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ORIGINAL ARTICLE

The restorative and state enhancing potential of abstract fractal-like imagery and interactive mindfulness interventions in virtual reality

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Abstract

The restorative and mental state enhancing effects of brief mindfulness-based interventions (MBIs) and restorative environments such as nature has been supported in the research literature. However, regular adoption of these practices is limited by practical constraints and motivational barriers. The current study addressed these challenges by introducing two novel approaches which utilise the immersive and interactive qualities of virtual reality (VR). This included an interactive MBI and an abstract restorative environment using fractal-like imagery. These approaches were explored using a comparative evaluation of two short (6 min) VR interventions: Passive VR (applying principles from restorative interventions) and Interactive VR (implementing a focused attention form of mindfulness meditation). A mixed methods approach revealed increased state mindfulness, reduced mental fatigue, and enhanced aspects of mood (calm/relaxation, anxiety) consistently between conditions. Between group differences revealed additional benefits for cognition (focus), mood (happiness and sadness), and motivational value with the interactive intervention. The abstract environment, used in both interventions, maintained comparable levels of perceived restoration with a nature VR control condition. The results provide preliminary evidence supporting the use of interactive approaches for mindfulness interventions and abstract versions of restorative environments.

Keywords Virtual reality · VR · Attention restoration · Mindfulness meditation · Interactive meditation · Well-being · Mood · Cognitive enhancement · Fractal · Abstract environment · Natural environment · Guided breathing

1 Introduction

Low mood, cognitive fatigue, and inattention on the job are commonly reported by individuals who work (American Psychological Association 2015; Caldwell et al. 2019; Killingsworth and Gilbert 2010). This poses significant risks for workplace well-being, safety, and performance (Cummings et al. 2016; Mehta 2022; Rupp et al. 2017; Sadeghniiat-Haghighi and Yazdi 2015). Accessing restorative environments (e.g. natural environments) and engaging in mindfulness-based interventions (MBIs) can improve an individual's capacity to enhance well-being and recover during negative mental states (Barton et al. 2020; Posner et al. 2015; Tang and Posner 2009).

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Prototypical restorative environments used throughout the restoration literature mainly comprise of aesthetically pleasing natural environments as they promote psychological distance from stressors and an effortless curiosity and fascination with surrounding stimuli (Hartig et al. 2014; Kaplan 1995). Restoration in these environments involves a replenishment of spent adaptive resources (e.g. executive attention) which have been overtaxed due to the demands of work and personal life (Hartig et al. 2014; Lymeus et al. 2018). Thus, restorative interventions are typically designed for states of cognitive fatigue, when executive attention requires time and space to recover (Kaplan 1995). The restoration of depleted cognitive resources ensures associated elements of health and well-being such as attention, fatigue and stress can improve simultaneously (Cohen 1980; Kaplan 1995; Lymeus et al. 2018; von Lindern et al. 2017).

MBIs include a family of self-regulation practices (e.g. guided meditation) which aim to cultivate mindfulness; a state of being attentive to and aware of what is taking place in the present moment (Brown and Ryan 2003). In difference to more conventional MBIs which develop broad mindfulness skills over long training periods (e.g. weekly 2.5 h classes over 8 weeks) (Johnson et al. 2020; Kabat-Zinn 1990), brief MBIs use short durations (e.g. 5 to 25 min) and are usually comprised of a single component of mindfulness practice, such as focused breathing (attending to the sensations of the breath) and body scan meditations (attending to physical sensations throughout different areas of the body) (Arch and Craske 2006; Ditto et al. 2006). Brief MBIs can help to reduce mind wandering and stress by narrowing the scope of attention and clearing the mind of thoughts about past or future events (Lymeus 2019; Mrazek et al. 2012).

Despite the benefits of restorative and mindfulness-based interventions, existing research relating to the use of meditative, restorative, and broader health promoting activities (e.g. physical exercise and healthy eating) has identified several common barriers to adoption. These barriers comprise of practical constraints (such as required time or physical location), a lack of positive outcomes (due to a lack of enjoyment or unmet expectations), negative mood and emotional responses (e.g. anxiety or boredom), inadequacy of knowledge and skills (of those perceived needed to partake), and sociocultural barriers (such as stigma or conflicts with cultural expectations) (Ajzen 1991; Anderson et al. 2019; Hunt et al. 2020; Laurie and Blandford 2016; Maiman and Becker 1974; Prochaska 2020; Van Cappellen et al. 2020). Individuals are often discouraged from incorporating these practices into their daily routines due to one or more of these factors (Hunt et al. 2020). Accordingly, researchers are evaluating new and novel techniques to improve accessibility and the outcomes of restorative and meditative interventions to increase participation by those unmotivated by traditional techniques (Li et al. 2020; Niksirat et al. 2019; Rupp et al. 2017). We continued in this vein by exploring the potential of virtual reality (VR) to offer innovative and accessible solutions relating to MBIs and restorative environments. With accessibility in mind, the reviewed literature and design concepts introduced focus on readily available VR systems suited for broad populations, without needing specialist equipment or training. This includes the design and evaluation of a virtual environment comprising abstract fractal-like imagery for restoration, and an interactive, movement-based approach to mindfulness practice. Utilising VR, these interventions seek to expand on conventional methods (e.g. passive, voice guided meditations and natural environments) and explore opportunities to overcome common barriers to adoption.

1.1 Restorative environments in VR

Modern VR systems utilise head mounted displays which can fully immerse the wearer's audio–visual perception within a virtual environment (VE) (Slater and Wilbur 1997). This is well suited to the integration of restorative environments, where a user's physical surroundings are replaced by a controlled perceptual field more conducive to restoration (Li et al. 2021). In VR, restorative interventions encourage relaxation within digitally rendered or 360° recorded nature environments, which have demonstrated immediate improvements for attentional performance and affective states (Blum et al. 2019; Islam et al. 2018; Li et al. 2020; Schutte et al. 2017; Valtchanov 2010). These VR interventions can create restorative and distraction free environmental conditions on demand, regardless of one's physical location. Thus, VR may grant improved access to restorative environments for those inhibited by physical restrictions such as heavily urbanised living and working locations (Hartig et al. 2011).

The process of restoration is not considered to be exclusive to natural environments (Stevenson et al. 2018) and VR presents opportunities to push the boundaries and explore alternatives (e.g. abstract environments) that may facilitate restoration. According to Attention Restoration Theory (ART), environments facilitate restoration when they minimise attentional demands and create experiences of "soft fascination" (attracting attention effortlessly without imposing cognitive demands), "being away" (escape from the stresses and reminders of daily life), "extent" (sustained interest over time), and "compatibility" (with the individual's goals and desires) (Kaplan 1995). These qualities are prominent in natural environments (Hartig et al. 2014; Home et al. 2012; Kaplan 1995), justifying the dominant use of nature imagery (e.g. pictures and videos of natural scenery) to facilitate restoration in restorative and mindfulness interventions (Döllinger et al. 2021; Ohly et al. 2016; Stevenson et al. 2018). Despite this, evidence of restoration when observing nature imagery remains inconsistent (Emfield and Neider 2014; Hartig et al. 1996; Hicks et al. 2020; Joye and Dewitte 2018), and researchers have questioned whether such interventions can sustain the observer's interest adequately (Li et al. 2020). Considering VR's immersive nature, which inherently creates psychological distance from physical reality, the research literature is lacking a thorough exploration of the range of environments which can sustain interest and be used to support restoration in VR. Aside urban settings, only a limited range of alternatives to nature have been studied, and these indicate a reduced restorative capacity compared with nature. These exposures have been limited to 2D images of geometrical patterns (Berto 2005), 2D images of abstract paintings (Valtchanov et al. 2010), and geometrical VR environments representative of urban environments (Valtchanov 2010). Thus, current designs have not fully explored the scope of aesthetically pleasing abstract environments available within VR (e.g. Du Plessis 2017).

Abstract environments can elicit fascination and curiosity as the viewer experiences novel imagery distinct from their everyday surroundings (Döllinger et al. 2021). These have few corporeal or natural counterparts, meaning individuals are less likely to have preconceived attitudes or unwanted emotions often triggered by real-life environments (Kitson et al. 2018). An important design consideration, however, is cognitive load and our limited capacity to process information such as complex environmental stimuli (Jiang et al. 2021; Sweller 1988). The dominant use of nature for restoration purposes is largely due to its ability to present fascinating phenomena with minimal cognitive load compared to urban environments (Grassini et al. 2019; Kaplan 1995). Like with urban environments, abstract imagery has the potential to overwhelm cognitive resources with unfamiliar, disordered, and visually complex stimuli. This may capture interest but generate fatigue over sustained periods (Ioannucci et al. 2021; Souchet et al. 2022).

