different from baseline and pre for fatigue (bottom right)

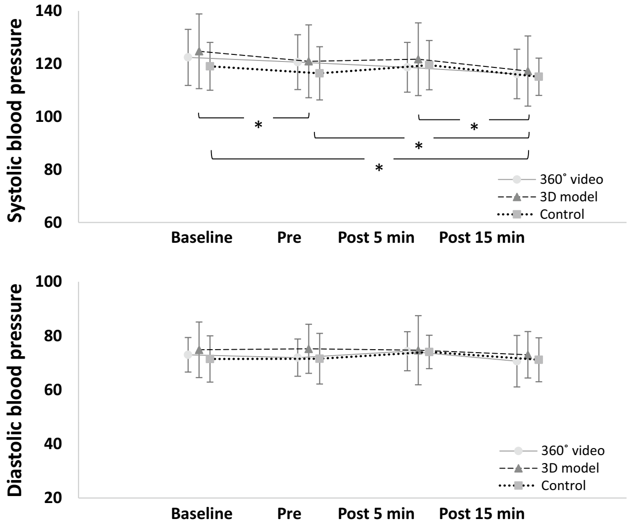


Fig. 7 Values (M ± SD) for systolic (top) and diastolic (bottom) blood pressure at four different time points; baseline, pre, post 5 min and post 15 min. Systolic blood pressure was significantly reduced at post 15 min compared to baseline, pre and post 5 min, and systolic blood pressure at pre was significantly reduced compared to baseline. No significant differences were observed for diastolic blood pressure

to blood pressure (Fig. 7), the mixed between-within subjects ANOVA found a significant effect of "time" for systolic blood pressure (F(3,171) = 13,55, $p < 0.001$, ηp = 0.192), but not a significant "time by condition" interaction (F(6,171) = 1.21, $p = 0.310$, ηp = 0.041). The post hoc analysis showed a significant difference between baseline versus pre ($p = 0.016$), baseline versus. 15 min post exposure ($p < 0.001$), pre versus. 15 min post exposure ($p = 0.004$), and 5 min post exposure versus. 15 min post exposure ($p < 0.001$). No significant effects of "time" (F(3,171) = 2.11; $p = 0.101$, ηp = 0.036) or "time by condition" interaction were found for diastolic blood pressure (F(6,171) = 0.374, $p = 0.895$, ηp = 0.013).

From the qualitative analysis, in relation to the overarching theme "psychophysiological recovery," two themes emerged: "enhanced positive affect," and "relaxation." While only a few participants, all in the 360° video condition and all men, reported to not have perceived a substantial change in their emotional state from before to after the virtual walk ("I feel pretty much like before doing the [virtual walk]"), many more, and in both conditions, made explicit references to experiencing positive emotional states as a result of the virtual walk. Such emotional states were identified as either within the domain of positive affect (high arousal and positive valence, e.g., "excited" or "energetic") or within the domain of tranquility (low arousal and positive valence, e.g., "relaxed" or "calm"). The voice of one participant depicts the impact of the virtual walk in facilitating the psychological recovery after viewing the sad movie:

"[I feel] happy. Little surprised of how quickly I forgot about the sad movie" (Woman, 35 years, 3D model).

