Harnessing Technology for Mental Well-being: An EEG Comparison of VR and Mobile-Based Mindfulness Meditation Interventions

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Abstract

As digital technology becomes increasingly integrated into daily life, its potential to enhance mental well-being is transforming the landscape of mental health care. Of particular interest is the rise of virtual reality (VR) technology. However, empirical research exploring VR's influence on mental well-being is limited. This study aimed to fill this gap by conducting a one-factor, between-subject experiment involving 60 participants, comparing the effects of VR and mobile-based mindfulness meditation interventions. Data were collected using self-report assessments and electroencephalograms. The findings suggest that VR-based mindfulness meditation significantly enhances subjective well-being by reducing anxiety and nervousness. However, mobile-based mindfulness meditation was found to be more effective than VR-based mindfulness meditation in improving psychological well-being. These results not only contribute to the growing research in digital mental health care, but also provide new insights into the therapeutic potential of VR technology, underscoring its importance for future interventions in mental health care.

Keywords: Mental well-being, subjective well-being, psychological well-being, EEG, VR-based mindfulness meditation

1. Introduction

The World Health Organization (WHO) asserts that mental health is a critical aspect of overall health and well-being, and it is a fundamental human right for all individuals (WHO, 2019). Despite the escalating global needs for mental health support, the current responses to this critical issue have been deemed insufficient and inadequate (WHO, 2022). The COVID-19 pandemic, in particular, has served to compound the severity of this situation. The American Psychological Association demonstrates that the pandemic has triggered an upsurge in demand across all treatment domains, notably in the areas of anxiety and depressive disorders (APA, 2021). Depressive and anxiety disorders have seen a relative surge in prevalence since the onset of the pandemic, with estimates indicating a rise of 27.6% and 25.6% respectively (Santomauro et al., 2021). This increase parallels growing public interests and demands for mental health services overall. Amid the COVID-19 pandemic, digital technologies, such as mobile applications, have emerged as viable tools for psychological intervention and mental health care (Prescott, 2022). Indeed, the global market for mental health and wellness applications is on a growth trajectory, with forecasts predicting its value to hit $17.5 billion by 2030 (Bloomberg, 2022).

WHO has recognized the benefits of psychological interventions, including mindfulness, for a broad range of populations and for addressing a variety of mental health conditions (WHO, 2022; Dawson et al., 2015). Particularly, Mindfulness meditation-based psychological interventions have shown promising efficacy in both clinical and non-clinical populations (van Agteren et al., 2021). In light of these findings, the recent advancements in virtual reality (VR) have garnered considerable scholarly and practical interests as a potential tool for delivering mindfulness-based psychological interventions (Damen & van Der Spek, 2018; Hatta et al., 2022; Schroeder et al., 2022). The physical restrictions necessitated by the pandemic underscore the potential of VR, which provides a secure and private virtual environment conducive to user engagement (Riva et al., 2019). The immersive display system of VR allows users to experience a heightened sense of presence, facilitating rich multisensory experiences unbound by temporal and spatial constraints, all from the comfort of their own homes (Slater & Wilbur, 1997).

The burgeoning field of research into VR influence on mindfulness meditation has grown in tandem with the recent popularization of VR applications for mental well-being (Bell et al., 2022). Previous studies have ventured into the realm of VR-enabled mindfulness meditation's impact on individual mental well-being

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(Arpaia et al., 2021; Damen & van Der Spek, 2018; Fodor et al., 2018), yet they present noteworthy limitations. Firstly, these studies often lack a comprehensive examination of multi-faceted mental well-being. According to Ryan and Deci (2001), there are two approaches to understanding mental well-being: the hedonic and eudaimonic perspectives. The hedonic perspective, also known as subjective well-being (SWB), views well-being in terms of the pursuit of happiness and the avoidance of pain. On the other hand, the eudaimonic perspective, or psychological well-being (PWB), is characterized by a sense of purpose and authenticity in life. Despite this theoretical groundwork, relatively little effort has been made to consider both aspects together in the field of technology-mediated well-being. Secondly, empirical comparisons between VR-based psychological interventions and traditional digital technologies, such as mobile applications, are lacking (Krishna et al., 2009).