Considering the potential for increased processing demands through abstract environments, we draw attention to research concerning perceptual fluency and fractals. Perceptual fluency refers to the experience of easily processing certain stimulus features (Alter and Oppenheimer 2009; Oppenheimer 2008). This can be enhanced through visual symmetry (Bertamini et al. 2013) which is a defining feature of fractals; shapes characterised by self-similar, repeated patterns that occur across a range of magnification scales (Fairbanks and Taylor 2016; Mandelbrot and Mandelbrot 1982). There are extensive examples of naturally occurring fractals (e.g. lightning, clouds, rivers, trees, mountains, coastlines) (Gouyet and Bug 1997; Mandelbrot and Mandelbrot 1982) and well-known human-made fractals (e.g. the Koch snowflake and the Mandelbrot set). Prior research has demonstrated that fractals are a strong source of perceptual fluency which present aesthetically pleasing and complex visual information without undue processing demands (Joye et al. 2016); similar to the effects of nature (Lymeus 2019). The restorative potential of fractal patterns is still largely unexplored, particularly in VR. This is in despite of their widely regarded aesthetic appeal (Kemp 1998; Mandelbrot 1989; Peitgen and Richter 1986; Spehar et al. 2003) and preliminary evidence indicating relaxing and restorative effects (Hagerhall et al. 2008). In the current study, we applied the principles of perceptual fluency within a series of fractal-like patterns to explore the restorative potential of abstract environments in VR.

1.2 Mindfulness-based interventions in VR

VR offers a unique and valuable tool when enhancing the accessibility of brief MBI's and their associated positive outcomes (Chandrasiri et al. 2020; Navarro-Haro et al. 2017; Seabrook et al. 2020). For instance, VR can reinforce and enhance mindfulness practice by delivering meditation guidance alongside restorative nature-based stimuli (Seabrook et al. 2020). For some users, this can enhance meditative states and offset some of the attentional effort incurred during more cognitively demanding meditation practices (Kaplan 2001; Lymeus et al. 2017). Meditating whilst immersed in a restorative VE also binds the meditator's scope of attention to what they perceive in VR (Seabrook et al. 2020). Thus, the user's attention is bound to complementary and tailored audio–visual stimuli, supporting positive outcomes from the practice (Kitson et al. 2018; Navarro-Haro et al. 2017) and minimising disruptions from the physical environment (Wang et al. 2022b). Accordingly, there is growing research interest using VR MBIs which synchronise vocally guided meditations with virtual nature environments (Chandrasiri et al. 2020; Döllinger et al. 2021; Navarro-Haro et al. 2017; Seabrook et al. 2020).

A recent review of VR mindfulness meditation interventions by Döllinger et al. (2021) found a clear dominance of passive approaches relying on vocal instructions to guide focus. With these approaches (closely aligned with conventional meditation), they found limited additional benefits for mindfulness induction compared with non-immersive approaches, concluding that interactive solutions should be explored as an alternative. We also suggest that passive VR approaches may lack motivational value for those disinterested or disengaged by traditional methods (Anderson et al. 2019), particularly when considering the scope for novel interactive methods in VR (Kitson et al. 2018).

A common limitation with passive mindfulness approaches is a lack of dynamic feedback present throughout the practice which is important during exercises that involve focused attention. A common entry point for mindfulness practitioners is focused attention meditation (FAM) which involves training the ability to sustain and monitor attention, disengage attention from distractions, and redirect attention to an intended object, body sensation, or movement (Lippelt et al. 2014; Lutz et al. 2008; Tops et al. 2014). During FAM, Feedback helps meditators to detect when attention has drifted and direct their focus back on task (Niksirat et al. 2019). This cannot be achieved using pre-defined vocal guidance only. A promising advancement is interventions which integrate biofeedback sensors with real-time monitoring of respiration, neural activity, heart tracking, and skin conductance (Döllinger et al. 2021; Kitson et al. 2018). This biological data can be relayed to the user through dynamic changes in the environment (i.e. music, sound, colour, lighting, object appearance, and animations) which helps users to detect and modulate internal states (Du Plessis 2017; Fernández-Aranda et al. 2012; Patibanda et al. 2017; Prpa et al. 2018; Tinga et al. 2019; Vidyarthi 2012). Currently, however, accessibility remains an issue; biofeedback configurations are often obtrusive and uncomfortable, requiring considerable financial cost, effort, and expertise to implement (Rockstroh et al. 2021). In the current study, accessible feedback mechanisms are considered as tools to guide FAM practice and facilitate the efficacy and motivational value of mindfulness interventions.

A largely unexplored mindfulness approach is the integration of FAM with mindful movements. Mindful movements typically involve paying attention to slow, continuous, gentle bodily movements which encourage present moment awareness (Salmon et al. 2010) and induce a state of relaxation (Benson et al. 1974; Niksirat et al. 2019). When integrated with FAM, it has been suggested that mindful movements provide additional opportunities to detect mind wandering, and that physical movement can mitigate some of the incurred cognitive demands (Clark et al. 2015). Adopting principles of FAM and mindful movement, Niksirat et al. (2019) developed a framework for attention regulation using the interactive capabilities of mindfulness-based mobile applications. The framework contains two key mechanisms: detection and feedback. The user is required to maintain a slow movement pattern, detected by finger movements across a touch screen or accelerometer and gyroscopic inputs as a device is in motion. This acts as a detection mechanism, identifying when movement and attention has drifted off-task. Restorative audio–visual stimulation is faded out to provide feedback, supporting continuous self-regulation which is fundamental to meditative practice (Lutz et al. 2008). Preliminary research utilising this framework supports its use for mindfulness meditation, with additional advantages for specific user groups (people who are easily distracted or have low confidence/motivation to meditate) and efficacy benefits when used in busy environments (Niksirat et al. 2019). The attention regulation framework is yet to be applied and evaluated within VR. In the design of an interactive VR MBI, we utilised the interactive capabilities (positional tracking of handheld controllers) of modern all in one VR headsets (e.g. Meta Quest) adopting these principles. This includes an integration of FAM and mindful movement as a tool for detection and feedback.

2 Development of the interventions: restorative and focused attention approaches

The VR interventions used in this study were designed with an emphasis on accessibility and engagement. This entails novel interventions using low-cost, portable (untethered) VR systems which require no specialised equipment or training to use. A short (6 min) duration was used which is ideal for efficacy and enjoyment, and remains practical for the work day (Bennett et al. 2019). We evaluated two distinct approaches: passive and interactive. The passive approach (Passive VR) is designed primarily for restoration and requires no direct input from the user. In the interactive version (Interactive VR), user movement is tracked, and real-time feedback is provided to facilitate attention regulation. Both approaches employ a visual breathing guide which was based on prior research demonstrating the positive effects of breathing exercises for attention restoration, physiology, mood, and mindfulness (Blum et al. 2019; Lin et al. 2014; Ma et al. 2017; Prpa et al. 2018; Russo et al. 2017). Both approaches also utilised the same abstract VE designed to promote restoration. The VR interventions were developed in Unity by Liminal VR as part of a research collaboration.

2.1 The virtual environment

The breathing guide forms the central focal point of the VE. This is a 3D sphere (passive version) or a circle (interactive version) which expands and retracts to encourage a steady breathing rate of 6 breaths per minute (Fig. 1b). The environment is restricted to a narrow field of view to ensure that the user's gaze is maintained in view of the breathing guide. It also lacks features that represent a prototypical environment such as a horizon. Instead, a minimalistic approach is adopted to encourage greater focus (Terzimehić et al. 2019) and reduce visual complexity and fatigue.

ART design principles were incorporated to create a surrounding VE which maximises the potential for restoration. Unlike prior mindfulness and restoration studies which mostly incorporate nature environments (Döllinger et al. 2021; Ohly et al. 2016; Stevenson et al. 2018), or nature-related stimuli (Prpa et al. 2018; Tinga et al. 2019), a purely abstract visual design is used. This includes a series of fractal-like symmetrical shapes. The presentation of these shapes becomes more complex over the course of the experience, often replicating each shape at different scales, and merging multiple shapes with different colours to form complex visual patterns. Complexity is adjusted over the course of the experience to sustain interest and manage fatigue (Hagerhall et al. 2015) (Fig. 1a). Slow tempo (50 BPM) calming music was used to encourage increased relaxation and set the conditions for restoration and meditative practice (Baldwin and Lewis 2017). Vocal guidance was used primarily at the beginning to provide instructions regarding the interaction and the breathing visualisation.