4 Discussion

4.1 Effectiveness of virtual green exercise

The overall results of this study show that, by using appropriate techniques to develop virtual natural environments, virtual green exercise can provide psychophysiological benefits with negligible side effects. In particular, the quantitative findings indicate that virtual green exercise was associated with high levels of enjoyment, relatively high levels of perceived environmental restorativeness and presence, and improvements in affect and blood pressure. The qualitative findings supported and extended these findings, indicating overall positive experiences, with participants reporting positive emotions (either in form of relaxation or positive affect), excitement, and feelings of "breaking from the routine." Moreover, the qualitative reports emphasized how participants appreciated viewing naturalistic scenarios and/or familiar places, which triggered curiosity and sense of belonging. The qualitative findings also supported the quantitative findings regarding presence, indicating that participants felt like "being in" the virtual world, and in some few cases even completely loose the sense of reality (i.e., forgetting they were in the laboratory). Altogether, these findings indicate an improvement of the virtual conditions compared to those used in previous studies, which typically report adverse effects of virtual exposure (Alkahtani et al. 2019; Browning et al. 2020a, b; Calogiuri et al. 2018; Frost et al. 2022; Mostajeran et al. 2021). In the present study, both VR conditions were associated with low levels of cybersickness symptoms, as indicated by the similar SSQ ratings in the VR conditions as compared to control, but also by the fact that only few participants mentioned experiencing cybersickness (either in form of dizziness or impaired postural stability) in the qualitative reports. In this regard, it should be noted that some of the items of the SSQ, such as fatigue and sweating, can be influenced by the participants' responses to physical exercise. Some participants walked at such speeds that they started sweating despite the conservative temperature in the laboratory (18°C), and this may have inflated the reported SSQ scores. The relatively low prevalence and severity of cybersickness observed in the present study compared to previous studies (Calogiuri et al. 2018), may be attributed to high levels of scene stability and matching of walking speed between the treadmill and the movement in the virtual environments (Chang et al. 2020; Litleskare & Calogiuri 2019; Saredakis et al. 2020).

4.2 Effects of virtual green exercise compared to control

The quantitative analysis revealed that virtual green exercise elicits higher levels of enjoyment compared to control (though, significant only in the 3D model condition). This finding is in line with previous studies on real green exercise versus. indoor exercise, which generally report higher levels of enjoyment after green exercise (Focht 2009; Lahart et al. 2019). Our results demonstrate that this effect may extend to virtual green exercise as well. The positive effects of virtual nature exposure on enjoyment was further bolstered by the large effect size ($\eta p = 0.158$) and qualitative reports that highlighted how the natural elements in the virtual environments were recurrently associated with enjoyment and even flow-like states. Since enjoyment is a strong motive for exercise participation (Dishman et al. 1985), also in the specific context of green exercise (Calogiuri & Chroni 2014), these results support the idea that virtual green exercise might be a useful tool to increase exercise participation (Litleskare et al. 2020).

In line with previous research, the present study found limited evidence of other additional benefits of virtual green exercise compared to control (Lahart et al. 2019). Apart from enjoyment, no additional benefits of virtual green exercise were observed among the quantitative measurers, including perceived exertion, heart rate, and psychophysiological recovery in the form of pre-post changes in affect and blood pressure. This suggest that the beneficial changes in affect and blood pressure after the VR conditions were primarily associated with the physical activity rather than the virtual nature experiences. These findings challenges previous analysis proposing that synergic benefits occur when combining physical activity and (virtual) nature exposure, leading to greater benefits compared to when each of these occur individually (Calogiuri et al. 2021). In this regard, one important issue to consider is whether virtual nature can elicit restorative effects similar to real nature. Some researchers have found that nature experiences mediated through technology is not as restorative as real nature experiences (Kahn et al. 2008), while others show that virtual nature experiences can be restorative (Liszio et al. 2018). In the present study, exposure to both virtual environments elicited fairly high levels of perceived environmental restorativeness, which were contrasted by qualitative reports referring to the virtual environments as artificial. These reports were not only related to graphics, but also to lack of detail and lack of sensorial elements that are typically associated with real nature. This was recurrently associated with lower ratings of presence and, in some cases, a general feeling that the virtual environment could not reproduce an authentic experience of real nature. Thus, the virtual environments limited ability to fully reproduce an authentic nature experience may impede the associated psychophysiological outcomes compared to real nature.