2.2 Interactive VR design

The interactive approach implements principles of the attention regulation framework (Niksirat et al. 2019), FAM, and mindful movement to support mindfulness in VR. The focal point of the exercise was the breathing visualisation, coupled with a movement pattern: spreading the arms outwards whilst breathing in, and bringing the arms back together whilst breathing out (Fig. 1c). The movement incorporates slow design principles (Grosse-Hering

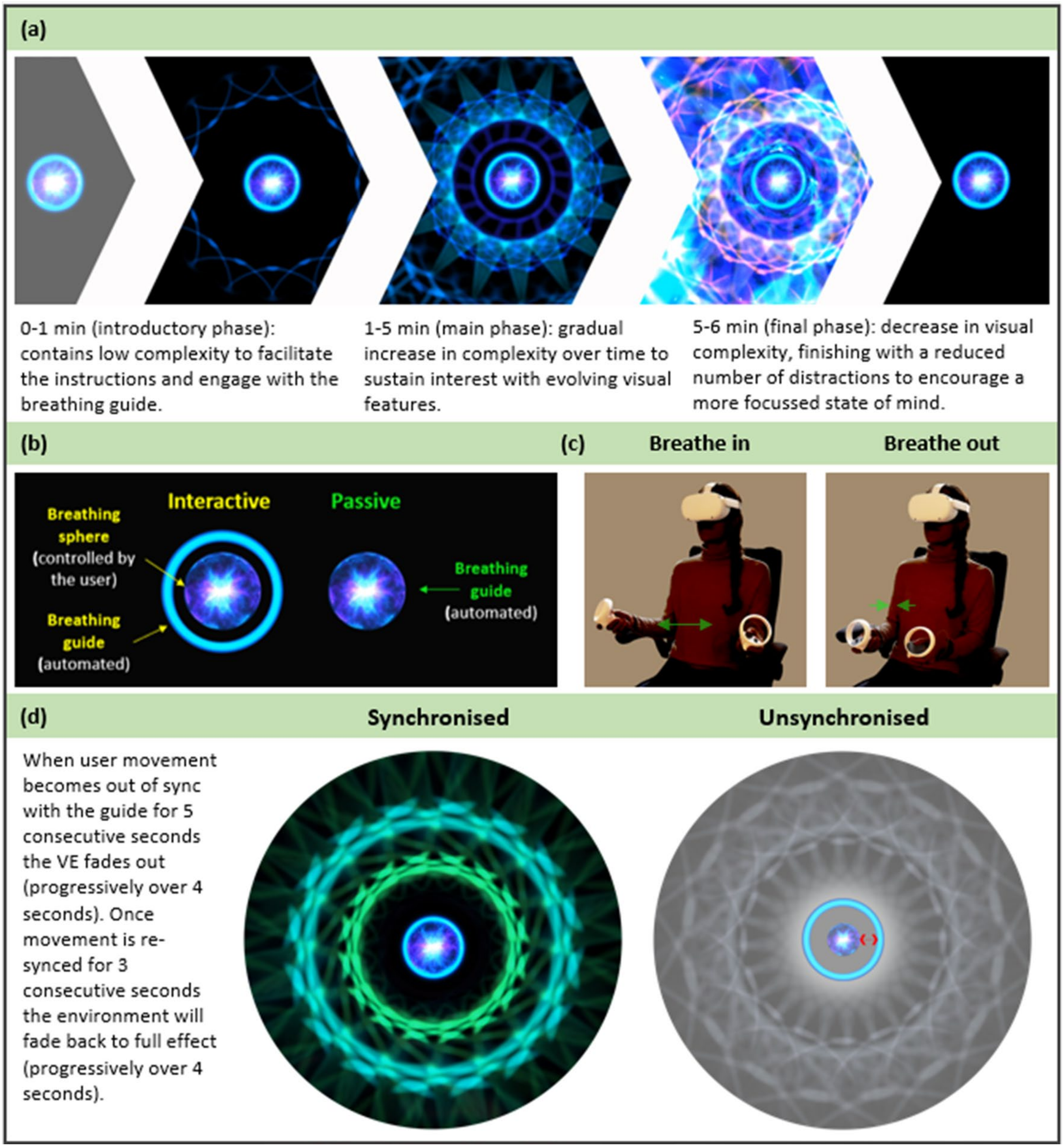

Fig. 1 Descriptions of the VR intervention designs including **a** the virtual environment (VE) progression, **b** passive and interactive versions of the breathing guide, **c** the movement pattern involved with the interactive version, and **d** details of the fade in/out sequence in the interactive version

et al. 2013) and repetitive motion geared towards the relaxation response (Benson et al. 1974). Previous studies have shown that large sweeping physical movements made by the user synchronised with the expansion/contraction of virtual objects can elevate mental states of calmness, clarity, and focus (Kitson et al. 2018). Movement is tracked through a handheld controller gripped in each hand (reliant on positional tracking) which changes the size of the central breathing sphere. The aim is to synchronise movement of the sphere with the movement of the outer breathing guide which moves automatically at a set breathing rate. The VR system detects when movement becomes desynchronised (e.g. too fast, slow, or idle), which then provides real-time feedback by fading out the surrounding environment and music (see Fig. 1d). This draws from the attention regulation framework where ongoing feedback stimulates active awareness of movement and attention, encouraging self-regulation as attention drifts from movement and breathing. The VE remains in full effect as movement is sustained in rhythm with the guide, acting as a visual indication of performance and providing intrinsic rewards to continue. This activity ends in the final minute of the exercise to limit the possibility of fatigue from sustained practice. At this stage, participants are encouraged to relinquish control and observe passively. Compared to previous VR mindfulness interventions that utilised dynamic feedback, the current approach employs feedback through built-in hardware features of the VR system. This is distinct from other interventions that required the use of additional biofeedback and respiratory sensors (Gromala et al. 2015; Järvelä et al. 2021; Kosunen et al. 2017, 2016; Wang et al. 2022a).

2.3 Passive VR design

The passive approach is closely aligned with the principal components of ART. To facilitate attention restoration, interventions should support effortless user engagement (Kaplan and Kaplan 1989), and accordingly, users should be able to "act in accordance with their own inclinations by simply letting their attention go to what they find interesting" (von Lindern et al. 2017, p. 187). Correspondingly, there is no input involved and users have no control over the VE. This is distinct from the interactive approach where the intent of the exercise is pre-defined and there is less freedom to fully attend to the surrounding VE. The breathing guide remains the focal point of the experience, following previous design approaches combining breathing guidance with restorative environments to support restoration (Blum et al. 2019). Participants were instructed to follow the guide during the introductory phase (Fig. 1b) and either continue breathing or spread awareness to the environment for the rest of the experience.

3 Study aims

This study evaluated the feasibility and benefits of implementing interactive forms of meditation and abstract forms of restorative environments in VR to support well-being and improve motivation. More specifically, we sought to assess whether (1) interactive forms of FAM can support mindfulness in VR, and (2) whether abstract environments provide suitable conditions for restoration to occur in VR. This involved quantitative comparison of the VR interventions across experiences of state mindfulness, perceived restoration, mood, cognitive state, and enjoyability. For mindfulness, we evaluated the interventions based on their ability to increase state mindfulness. Attentional states were also used as an indicator of mindfulness due to the intrinsic nature of attention within FAM (Lutz et al. 2008). For restoration, we assessed whether the interventions met the criteria of ART and reduced mental fatigue compared with a VR nature intervention. We predicted that the passive VR intervention would be more beneficial for restoration and the interactive VR intervention would be better suited for mindfulness. Due to the novelty of the passive and interactive VR interventions, we also included a qualitative evaluation of these approaches to gain deeper insights into participants experiences which expand on the quantitative measures. This included a series of open-ended questions to explore participants overall reactions and uncover perceptions of the motivational and practical use of VR.

4 Method

4.1 Participants and design

The study was conducted online using a mixed within-between design. We implemented an unsupervised online VR study as online studies are feasible, ecologically valid, and generate reliable data whilst complying with COVID-19 restrictions (Mottelson et al. 2021). Each participant completed a single testing session which involved a pre-intervention survey (T1), followed by exposure to a single VR intervention, and a final post-intervention survey (T2). Sixty-eight participants were initially recruited. Ten were excluded due to testing disruptions and hardware issues. The final sample comprised 58 participants with 32 males, 25 females, and 1 who preferred not to say. Average age was 42.1 years (SD = 14.7). Participants required access to a VR headset to experience the VR intervention. Recruitment was conducted via social media (Facebook and Reddit) and a notification system within the Liminal VR application. Once participants had registered for the study, they pre-arranged a day to complete the testing session.

Participants were allocated to one of three VR conditions: Interactive VR, Passive VR, or Nature VR. The nature condition was a 360° nature video accessed via the YouTube VR application. The video cycled through a variety of nature scenes (e.g. beaches, waterfalls, mountains, rivers) which are observed whilst listening to calming music. The use of pre-recorded 360° nature footage replicates previous approaches which have found restorative effects (Browning et al. 2020; Chung et al. 2018; Schutte et al. 2017; Stewart and Haaga 2018). Nature VR was included as a control to compare the restorative effects of abstract and nature environments. Passive VR and Nature VR were both described as restorative interventions (involving passive relaxation), whereas Interactive VR was described as a mindfulness intervention (involving interactive meditation). Group allocation was pseudo-randomised. Some participants who had technical difficulties installing the software for Passive VR or Interactive VR were automatically allocated to the Nature VR condition (using the YouTube VR app). Participant allocation to each group included Passive VR ($n = 19$), Interactive VR ($n = 19$), and Nature VR ($n = 20$).

4.2 Measures

4.2.1 Sample characteristics

Demographic information including age, gender, and country of residence were recorded. Participants indicated their prior experience using VR (1 = "none", 2 = "low", 3 = "moderate", 4 = "high"). They also reported their level of experience with meditation practices (1 = "none", 2 = "basic", 3 = "intermediate", 4 = "expert") and how frequently they currently practiced meditation (1 = "never", 2 = "occasionally", 3 = "several times a week", 4 = "most days").

4.2.2 State change measurements

A visual analogue scale (VAS) similar to that used by (Navarro-Haro et al. 2017) was used to measure changes in mood and cognition pre- and post-intervention. Participants were asked to rate from 1 to 7 points on the VAS (1 = "not feeling this at all"; 7 = "feeling this extremely") for the following mood states: happiness, sadness, anger, surprise, anxiety, calm/relaxed, and vigour/energy. Two items (mental fatigue and focus) were included to capture some of the cognitive factors associated with restoration and mindfulness meditation.

An adapted (shortened) version of the State Mindfulness Scale (SMS) (Tanay and Bernstein 2013) was used to measure changes in state mindfulness. The original version includes 23 items using a 5-point scale (1 = "not at all" to 5 = "extremely"). Five Items from the State Mindfulness of Mind factor were chosen focusing on items which reflected participant's awareness of the present moment, e.g. "I felt closely connected to the present moment" and "I noticed many small details of my experience". In the pre-intervention version, participants were asked to relate their answers to the 5-min period before they started the research study. The post-intervention questions were related to the time during the VR experience. Scores from all items on the SMS were averaged to create an overall state mindfulness score.

4.2.3 Post-intervention measurements

A modified version of the Perceived Restoration of Activities Scale (PRAS) (Basu et al. 2018; Norling et al. 2008) was used to measure the perceived restoration of each VR intervention. Items from three subscales were included: "Being away", "Fascination", and "Extent". The subscale "Compatibility" was excluded as the items were deemed irrelevant. Participants rated from 1 ("not at all") to 5 ("extremely") to the extent they agreed with each item. Using the same scale, an additional question regarding enjoyment was included ("I enjoyed doing this activity"). Ratings of the perceived complexity and familiarity of the VE were also recorded from 1 ("not complex/familiar at all") to 5 ("extremely complex/familiar").

Participants also indicated how much physical and mental effort was involved during the VR experience. A visual analogue scale (0 = "no effort"; 7 = "max effort") was used for physical and mental effort separately.

4.2.4 Open-ended questions

Participants in the experimental conditions (Passive VR and Interactive VR) were asked a series of open-ended questions in written format. Open question 1 (OQ1): "*In as much detail as possible, please summarise your overall reaction to the virtual reality experience*". Open question 2 (OQ2) explored the motivational aspects of the intervention (uptake likelihood): "*Is this type of VR experience something you would use on a regular basis?*" (answering "yes", "no", or "unsure", with an explanation why). Lastly, additional questions were intended to explore in more detail two of the key features of interest: the abstract environment and the interactive approach to meditation. For the interactive condition, participants were asked open question 3 (OQ3): "*If you have practiced any guided relaxation exercises in the past outside of virtual reality (e.g., meditation, guided breathing) how does this compare to your past experiences?*". For the passive condition, participants were asked open question 4 (OQ4): *"How would you compare your sense of relaxation in the VR environment to what you might experience in a real-world nature environment?"*.

5 Statistical analysis

5.1 Quantitative

We applied robust inferential statistics to participant demographic, mood, and cognitive measures due to minor-to-moderate departures from normality and some outlying data (Mair and Wilcox 2019). Trimmed means analysis (using the default 20% trim level) was implemented in the statistical program R version 4.1.0 (R Core Team 2021) using the WRS2 package (Mair and Wilcox 2019). For all sample characteristics, one-way ANOVAs were performed using the *t1way* function to identify between group differences (3 levels: Interactive VR, Passive VR, and Nature VR) (Table 4). For all state change VAS mood measures (happiness, sadness, anger, surprise, anxiety, calm/relaxed, and vigour/energy) and SMS, we first performed mixed within-between ANOVAs using the *bwtrim* function with group (3 levels:

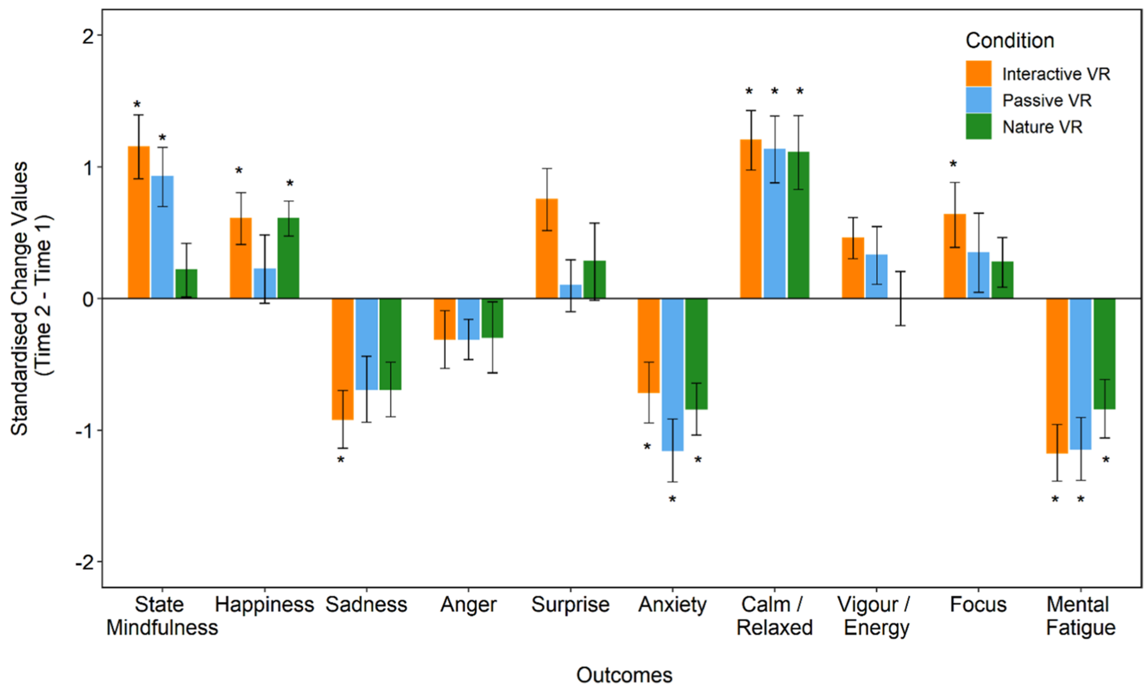

Fig. 2 Standardised change values (T2–T1) for all outcomes as a function of condition. Standard error bars represented in black lines. Notes. *$p<.017$ (Bonferroni corrected)

Interactive VR, Passive VR, Nature VR) as the between subjects factor and time (2 levels: pre- vs post-measurement) as the within subjects factor. Where significant time or condition*time interaction effects were identified, post hoc paired samples *t* tests using the *yuend* function were implemented to identify changes from T1 to T2 for all conditions, (Full results are presented in Table 6.) It should be noted that the plot in Fig. 2, presents standardised change values (T2–T1 / σ_{T1}) for all the state change measurements.

Where main condition effects were identified, independent samples t tests were implemented using the *yuen* function to compare conditions at the pre- and post-measurement time points separately (Mair and Wilcox 2019). For all post hoc comparisons, an adjusted alpha level of 0.017 ($p=0.50/3$, two-tailed) was applied to control for multiple comparisons. Explanatory effect sizes ($\hat{\xi}$) (a robust measure of effect size; Wilcox and Tian 2011) are reported for all paired samples t tests with values of 0.10, 0.30, and 0.50 representing small, medium, and large effects, respectively (Mair and Wilcox 2019).

5.2 Qualitative

Responses to the open-ended questions were collated for each participant. Data analysis was guided by the six steps of reflexive thematic analysis outlined by Braun et al. (2019). Themes were identified by the lead researcher using an inductive approach. This involved a process of familiarisation and generating codes which were organised into a range of meaningful groups (Tuckett 2005). Throughout each group of codes, preliminary themes were identified that were consistent throughout the data set. Each of these themes were reviewed and discussed between the lead researcher and author JS before being finalised.