4.3 Differences between 360° video and 3D model

To date, very little published evidence exists on the way users perceive and respond to virtual green exercise settings developed with different techniques, such as 360° videos and 3D models. To the best of the authors' knowledge, only two studies have compared 360° nature videos with a matching 3D model (Nukarinen et al. 2020; Yeo et al. 2020), and the findings in these studies indicate that the latter elicited (to some extent) more positive psychological responses than the former. Although these studies investigated such differences in a predominantly sedentary context (i.e., either while the participants sat on a chair (Nukarinen et al. 2020) or while they could stand and move in a limited space (Yeo et al. 2020), the findings of the present study are partly in line with this previous literature. More specifically, compared with control, the 3D model elicited higher levels of enjoyment, while the 360° video was associated with a slower walking speed. However, statistically significant differences were not observed for either of these measurements when comparing directly the 360° video and 3D model conditions. From the qualitative analysis, indications also emerged suggesting higher levels of presence and lower incidence of cybersickness in the 3D model compared to the 360° video, though these findings should be treated with caution, as they were not supported by the quantitative findings (albeit a non-significant statistical tendency was observed for the item "being there"). In particular, the qualitative reports indicated that some participants in the 360° video condition experienced cybersickness in the form of dizziness and challenges in maintaining balance while no participant in the 3D model condition mentioned such challenges. The potential for more issues related to cybersickness in the 360° video video would be in agreement with a recent review of factors influencing cybersickness, which highlighted that 360° videos are more susceptible to cybersickness than 3D models (Saredakis et al. 2020). Furthermore, researchers have proposed the idea that realistic looking simulations that fail to meet people's expectations when it comes to accurate movement control may increase the risk of cybersickness (Venkatakrishnan et al. 2020). 360° videos are arguably realistic looking, which might make them susceptible to such effects. Although these issues related to cybersickness were minor in the present study it might have impacted other outcomes in the 360° video condition (namely enjoyment and walking speed), which emphasize the importance of identifying strategies to minimize negative aspects of VR exposure, such as cybersickness, in order to improve the effectiveness of experiences in VR.

4.4 Strengths and limitations

Strengths of this study include the blinding of participants and examiner, and the controlled laboratory environment. The low levels of cybersickness should also be considered a strength, due its negative impact on other outcomes in similar studies. The only added benefit of virtual green exercise compared to control was higher levels of enjoyment following exposure to the 3D model. The lack of an experimental condition applying a virtual non-natural environment limits our ability to attribute this finding specifically to the environment and not to the VR-technology alone. This was in particular highlighted by the qualitative reports that the novelty of the technology contributed to the ratings of enjoyment. However, the lack of a similar improvement of enjoyment after the 360° video, and the qualitative reports that the natural elements in the virtual environments contributed to enjoyment, suggest that the novelty of VR in and of itself does not result in high levels of enjoyment. Another issue in the present study was that HR was not expressed as a percentage of each individual's maximal heart rate, which limits its precision as a measure of exercise intensity. This was a calculated tradeoff because a measurement of maximal heart rate requires a highly intense and exhausting experience. In turn, this might have influenced the type of volunteers enlisting for this study and would definitely increase the load and the time commitment for the participants. Age-predicted maximal HR was not considered due to the limitations of these equations (Shookster et al. 2020).

5 Conclusions

Both virtual green exercise conditions were generally well received by participants without causing concerning levels of negative side effects, such as cybersickness and negative affective responses. However, compared with treadmill walking with no exposure to VR, only one of the installations (the 3D model) provided some additional benefits (i.e., greater enjoyment), while the 360° video was associated with negative behavioral outcomes in the form of slower waking speed leading to reduced exercise output. Neither of the virtual conditions provided greater health benefits in terms of psychophysiological recovery compared with treadmill walking. Nevertheless, the findings of this study provide important insights regarding to the possibility of adopting virtual green exercise as a tool within health care settings, physical activity promotion, and research projects. In particular, the use of 3D model based virtual green exercise within physical activity promotion may be a promising area to explore, as enjoyment is an important component of exercise motivation. More research is, however, needed in this field, especially to establish possible long-term behavioral benefits of virtual green exercise interventions. This study also highlights limitations in the ability of virtual green exercise to fully reproduce the effects of experiences in real nature. Further research and optimization of virtual experiences of natural environments is required to achieve the full potential of this technology, preferably in accordance with current recommendations for this specific field of research (Joseph et al. 2020; Litleskare et al. 2020).