6 Results

6.1 Sample characteristics

Descriptive statistics and results from one-way ANOVAs are presented in Table 4. On average, participants reported intermediate levels of VR experience (mean = 3.2), basic meditation experience (mean = 2.3), and occasional meditation frequency (mean = 2.1). There were no significant differences between groups relating to age, VR experience, meditation experience, or meditation frequency. Country of residence spanned across nine countries including the USA ($n=29$), Australia ($n=10$), UK ($n=8$), Canada ($n=4$), Ukraine ($n=3$), Russian Federation ($n=1$), Denmark ($n = 1$), Ireland ($n = 1$), and Italy ($n = 1$). Most participants used a Meta Quest 2 headset to complete the task ($n = 47$) with the remaining using Meta Quest 1 ($n = 6$), HTC Vive ($n = 3$), or other ($n = 2$).

6.2 Quantitative findings

6.2.1 State change data

Descriptive and test statistics for state change data (T2–T1) are presented in Tables 5 and 6. For all VR conditions, there were significant reductions in mental fatigue and anxiety, and increased calmness/relaxation (all P's < 0.05). State mindfulness significantly increased for the interactive and passive VR conditions, with no change for the nature VR group. There was significantly increased focus and decreased sadness for those who completed the interactive VR intervention, with no changes in the other VR groups. Happiness was significantly increased in the nature VR and interactive VR conditions, but not the passive VR condition. There were no significant changes over time for anger, surprise, or vigour/energy within any of the conditions.

A main condition effect was found for happiness scores. Pre-intervention happiness scores were significantly higher in the nature VR versus passive VR condition ($T_y[22.06] = 2.82$, $P = 0.010$, $\xi = 0.47$). No other comparisons were significant (Interactive VR and Passive VR [$T_y[21.05] = 1.20$, $P = 0.245$, $\xi = 0.25$], Interactive VR and Nature VR [$T_y[22.26] = 1.18$, $P = 0.252$, $\xi = 0.23$]). Post-intervention happiness scores were significantly higher in the nature VR than passive VR condition ($T_y[22.41] = 3.32$, $P = 0.003$, $\xi = 0.68$). No other comparisons were significant (Interactive VR and Passive VR [$T_y[23.98] = 2.29$, $P = 0.031$, $\xi = 0.41$], Interactive VR and Nature VR [$T_y[22.22] = 0.76$, $P = 0.454$, $\xi = 0.23$]).

6.2.2 Post-data

Descriptive statistics and one-way ANOVAs results for the post-intervention measures are presented in Table 1. Both physical and mental effort significantly differed between conditions. This effect was further probed using between samples t tests. The interactive VR condition involved significantly greater physical effort than the passive VR condition ($T_y[18.23] = 4.27$, $p < .001$, $\xi = 0.61$). There were no significant differences between the interactive VR and nature VR ($T_y[22.99] = 2.32$, $p = 0.030$, $\xi = 0.36$) or the passive VR and nature VR conditions ($T_y[17.47] = 1.53$, $p = 0.143$, $\xi = 0.55$). The interactive VR condition also involved significantly greater mental effort than the passive VR condition ($T_y[24.00] = 2.65$, $P = 0.014$, $\xi = 0.49$). There were no differences between the interactive VR and nature VR ($T_y[22.36] = 1.90$, $P = 0.070$, $\xi = 0.34$) or passive VR and nature VR conditions ($T_y[22.30] = 0.57$, $P = 0.574$, $\xi = 0.14$) in terms of mental effort.

There were no significant group differences on the PRAS or any of its subscales (away, extent and fascination; all P's > 0.05). There were also no significant differences in enjoyment between conditions, or any differences in the perceived complexity or familiarity of the virtual environments (all P's > 0.05).

Table 2 Frequency of responses to OQ2

Condition	Response (%)			
	Yes	No	Unsure	No/unsure combined
Interactive VR	73.68	5.26	21.05	26.31
Passive VR	36.84	15.79	47.37	63.16
Nature VR	70.00	0	30.00	30.00

Row totals do not sum to 100% due to rounding

Table 1 Descriptive statistics and results from one-way ANOVAs for post-intervention data

Outcome	Descriptive statistics			Test statistics				
	Interactive	Passive	Nature	One-way ANOVA				
	M (SD)	M (SD)	M (SD)	*F*	df1	df2	*P*	ξ
PRAS	3.53 (0.82)	3.48 (0.65)	3.65 (0.76)	0.29	2	23.11	.749	0.22
Being Away	3.42 (1.05)	3.44 (0.85)	3.58 (0.79)	0.04	2	23.33	.964	0.20
Extent	3.68 (0.89)	3.56 (0.67)	3.72 (0.86)	0.86	2	22.29	.436	0.28
Fascination	3.49 (0.79)	3.44 (0.78)	3.65 (0.84)	0.12	2	22.43	.885	0.20
Enjoyment	4.16 (1.01)	4.05 (0.71)	4.30 (0.73)	0.59	2	22.82	.561	0.25
Mental Effort	3.21 (2.07)	1.79 (1.87)	2.15 (1.95)	3.69	2	23.10	.041*	0.42
Physical Effort	2.21 (1.84)	0.74 (1.63)	1.20 (1.32)	9.01	2	21.04	.001*	0.54
Complexity	2.05 (0.91)	2.74 (1.05)	2.75 (1.37)	1.86	2	22.03	.179	0.36
Familiarity	2.68 (1.29)	2.53 (0.90)	2.80 (1.20)	0.23	2	20.13	.798	0.24

*Indicate significant values ($P < .05$)

The frequency of responses to OQ2 concerning uptake likelihood: "*Is this type of VR experience something you would use on a regular basis?*" is presented in Table 2. Logistic regression was used to compare the likelihood of participants selecting "Yes" in the interactive VR and nature VR conditions compared with the passive VR condition. As there were zero observations of "No" in the nature condition, the "Unsure" and "No" categories were combined into a single category for regression analysis. Allocation to the nature VR (OR = 4.0, 95% CI [1.05, 15.2], $P = 0.04$) and interactive VR (OR = 4.8, 95% CI [1.20, 19.13], $P = 0.03$) conditions was associated with increased odds (≥ 4.0) of reporting intention to use the VR experience compared to participants in the passive VR condition.

6.3 Qualitative analysis

Four superordinate themes were identified with an additional eight subordinate themes (see Table 3). Themes for the interactive VR and passive VR groups were first considered separately. Two of the main themes ("Enjoyment" and "Noticing attentional states") are reported together due convergence between the groups. The other two main themes were unique to each VR group. These were generated from the additional open-ended questions presented separately to the passive VR and interactive VR groups: "Relaxing in VR vs real life" (Passive VR) and "Novel experiences of meditation" (Interactive VR). Quotes are italicised with participants identified according to their assigned group and number: Interactive VR (I 1–19), Passive VR (P 1–19).

6.3.1 Enjoyment

This theme relates to participants overall sense of enjoyment, informed by their sense of well-being, reactions to the environment, and their interest levels during the experiences.

6.3.1.1 Changes in well-being Across both VR conditions, reports of increased calm and relaxation were dominant, indicating a strong sense of enjoyment, for example: *"I was moved to a relaxing state in minutes it was quite wonderful"* (P13), "*My anxiety is clearly lowered and easily replaced with a relaxed calm. I feel mentally comfortable when I did not before the experience*" (I9). When describing the features they found calming, most participants highlighted the visual elements and the breathing guidance, e.g. "*the combination of the breathing, sound and the geometric patterns I found very calming*" (P6). This experience was not universal, however, with one participant noting "*when the orb faded I felt the most serene and then slightly anxious/alone*" (P2).

While calm, a small number of participants in the passive VR group reported feeling tired or sleepy. This was mostly reported as a positive sensation, e.g. *"stress and anxiety have definitely felt less during the course of the experience, to the point that I was able to relax so much I almost fell asleep"* (P6).

Two participants expressed a sense of frustration whilst using the interactive VR experience which appeared to reduce enjoyment: "*I would have preferred to be able to see my hands/controllers in some way. Not having them show makes it feel like the app is broken*" (I3), and "*I find out that coordination between my movement and orb radius was not perfect and it frustrates me a bit"* (I19).

6.3.1.2 Aesthetic response Contributing to the overall enjoyment of the interventions, many participants described that the abstract VE was pleasing to observe, for example: *"I was really amazed by the visual kaleidoscope effects, and it felt like my head was getting refreshed. The movements really captivated me, the way they gyrate and spin around"* (P15), "*The colours were beautiful and vibrant, they were perfect"* (P7), and "*All the colours and shapes were fascinating to watch and very relaxing*" (P4).

Reactions to the visual elements were not always consistent, for example: "*The colours were beautiful and vibrant, they were perfect … I loved the circular patterns too, but sometimes the constant pulsing was a little too much*" (P7) and "*the middle part was a little too colourful for me and the end with the black/blue colour was my favourite and most calming/relaxing period*" (P1).