Funding The research activity of the authors was primarily funded by their institutions, namely University of South-Eastern Norway and Inland Norway University of Applied Sciences. The study received funding from the Regional Research Fond – Innlandet, Norway (grant n. 292761). As part of the GoGreenRoutes project, G.C., O.E.F., F.F., and S.L. received funding by the European Union's Horizon 2020 research and innovation program under grant agreement No. 869764. Open Access funding provided by Inland Norway University Of Applied Sciences.

Availability of data and material The datasets generated during and analyze during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

References

Akers A, Barton J, Cossey R, Gainsford P, Griffin M, Micklewright D (2012) Visual color perception in green exercise: positive effects on mood and perceived exertion. Environ Sci Technol 46(16):8661–8666. https://doi.org/10.1021/es301685g

Alkahtani S, Eisa A, Kannas J, Shamlan G (2019) Effect of acute high-intensity interval cycling while viewing a virtual natural scene on mood and eating behavior in men: a randomized pilot trial. Clinical Nut Experimental 28:92–101. https://doi.org/10.1016/j.yclnex.2019.10.003

Borg GAV (1982) Psychophysical bases of perceived exertion. Med Sci Sports Exerc 14(5):377–381. https://doi.org/10.1249/00005768-198205000-00012

Botella C, Fernandez-Alvarez J, Guillen V, Garcia-Palacios A, Banos R (2017) Recent progress in virtual reality exposure therapy for phobias: a systematic review. Curr Psychiatry Rep 19(7):42. https://doi.org/10.1007/s11920-017-0788-4

Bowman, D. A., & McMahan, R. P. (2007). Virtual reality: How much immersion is enough? *Computer*, *40*(7), 36- https://doi.org/10.1109/Mc.2007.257

Browning MHEM, Shipley N, McAnirlin O, Becker D, Yu C-P, Hartig T, Dzhambov AM (2020a) An actual natural setting improves mood better than its virtual counterpart: a meta-analysis of experimental data. Frontiers Psychol. https://doi.org/10.3389/fpsyg.2020.02200

Browning MHEM, Saeidi-Rizi F, McAnirlin O, Yoon H, Pei Y (2020b) The role of methodological choices in the effects of experimental exposure to simulated natural landscapes on human health and cognitive performance: a systematic review. Environ Behav. https://doi.org/10.1177/0013916520906481

Calogiuri G, Nordtug H, Weydahl A (2015) The Potential of Using Exercise in Nature as an Intervention to Enhance Exercise Behavior: Results from a Pilot Study. Percept Mot Skills 121(2):350–370.

Calogiuri, G., & Chroni, S. (2014). The impact of the natural environment on the promotion of active living: An integrative systematic review. *BMC Public Health*, *14*. 873 https://doi.org/10.1186/1471-2458-14-873.

Calogiuri, G., Mikkila, S., & Weydahl, A. (2013). *Can Promotion of Outdoor Activities Impact People's Vitamin D Levels? Promising Findings from a Pilot Study*. In EIIC - Proceedings in EIIC - The 2nd Electronic International Interdisciplinary Conference.

Calogiuri, G., Patil, G. G., & Aamodt, G. (2016). Is Green Exercise for All? A Descriptive Study of Green Exercise Habits and Promoting Factors in Adult Norwegians. International Journal of Environmental Research and Public Health, 13(11): 1165 https://doi.org/10.3390/Ijerph13111165

Calogiuri, G., Litleskare, S., Fagerheim, K. A., Rydgren, T. L., Brambilla, E., & Thurston, M. (2018). Experiencing Nature through Immersive Virtual Environments: Environmental Perceptions, Physical Engagement, and Affective Responses during a Simulated Nature Walk. *Frontiers in Psychology*, *8*. 2321 https://doi.org/10.3389/Fpsyg.2017.02321

Calogiuri, G., Litleskare, S., & Fröhlich, F. (2021). Physical Activity and Virtual Nature: Perspectives on the Health and Behavioral Benefits of Virtual Green Exercise. In *Nature and Health* (s. 127–146). Routledge. https://doi.org/10.4324/9781003154419-10

Chan SHM, Qiu L, Esposito G, Mai KP, Tam K-P, Cui J (2021) Nature in virtual reality improves mood and reduces stress: Evidence from young adults and senior citizens. Virtual Reality. https://doi.org/10.1007/s10055-021-00604-4

Chang E, Kim HT, Yoo B (2020) Virtual Reality Sickness: A Review of Causes and Measurements. International Journal of Human-Computer Interaction. https://doi.org/10.1080/10447318.2020.1778351

Dishman RK, Sallis JF, Orenstein DR (1985) The determinants of physical activity and exercise. Public Health Rep 100(2):158–171

Duncan MJ, Clarke ND, Birch SL, Tallis J, Hankey J, Bryant E, Eyre ELJ (2014) The Effect of Green Exercise on Blood Pressure, Heart Rate and Mood State in Primary School Children. Int J Environ Res Public Health 11(4):3678–3688. https://doi.org/10.3390/ijerph110403678

Focht, B. C. (2009). Brief Walks in Outdoor and Laboratory Environments: Effects on Affective Responses, Enjoyment, and Intentions to Walk for Exercise. *Research Quarterly for Exercise and Sport*, *80*(3), 611–620. common

Frost S, Kannis-Dymand L, Schaffer V, Millear P, Allen A, Stallman H, Mason J, Wood A, Atkinson-Nolte J (2022) Virtual immersion in nature and psychological well-being: A systematic literature review. J Environ Psychol 80:101765. https://doi.org/10.1016/j.jenvp.2022.101765

Frumkin H, Bratman GN, Breslow SJ, Cochran B, Kahn PH, Lawler JJ, Levin PS, Tandon PS, Varanasi U, Wolf KL, Wood SA (2017) Nature Contact and Human Health: A Research Agenda. Environ Health Perspect 125(7):075001. https://doi.org/10.1289/EHP1663

Godin G, Shephard R (1985) A simple method to assess exercise behavior in the community. Canadian Journal of Applied Sport Science 10(3):141–146

Grassini S, Laumann K, Rasmussen Skogstad M (2020) The Use of Virtual Reality Alone Does Not Promote Training Performance (but Sense of Presence Does). Front Psychol. https://doi.org/10.3389/fpsyg.2020.01743

Guna J, Gersak G, Humar I, Song J, Drnovsek J, Pogacnik M (2019) Influence of video content type on users' virtual reality sickness perception and physiological response. Future Generation Computer Systems-the International Journal of Escience 91:263–276. https://doi.org/10.1016/j.future.2018.08.049

Harte JL, Eifert GH (1995) The effects of running, environment, and attentional focus on athletes' catecholamine and cortisol levels and mood. Psychophysiology 32(1):49–54

Hartig T, Korpela K, Evans GW, Gärling T (1997) A measure of restorative quality in environments. Scandinavian Housing and Planning Research 14(4):175–194. https://doi.org/10.1080/02815739708730435

Hartig T, Evans GW, Jamner LD, Davis DS, Garling T (2003) Tracking restoration in natural and urban field settings. J Environ Psychol 23(2):109–123. https://doi.org/10.1016/S0272-4944(02)00109-3