6.3.1.3 Sustained interest Some participants reflected on how the VE sustained their interest: "*The visuals were interesting and changed to keep me looking around"* (P8), "*I was sucked into the experience. I really enjoyed how the visuals kept changing over time as they compounded and got more complex with different colours"* (P11), "*There was constant points of interest that kept changing in my peripheral vision as I was watching the centre orb which kept the experience fresh"* (P17), and *"I liked that the colours and patterns became more intense as the experience went on"* (I3).

Table 3 Main themes and sub-themes identified through qualitative analysis

Themes	Sub-themes
Enjoyment	Changes in well-being Aesthetic response Sustained interest
Noticing attentional states	Present moment awareness Heightened focus Mind wandering
Relaxing in VR vs real life	Relaxation preferences A controlled environment
Novel experiences of meditation	

Considering the interventions as a whole, one participant described the experience as "*Slightly boring*" (I12). This was contrasted by two others who compared their sense of boredom to their own previous experiences: "*The VR experience was calming but not boring as some experiences can be" (P17)* and *"I knew that it was going to last 6 min, so I didn't get bored, which is typically what happens"* (P13).

6.3.2 Noticing attentional states

This theme includes how respondents perceived their state of attention during the VR interventions, including their awareness of the present moment and changes in their sense of focus.

6.3.2.1 Present moment awareness Participants frequently described an increased awareness of the present moment. This was most evident in the interactive VR group responses who spoke about the present moment overtly, e.g. "*it helped to feel in the present moment moving my arms with the orb. I meditate often, but also doing a physical activity like so, may make you more aware of the present moment"* (I7) and "*I do think relaxing music paired with calming/entrancing visuals kept me in the present moment*" (I17). Participants across both groups also outlined a greater awareness of specific present moment sensations or feelings. This included awareness of the external environment, e.g. "*It was psychedelic and put me into a different state of consciousness, bringing my focus to what I was seeing and hearing through the experience"* (P14) and an awareness of inner experiences, e.g. "*I felt like I was isolated during the experience and focused solely on myself*" (I18).

6.3.2.2 Heightened focus An improved sense of focus was frequently reported amongst the interactive VR group. This typically involved feeling more focused during the experience, e.g. *"It surprised me a little as to how well it gained my focus in a short time"* (I14), "*This is very similar to my mediation I do as a Buddhist. Keeping the mind clear to focus"* (I13), and "*for me it's super difficult to keep my mind blank when I am trying to meditate, this VR experience helps me to focus and relax*" (I2). Participants elaborated, describing aspects of the interactive VR experience perceived to enhance their focus, e.g. "*it allowed me to only focus on two things, breathing and focusing on my movement, since it was only these, my focus was…more focused*" (I6).

In both groups, participants described how VR helped to maintain attention on the given exercises, e.g. "*Too many things happen in the real world to pull concentration, VR can remove those obstacles*" (P13), "*VR helps me to maintain my attention in the experience and not get distracted*" (I5), and "*I think the VR provides more separation from the real world and therefore more relaxation*" (P9).

6.3.2.3 Mind wandering Some participants in the interactive VR group reported moments of mind wandering. In one case this was a positive experience, as they described losing focus during the focused attention exercise: *"During the experience, I had to re-focus a couple of times, but it wasn't disturbing…it was really pleasant"* (I11). In another instance, mind wandering lead to some confusion: "*I became very aware of my mind wandering a lot and I don't know if that's a good or bad thing*" (I3). Sustained attention was not a goal in the passive VR intervention; therefore, mind wandering was experienced differently: "*It let my mind wander into different experiences, the 3D affect, concentrating on my breathing, giving me the opportunity to experience all the details*" (P12).

6.3.3 Relaxing in VR vs real life

In the passive VR group, respondents compared their ability to relax in virtual and real-life scenarios. This included a mixture of preferences but also a well-valued advantage of VR relating to the control of external factors.

6.3.3.1 Relaxation preferences Respondents had mixed relaxation preferences when comparing the abstract VR environment to real-life nature environments. Some preferred relaxing in VR, for example: "*There is nothing like leaving the real world for the experience of peace and tranquillity this VR experience gives you*" (P16) and "*It's definitely not anything I would find in real life. The sense of relaxation is outstanding in VR*" (P15). This was the opposite for others, e.g. "*it did not provide a sense of relaxation that was as good as being out in nature e.g., a forest or beach*" (P18), "*nothing beats laying down next to a river with the wind blowing and the soft sound of nature*" (P10).

6.3.3.2 A controlled environment Participants often described how VR provides an element of control which is difficult to achieve when relaxing in real-life nature environments, for example: "*VR removes all the unpredictable elements that can ruin a real-world nature experience. It's predictable, which in itself, is a relaxing notion*" (P14), "*Since I can control most external distractions before starting, I'm almost relaxed to begin with knowing that I can dive right in*" (P11) and *"I cannot fully relax due to people or insects or smells. However, I found this very relaxing due to the lack of these worries, as well as my control of the environment outside of the headset*" (P3). The ability to easily enter a new environment and relax without safety concerns was also considered a major advantage of VR:

> I can get away from everything and everyone. It's hard to disconnect in the real-world...especially when living

> in towns/cities. We always have to have a 'constant' awareness, even in a nature setting. You just don't know who may be around. There are so many news reports of people being attacked etc whilst out running/walking and/or in parks, that I cannot fully let my senses go. It's also a time issue too, travelling there and back. In the VR environment, with the press of button—I am a world away in seconds. Amazing (P7).

6.3.4 Novel experiences of meditation

Participants in the interactive VR group compared the VR intervention with their own previous experiences of meditation. In all cases, the intervention was seen as something novel. Movement was reported as a factor which enhanced enjoyment, e.g. *"direct control of experience by my movement was something new and fascinating"* (I19) and "*This is the first time I've done any physical activity alongside the meditating before, so it really shed a light on visual meditation. I would recommend this to others, it is an intriguing experience"* (I7). Movement-based meditation also offered an alternative for one person who has difficulties with sedentary approaches: *"for me to have a moving meditation it's the best, it helps me to calm down, in a meditation that you stay still, it is very difficult for me"* (I11). Reactions to the movement were not consistently positive, for example one participant "*would have liked the breathing on my own with no hands a little sooner*" (I4).

The visual component was another novel aspect which people found assisted the meditation practice. Some described easing some of the challenges with meditation, e.g. "*I felt like with added visuals I was more easily able to let things mentally melt away and not fight to keep them that way"* (I9) and,

> I have done some meditation in the past, but this is totally different in a VR experience. it is more easy to let go because the image is already there. You don't have to think, you just have to let go, and follow the guide (I11).

Two other participants compared the interactive experience with previous audio-guided meditations they have tried, hinting at a preference for visually guided meditation as it helped them focus: "*I liked that there wasn't too much talking. I've tried Headspace before but the guy talks too much for me and I find it distracting*" (I3) and,

> I tried an app before it is great as well but I think the VR experience is more helpful for beginners as it helps you to really focus. Audios are good too but if you close your eyes you could get a bit sleepy or if you open your eyes your thoughts start to come to your mind (I2).

In contrast, two participants hinted that the environment was distracting during the focused attention practice: "*The graphics was memorizing, I felt like I wanted to wander from my hand movements and just focus on the surrounding, but I kept the hand movements going*" (I6). For the second participant, they felt better able to appreciate the environment once the interactive phase of the experience stopped: "*I did think the meditation was a little busy on screen during the arm portion, but I enjoyed that without the arm motions*" (I15).

7 Discussion

The current study employed various quantitative measures of restoration, mindfulness, mood, mental state, and motivation to explore the efficacy, feasibility, and acceptability of passive and interactive VR experiences. We also used a complementary qualitative approach which revealed further insights into participant's experiences. Participants who experienced passive and interactive VR experiences reported enjoyment, increased state mindfulness, and enhanced aspects of well-being (calm/relaxation, anxiety, and mental fatigue). The abstract VE, used in both interventions, contributed to increased enjoyment, sustained interest, and a sense of novelty. Furthermore, the addition of interactive guidance (sustained mindful movement and dynamic feedback) provided additional well-being benefits for cognition (focus) and mood (happiness and sadness) and presented greater motivational value (uptake likelihood) than the passive version. These findings are discussed whilst considering the feasibility of interactive approaches for MBIs and abstract forms of restorative environments.

7.1 Interactive mindfulness meditation

Upon recognising the scope for potentially more engaging and effective approaches to VR mindfulness meditation (Döllinger et al. 2021), the interactive intervention introduces a unique approach where focus is guided and informed by the movement of the meditator. This expands on the current mindfulness VR literature which has predominantly used vocal guidance with limited feedback to guide the practice (Chandrasiri et al. 2020; Navarro-Haro et al. 2017; Seabrook et al. 2020). The evidence gathered here supports the use of interactive guidance. A central objective of mindfulness practice is generating a quality of attention more attuned to the present moment (Bishop et al. 2004). This was reflected in increased state mindfulness scores and qualitative comments that described greater momentary awareness in the interactive VR group. It should be highlighted that we adopted the view of Brown and Ryan (2003) that present moment awareness is the foundational component of mindfulness. However, we did not examine other attributes which have been associated with mindfulness, such as curiosity, openness, and acceptance (Bishop et al. 2004). Future research will need to clarify the impact of interactive MBIs on these additional mindfulness attributes.