Joseph A, Browning MHEM, Jiang S (2020) Using Immersive Virtual Environments (IVEs) to Conduct Environmental Design Research: A Primer and Decision Framework. HERD. https://doi.org/10.1177/1937586720924787

Kahn PH, Friedman B, Gill B, Hagman J, Severson RL, Freier NG, Feldman EN, Carrère S, Stolyar A (2008) A plasma display window?—The shifting baseline problem in a technologically mediated natural world. J Environ Psychol 28(2):192–199. https://doi.org/10.1016/j.jenvp.2007.10.008

Kajosaari A, Pasanen TP (2021) Restorative benefits of everyday green exercise: A spatial approach. Landsc Urban Plan 206:103978. https://doi.org/10.1016/j.landurbplan.2020.103978

Kaplan, R. (1989). *The Experience of Nature: A Psychological Perspective*. Cambridge University Press.

Kaplan, S. (1995). The Restorative Benefits of Nature—Toward an Integrative Framework. *Journal of Environmental Psychology*, *15*(3), 169–182. https://doi.org/10.1016/0272-4944(95)90001-2

Kennedy RS, Lane N, Berbaum K, Lilienthal M (1993) Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. Int J Aviat Psychol 3(3):203–220

Kennedy RS, Drexler J, Kennedy RC (2010) Research in visually induced motion sickness. Appl Ergon 41(4):494–503. https://doi.org/10.1016/j.apergo.2009.11.006

Knaust T, Felnhofer A, Kothgassner OD, Höllmer H, Gorzka R-J, Schulz H (2021) Exposure to virtual nature: The impact of different immersion levels on skin conductance level, heart rate, and perceived relaxation. Virtual Reality. https://doi.org/10.1007/s10055-021-00595-2

Lacharité-Lemieux, M., Brunelle, J.-P., & Dionne, I. J. (2015). Adherence to exercise and affective responses: Comparison between outdoor and indoor training. *Menopause (New York, N.Y.)*, *22*(7), 731–740. https://doi.org/10.1097/GME.0000000000000366

Lahart, I., Darcy, P., Gidlow, C., & Calogiuri, G. (2019). The Effects of Green Exercise on Physical and Mental Wellbeing: A Systematic Review. *Int J Environ Res Public Health*, *16*(8). https://doi.org/10.3390/ijerph16081352

LaViola J (2000) A Discussion of Cybersickness in Virtual Environments. ACM SIGCHI Bull 32(1):47–56. https://doi.org/10.1145/333329.333344

Liszio S, Graf L, Masuch M (2018) The Relaxing Effect of Virtual Nature: Immersive Technology Provides Relief in Acute Stress Situations. Annu Rev Cyberther Telemed 16:87–93

Litleskare S, Calogiuri G (2019) Camera Stabilization in 360 degrees Videos and Its Impact on Cyber Sickness, Environmental Perceptions, and Psychophysiological Responses to a Simulated Nature Walk: A Single-Blinded Randomized Trial. Front Psychol 10:2436. https://doi.org/10.3389/fpsyg.2019.02436

Litleskare, S., MacIntyre, T. E., & Calogiuri, G. (2020). Enable, Reconnect and Augment: A New ERA of Virtual Nature Research and Application. *Int J Environ Res Public Health*, *17*(5). https://doi.org/10.3390/ijerph17051738

Lox C, Jackson S, Tuholski S, Wasley D, Treasure D (2000) Revisiting the measurement of exercise-induced feeling states: The physical activity affect scale (PAAS). Meas Phys Educ Exerc Sci 4:79–95. https://doi.org/10.1207/S15327841Mpee0402_4

Mayer FS, Frantz CM, Bruehlman-Senecal E, Dolliver K (2009) Why Is Nature Beneficial? The Role of Connectedness to Nature. Environ Behav 41(5):607–643. https://doi.org/10.1177/0013916508319745