Of interest, state mindfulness scores increased in both experimental interventions within abstract restorative environments, with no such effect in the nature control. These findings make a unique contribution to prior VR studies which have increased mindfulness primarily by using vocally guided meditations in nature (Chandrasiri et al. 2020; Navarro-Haro et al. 2017; Seabrook et al. 2020). We theorise that the use of a visual breathing guide shared by both experimental conditions helped generate present moment awareness, as breathing is extensively used as an attentional anchor for focused attention-based practices (Bishop et al. 2004; Colzato et al. 2016; Kajimura et al. 2020). Despite these similarities, the inclusion of the interactive components led to a more holistic range of health benefits commonly associated with mindfulness-based practices. Most notably, the interactive intervention was unique in that it increased participant's sense of focus; corroborated by both the quantitative and qualitative assessments. This aligns with previous investigations reporting attentional benefits following brief MBIs (Colzato et al. 2016; Mrazek et al. 2012; Norris et al. 2018). Increased focus following the interactive VR intervention is likely due to the addition of focused attention to movement which was excluded from the passive VR intervention. This is supported by research conducted by Hussien Ahmed et al. (2017) who found that the combination of visual and movement meditation modalities helped to trigger focus during states of mind wandering. Further research is needed to clarify the impact of movement on attentional functioning during meditation.

The efficacy of MBIs should also be considered alongside the meditator's motivation and adoption. Negative emotional reactions such as boredom, perceived learning requirements, and time demands commonly associated with meditation (Anderson et al. 2019) may inhibit regular and widespread adoption of meditative practices. Although participants in the current study indicated practicing meditation infrequently, most who completed the interactive VR intervention indicated that they would adopt similar activities on a regular basis. The quantitative analysis also favoured the interactive condition across the mood and cognitive factors assessed, which corroborates prior reports of affective and emotional benefits associated with online approaches to FAM (Kemper and Rao 2017). These beneficial outcomes are particularly promising from a motivational and adoption standpoint, considering the short duration of the intervention (6 min) which required no prior training, even for participants with low meditation experience. There were, however, some negative reactions identified through the qualitative analysis including frustration and boredom. Although most participants reported positive increases in well-being, it is important to account for the spectrum of experiences to encourage more widespread adoption.

We suggest the interactive design approach is particularly well suited to less experienced meditators due to the incorporation of guided movement, detection, and feedback mechanisms dedicated to supporting attentional focus and self-regulation. The focus required in FAM is a difficult skill which requires practice (Lutz et al. 2008) and experiences of mind wandering and fatigue are common (Frewen et al. 2016; Hasenkamp et al. 2012; Lutz et al. 2015). In the current study, focused attention practice was associated with reduced mental fatigue and the qualitative analysis revealed few reports of mind wandering. In one case, the act of re-engaging focus once it had drifted off task was reported as a positive experience. This requires further investigation but supports the use of dynamic feedback to detect mind wandering and reward sustained attention with aesthetically pleasing audio–visual stimulation (Niksirat et al. 2019). In contrast, one participant reported that mind wandering induced confusion, which could be remedied with long term training interventions in VR aiming to equip novice meditators with broader knowledge, confidence, and skill (Feinberg et al. 2022). Qualitative comments also revealed a broad sense of enjoyment from the movement and visual aspects of the interactive intervention. These elements enhanced the practice for some people and offered something new and engaging to their experiences of meditation. However, although these novel elements of the VR intervention were engaging following participants' initial usage, it is probable that engagement will decrease as familiarity increases over time. Considering this, along with the less positive reactions from some participants towards the interactive approach, it is imperative to have access to a variety of methods that cater to a broad and evolving spectrum of needs and preferences. This could include additional interaction methods (such as eye tracking), feedback (such as haptic feedback), and environmental approaches available in VR.

Overall, the evidence gathered shows positive signs that interactive forms of MBIs present strong motivational value. However, considering the challenges often faced when forming new health related habits and behaviours (Ajzen 1991; Hunt et al. 2020; Maiman and Becker 1974; Prochaska 2020), a more extensive examination of motivation which looks at behaviour change and VR adoption over time is required (Dehghani et al. 2022).

7.2 Abstract restorative environments

The restorative capacity of nature over other (e.g. urban) environments is well documented within the ART literature (Kaplan 1995; Ohly et al. 2016; Stevenson et al. 2018). We found comparable effects for perceived restoration (such as being away, having soft fascination, and sustained interest) between abstract and nature conditions, indicating equal restorative capacity of the abstract VE. Reported mental fatigue also reduced consistently following each intervention. This is a promising indicator of restoration considering the core goal of restorative interventions to enable recovery of depleted cognitive resources (Kaplan 1995). In most cases, participant's reactions to the abstract VE were positive, revealing a sense of aesthetic pleasure, relaxation, and sustained interest; effects more commonly attributed to nature environments (Kaplan 1995; Ulrich 1983). The qualitative analysis, however, did also reveal some mixed reactions to the VE, particularly during the more complex phases of the environment progression (Fig. 1a). This may be accounted for by individual differences in aesthetic preference for complexity (Street et al. 2016), or possibly, reduced perceptual fluency and symmetry as more abstract patterns were introduced to the VE (Joye et al. 2016).

In further support of restorative effects, the abstract VE appeared to have complementary effects when paired with an interactive form of FAM. This was evident within qualitative comments regarding the novel and facilitatory effects of visual guidance and stimulation for meditation. Originally, we had anticipated fewer restorative benefits due to the more demanding nature of the interactive intervention. Indeed, the interaction condition involved greater physical and mental effort, but mental fatigue was consistently reduced on average across conditions. In line with prior research (Blum et al. 2019; Lymeus et al. 2017; Niksirat et al. 2019), we theorise that exposure to a restorative environment helped offset the cognitive demands of the focused attention exercise. Granted, however, we cannot confirm the impact of the environment in this regard. We sought to minimise cognitive demands by pairing the exercise with a restorative environment, using a short duration, ending the interactive component early, and pairing the activity with a mindful movement; a combination of which likely reduced the potential for fatigue (Clark et al. 2015; Lymeus et al. 2017).

The evidence of restoration in the current study contrasts prior evidence of reduced restorative effects during abstract environment exposures (Berto 2005; Valtchanov 2010; Valtchanov et al. 2010). The main reason for this, we suggest, is a design process in the current study which closely factors the core components of ART. Overall, the findings support the use of evolving fractal-like patterns to sustain interest with softly fascinating stimuli, without overwhelming cognitive resources (Hagerhall et al. 2008; Joye et al. 2016). Future work should expand this research and look to maximise the restorative potential of abstract environments and reinforce VR health interventions. These findings come at a pivotal time when consumer interest in VR is growing (Rizzo et al. 2019). Thus, VR designers are tasked with applying multi-sensory inputs which complement an expansive range of desired user outcomes (e.g. benefits in mood, cognition, mindfulness, and restoration) and individual preferences.

7.3 Limitations and future research

Despite promising findings regarding the efficacy of interactive MBIs and abstract restorative environments, we relied primarily on participant subjective reports. However, the mixed methods approach allowed us to explore subjective experiences across a wide range of outcomes. This was suitable considering the novel integration of factors used (interactive guidance, dynamic feedback, mindful movement, fractal patterns) which contain relatively unknown and unexplored effects in VR. Future studies could measure cognitive and affective enhancement using behavioural and physiological measures (Norris et al. 2018; Rupp et al. 2017), mindfulness induction using additional measures of state mindfulness (Brown and Ryan 2003; Tanay and Bernstein 2013), and restorative assessments following cognitive fatigue and stress induction (Stevenson et al. 2018). In addition, future research should utilise broader active control conditions (such as traditional non-VR forms of brief MBIs) and no-treatment conditions to further substantiate the effects of interactive MBIs and abstract restorative environments in VR.

The online nature of the study presented some limitations. Despite clarifying with participants whether they encountered specific issues during the study, we could not verify whether the instructions were followed precisely as they were given. During recruitment, we also acknowledge that the assignment of participants who faced technical difficulties when installing the Passive VR and Interactive VR software to the Nature VR condition may have caused variance between groups regarding their technical expertise. Despite these limitations, the online testing methods employed enhanced the ecological validity of the study whereby participants could take part in natural (i.e. at home) settings.