Meredith GR, Rakow DA, Eldermire ERB, Madsen CG, Shelley SP, Sachs NA (2020) Minimum Time Dose in Nature to Positively Impact the Mental Health of College-Aged Students, and How to Measure It: A Scoping Review. Front Psychol. https://doi.org/10.3389/fpsyg.2019.02942

Mieras, M. E., Heesch, M. W. S., & Slivka, D. R. (2014). Physiological and Psychological Responses to Outdoor vs. Laboratory Cycling. *The Journal of Strength & Conditioning Research*, *28*(8), 2324–2329. https://doi.org/10.1519/JSC.0000000000000384

Mostajeran F, Krzikawski J, Steinicke F, Kühn S (2021) Effects of exposure to immersive videos and photo slideshows of forest and urban environments. Sci Rep 11(1):3994. https://doi.org/10.1038/s41598-021-83277-y

Nichols, S., Haldane, C., & Wilson, J. R. (2000). Measurement of presence and its consequences in virtual environments. *International Journal of Human-Computer Studies*, *52*(3), 471–491.

Nukarinen, T., Istance, H. O., Rantala, J., Mäkelä, J., Korpela, K., Ronkainen, K., Surakka, V., & Raisamo, R. (2020). Physiological and Psychological Restoration in Matched Real and Virtual Natural Environments. *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*, 1–8. https://doi.org/10.1145/3334480.3382956

Oman CM (1990) Motion sickness: A synthesis and evaluation of the sensory conflict theory. Can J Physiol Pharmacol 68(2):294–303. https://doi.org/10.1139/y90-044

Pretty J, Peacock J, Sellens M, Griffin M (2005) The mental and physical health outcomes of green exercise. Int J Environ Health Res 15(5):319–337. https://doi.org/10.1080/09603120500155963

Pretty, J., Griffin, M., Sellens, M., & Pretty, C. (2003). *Green Exercise: Complementary Roles of Nature, Exercise and Diet in Physical and Emotional Well-Being and Implications for Public Health Policy*.

Reason JT (1978) Motion sickness adaptation: A neural mismatch model. J R Soc Med 71(11):819–829

Riccio GE, Stoffregen TA (1991) An ecological theory of motion sickness and postural instability. Ecol Psychol 3(3):195–240

Rogerson, M., Barton, J., Pretty, J., & Gladwell, V. (2019). The green exercise concept: To intertwining pathways to health and well-being. I *Physical activity in natural setting: Green and blue exercise* (1. utg., s. 75–94). Routledge.

Rottenberg, J., Ray, R. D., & Gross, J. J. (2007). Emotion elicitation using films. I *Handbook of emotion elicitation and assessment* (s. 9–28). Oxford University Press.

Russell, J. A. (1980). A Circumplex Model of Affect. *Journal of Personality and Social Psychology*, *39*(6), 1161–1178. https://doi.org/10.1037/h0077714

Saredakis D, Szpak A, Birckhead B, Keage HAD, Rizzo A, Loetscher T (2020) Factors Associated With Virtual Reality Sickness in Head-Mounted Displays: A Systematic Review and Meta-Analysis. Front Hum Neurosci. https://doi.org/10.3389/fnhum.2020.00096

Sharples S, Cobb S, Moody A, Wilson JR (2008) Virtual reality induced symptoms and effects (VRISE): Comparison of head mounted display (HMD), desktop and projection display systems. Displays 29(2):58–69. https://doi.org/10.1016/j.displa.2007.09.005

Shookster D, Lindsey B, Cortes N, Martin JR (2020) Accuracy of Commonly Used Age-Predicted Maximal Heart Rate Equations. Int J Exerc Sci 13(7):1242–1250

Slater M, Usoh M, Steed A (1995) Taking Steps: The influence of a Walking Technique on Presence in Virtual Reality. ACM Transactions on Computer-Human Interaction 2(3):201–219

Slater, M., & Wilbur, S. (1997). A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments. *Presence-Teleoperators and Virtual Environments*, *6*(6), 603–616. https://doi.org/10.1162/pres.1997.6.6.603

Smith JW (2015) Immersive Virtual Environment Technology to Supplement Environmental Perception, Preference and Behavior Research: A Review with Applications. Int J Environ Res Public Health 12(9):11486–11505. https://doi.org/10.3390/ijerph120911486

Steuer, J. (1992). Defining Virtual Reality—Dimensions Determining Telepresence. *Journal of Communication*, *42*(4), 73–93. https://doi.org/10.1111/j.1460-2466.1992.tb00812.x

Triberti S, Repetto C, Riva G (2014) Psychological factors influencing the effectiveness of virtual reality-based analgesia: A systematic review. Cyberpsychol Behav Soc Netw 17(6):335–345. https://doi.org/10.1089/cyber.2014.0054

Venkatakrishnan, R., Venkatakrishnan, R., Bhargava, A., Lucaites, K., Solini, H., Volonte, M., Robb, A., Babu, S. V., Lin, W.-C., & Lin, Y.-X. (2020). Comparative Evaluation of the Effects of Motion Control on Cybersickness in Immersive Virtual Environments. 2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), 672–681. https://doi.org/10.1109/VR46266.2020.00090

Weech, S., Kenny, S., & Barnett-Cowan, M. (2019). Presence and Cybersickness in Virtual Reality Are Negatively Related: A Review. *Frontiers in Psychology*, *10*. 158 https://doi.org/10.3389/fpsyg.2019.00158

White MP, Pahl S, Ashbullby KJ, Burton F, Depledge MH (2015) The Effects of Exercising in Different Natural Environments on Psycho-Physiological Outcomes in Post-Menopausal Women: A Simulation Study. Int J Environ Res Public Health 12(9):11929–11953. https://doi.org/10.3390/ijerph120911929

White MP, Elliott LR, Taylor T, Wheeler BW, Spencer A, Bone A, Depledge MH, Fleming LE (2016) Recreational physical activity in natural environments and implications for health: A population based cross-sectional study in England. Prev Med 91:383–388. https://doi.org/10.1016/j.ypmed.2016.08.023

White MP, Yeo NL, Vassiljev P, Lundstedt R, Wallergard M, Albin M, Lohmus M (2018) A prescription for «nature»—The potential of using virtual nature in therapeutics. Neuropsychiatr Dis Treat 14:3001–3013. https://doi.org/10.2147/Ndt.S179038

White MP, Alcock I, Grellier J, Wheeler BW, Hartig T, Warber SL, Bone A, Depledge MH, Fleming LE (2019) Spending at least 120 minutes a week in nature is associated with good health and wellbeing. Sci Rep 9(1):7730. https://doi.org/10.1038/s41598-019-44097-3

Yeo NL, White MP, Alcock I, Garside R, Dean SG, Smalley AJ, Gatersleben B (2020) What is the best way of delivering virtual nature for improving mood? An experimental comparison of high definition TV, 360° video, and computer generated virtual reality. J Environ Psychol. https://doi.org/10.1016/j.jenvp.2020.101500

Yildirim C (2020) Don't make me sick: Investigating the incidence of cybersickness in commercial virtual reality headsets. Virtual Reality 24(2):231–239. https://doi.org/10.1007/s10055-019-00401-0

Yin J, Zhu S, MacNaughton P, Allen JG, Spengler JD (2018) Physiological and cognitive performance of exposure to biophilic indoor environment. Build Environ 132:255–262. https://doi.org/10.1016/j.buildenv.2018.01.006

Doctoral dissertation no. 137
2022

Virtual green exercise - developing a new concept for health promotion

Dissertation for the degree of dr.philos.

Sigbjørn Litleskare

ISBN: 978-82-7206-695-5 (print)
ISBN: 978-82-7206-696-2 (online)

usn.no