In VR, we applied techniques from mindfulness meditation and restorative interventions, recognising the immersive benefits of VR which ease access to interventions regardless of one's physical location or the presence of distractions (Li et al. 2021; Navarro-Haro et al. 2017). The qualitative analysis supports this integration, revealing an appreciation of VR by allowing participants to relax in a controlled, predictable environment, and maintain attention on the intended activity without external distractions. For some participants, these benefits were considered difficult to attain when trying to relax outside of VR. These findings contribute to prior evidence regarding the relaxation benefits of VR for general populations (Riches et al. 2021). Still, we recognise that more widespread adoption of VR is hampered by digital divides due to social and financial inequalities (Ramsetty and Adams 2020; Riches et al. 2021). Also, VR use faces practical (e.g. discomfort, space limitations) and socio-cultural (e.g. acceptance) barriers which might prevent uptake across all industries and social contexts (Al Farsi et al. 2021; Dehghani et al. 2022; Naylor et al. 2019; Sagnier et al. 2020). We purposely used low-cost consumer-ready VR hardware, with short experiential duration, and alternative approaches (passive and interactive) to address some of these challenges. Future research could examine VR workplace adoption over time and across different cultures and industries to inform the development of future VR health interventions.

8 Conclusion

This study builds upon prior research which recognises the role of MBIs and restorative environments to help regulate mood and improve cognitive performance in-the-moment as negative states arise (Barton et al. 2020; Posner et al. 2015; Tang and Posner 2009). Expanding on conventional methods, we implemented novel VR approaches to address the accessibility and motivational barriers which inhibit these practices (Ajzen 1991; Anderson et al. 2019; Hunt et al. 2020; Maiman and Becker 1974; Prochaska 2020). These approaches advance on preliminary research in the field involving interactive MBIs applying the attention regulation framework (Niksirat et al. 2019) and restorative environments comprising abstract fractal-like patterns (Hagerhall et al. 2008; Joye et al. 2016). We found that interactive MBIs and abstract fractal-like environments facilitated increased mindfulness, restoration, and improved well-being when experienced in VR, whilst creating motivational value through novel and aesthetically pleasing designs. Despite broader benefits found in the interactive VR condition, we encourage future research to consider both interactive and passive VR approaches to accommodate individual differences in preference, physical ability, meditation experience, and mental state (e.g. stress or fatigue). The study findings are important for individuals who are currently unmotivated by conventional practices or unable to access restorative environments. VR is a burgeoning technology with vast potential to improve health and well-being. With increased interest, research, investment, and diversity, the efficacy and adoption of VR health interventions will continue to improve.

Appendix

See Table 4, 5 and 6.

Table 4 Descriptive statistics for sample characteristics by condition

Variable	Descriptive Statistics			One-way ANOVA				
	Interactive	Passive	Nature	*F*	*df1*	*df2*	*P*	*ξ*
	M (SD)	M (SD)	M (SD)					
Age	43.1 (15.4)	38.7 (12.7)	44.5 (16.0)	0.86	2	22.67	.440	0.28
VR Experience	3.3 (0.7)	3.2 (0.9)	3.1 (0.8)	0.39	2	21.55	.681	0.23
Meditation experience	2.3 (0.7)	2.4 (0.7)	2.1 (0.9)	0.39	2	22.06	.681	0.27
Meditation frequency	2.3 (0.7)	2.1 (1.1)	2.0 (0.9)	3.37	2	22.73	.052	0.30

Table 5 Descriptive statistics (means and standard deviations) of state change measures presented as a function of condition

Outcome	Interactive				Passive				Nature			
	Time 1		Time 2		Time 1		Time 2		Time 1		Time 2	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
State Mindfulness	3.1	0.7	4.0	0.6	3.0	0.9	3.7	0.7	3.4	0.8	3.5	0.7
Happiness	3.7	1.5	4.7	1.7	3.0	1.4	3.3	1.6	4.1	1.5	5.1	1.5
Sadness	1.8	2.0	0.5	0.9	1.5	1.7	0.5	0.8	1.5	1.6	0.5	0.8
Anger	0.6	1.1	0.4	0.8	0.5	1.0	0.3	0.6	0.5	1.0	0.2	0.4
Surprise	0.7	1.0	2.0	1.9	0.9	1.7	1.0	1.4	0.7	1.8	1.1	1.7
Anxiety	2.2	1.9	1.1	1.3	2.5	2.1	0.7	1.0	2.1	1.8	0.8	1.0
Calm/Relaxed	3.3	1.5	5.1	1.3	3.5	1.5	5.2	1.7	3.6	1.8	5.3	1.5
Vigour/Energy	2.9	1.3	3.6	1.4	1.8	1.5	2.4	1.7	2.8	2.1	2.8	1.2
Focus	3.5	1.8	4.6	1.7	2.9	1.7	3.5	2.0	3.0	1.6	3.5	2.0
Mental Fatigue	3.3	2.7	1.2	1.3	3.2	2.2	1.1	1.2	3.0	2.1	1.5	1.6

Table 6 Summary of inferential statistics for state change data

Outcome	Mixed ANOVA				Post hoc tests					
	Q	*df1*	*df2*	*p*	Comparison		T_y	*df1*	*p*	*ξ*
State mindfulness										
Condition	0.64	2	23.80	.537	Interactive	T1–T2	5.02	12	< .001*	0.76
Time	48.64	1	32.85	< .001	Passive	T1–T2	6.04	12	< .001*	0.59
Interaction	7.44	2	23.58	.003	Nature	T1–T2	1.04	11	.320	0.15
Happiness										
Condition	6.71	2	23.50	.005	Interactive	T1–T2	2.94	12	.012*	0.33
Time	13.59	1	28.26	.001	Passive	T1–T2	0.84	12	.417	0.21
Interaction	0.68	2	21.52	.517	Nature	T1–T2	3.98	11	.002*	0.46
Sadness										
Condition	0.03	2	23.80	.968	Interactive	T1–T2	−3.09	12	.009*	0.57
Time	14.62	1	35.11	< .001	Passive	T1–T2	−1.72	12	.110	0.4
Interaction	0.27	2	23.82	.768	Nature	T1–T2	−1.96	11	.075	0.45
Anger										
Condition	0.65	2	22.38	.530	Interactive	T1–T2	−0.99	12	.343	0.15
Time	1.68	1	28.91	.205	Passive	T1–T2	−0.99	12	.343	0.08
Interaction	0.10	2	21.09	.909	Nature	T1–T2	−0.08	11	.631	0.09
Surprise										
Condition	2.78	2	22.47	.083	Interactive	T1–T2	2.55	12	.025	0.41
Time	10.67	1	31.90	.003	Passive	T1–T2	1.41	12	.185	0.21
Interaction	0.95	2	23.34	.403	Nature	T1–T2	1.52	11	.156	0.49
Anxiety										
Condition	0.20	2	23.26	.820	Interactive	T1–T2	−3.43	12	.005*	0.47
Time	37.17	1	26.42	< .001**	Passive	T1–T2	−3.41	12	.005*	0.67
Interaction	0.64	2	22.14	.538	Nature	T1–T2	−4.68	11	< .001*	0.65
Calm/relaxed										
Condition	0.44	2	23.04	.648	Interactive	T1–T2	4.94	12	< .001*	0.69
Time	39.31	1	33.13	< .001	Passive	T1–T2	3.57	12	.004*	0.65
Interaction	0.09	2	23.24	.918	Nature	T1–T2	2.89	11	.015*	0.6
Vigour/energy										
Condition	2.64	2	23.75	.093	Interactive	T1–T2	2.01	12	.068	0.25
Time	5.41	1	29.72	.027	Passive	T1–T2	1.18	12	.262	0.23
Interaction	0.09	2	23.10	.911	Nature	T1–T2	1.14	11	.280	0.17
Focus										
Condition	1.78	2	23.97	.191	Interactive	T1–T2	2.84	12	.015*	0.39
Time	8.32	1	27.30	.008	Passive	T1–T2	1.16	12	.267	0.23
Interaction	1.25	2	22.16	.307	Nature	T1–T2	1.33	11	.210	0.16
Mental fatigue										
Condition	0.01	2	23.76	.989	Interactive	T1–T2	4.61	12	.001*	0.65
Time	55.34	1	34.86	< .001*	Passive	T1–T2	5.01	12	< .001*	0.56
Interaction	0.10	2	23.82	.902	Nature	T1–T2	3.50	11	.005*	0.56

For post hoc tests *$p < .017$ (Bonferroni corrected)

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Declarations

Conflict of interest ACB is employed part-time by virtual reality software company Liminal VR. LKB has a funded collaboration with the virtual reality software company Liminal VR. The remaining 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.

Ethics statement The present study received ethics approval from the Deakin Human Ethics Advisory Group and was conducted in accordance with the Declaration of Helsinki. Participation was voluntary and there was no remuneration for participants. Each participant was informed of the consent process within a written plain language statement. Consent was given by submitting survey answers in the final survey. Participants were given the opportunity to withdraw their consent at any time which would end their participation.

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