This study endeavors to address these research gaps by examining VR-based mindfulness meditation's effect on the dual dimensions of mental well-being, SWB and PWB. Our investigation is guided by the following research questions:

1) Does VR-based mindfulness meditation enhance users' SWB?

2) Does VR-based mindfulness meditation enhance users' PWB?

3) Is VR-based mindfulness meditation more effective than mobile-based mindfulness meditation?

We adopt a neuropsychological measurement approach to assess users' subjective well-being by analyzing users' brainwave data during meditation sessions. This enables a comparison between user evaluations of emotional experiences while employing technology and physiological indicators captured by an electroencephalogram (EEG) headset (Acabchuk et al., 2021; Hunkin et al., 2021; Stapleton et al., 2020). Moreover, this study contrasts VR-based mindfulness meditation's effects with those of mobile-based mindfulness meditation, providing empirical insights into their relative efficacy.

In doing so, this study offers significant implications for both academia and industry. It enriches academic understanding of technology-mediated applications for mental well-being by scrutinizing users' brain activities via EEG. Furthermore, by examining SWB and PWB concurrently, this study adds depth to the literature on technology for well-being. For practice, this research sheds light on how VR can be strategically employed to enhance mental well-being, a topic of particular relevance in the current societal climate marked by increased stress and mental health issues. Mental health practitioners and developers of well-being apps can utilize these insights to tailor their approaches, potentially opting for VR for specific therapeutic outcomes.

2. Literature Review

2.1 Mental Well-being

According to WHO, mental health is "a state of well-being in which the individuals realize their own abilities, can cope with the normal stresses of life, can work productively and fruitfully, and are able to make a contribution to their community" (WHO, 2004). The definition of mental health is intrinsically tied to the concept of mental well-being. Mental well-being refers to a positive state of mind and body, feeling safe and able to cope, with a sense of connection with people, communities, and the wider environment (Ryan & Deci, 2001). It encapsulates both subjective and psychological dimensions.

Research has been devoted to the application of digital technology in promoting mental well-being, which can be categorized into three main research streams. The first research stream focuses on online therapy and telepsychiatry. Researchers have examined how digital technology has enabled the provision of mental health services online. Online therapy and telepsychiatry have made mental health services more accessible and convenient, particularly important during times when in-person therapy is not possible, such as during the COVID-19 pandemic (Markowitz et al., 2021; Shore et al., 2020; Wright & Caudill, 2020). The second research stream focuses on mobile applications, which have examined the use of mobile applications in enhancing mental health. These applications often feature mindfulness exercises, cognitive behavioral therapy techniques, mood tracking, and psychoeducation, showing promising results in alleviating symptoms of depression, anxiety, and stress (Donker et al., 2013; Firth et al., 2017; Linardon et al., 2019). The third research stream focuses on wearables and biofeedback, which examine how technology helps people track physiological indicators such as heart rate variability, skin temperature, and sleep patterns, providing real-time feedback to users. This technology has shown potential in managing stress and promoting overall mental well-being (De Witte et al., 2019; Sano et al., 2018; Schoenberg & David, 2014).

2.2 VR for Mental Well-being

Recently, the field of mental well-being has witnessed a surge of interest towards VR technology. Prior research has begun to delineate the scope of VR's potential in managing psychological ailments, particularly stress and anxiety disorder (Maples-Keller et al., 2017). A noteworthy methodology employed by these studies involves the gradual exposure of individuals to anxiety-inducing stimuli within a controlled, VR environment. Findings suggest that such VR-based interventions can facilitate individuals' management of stress and anxiety in everyday life (Fodor et al., 2018). Additionally, VR has also demonstrated potential in promoting mindfulness and meditation practices. Researchers argue that the technology's ability to simulate a serene and distraction-free environment effectively amplifies the focus and relaxation integral to these practices, thereby enhancing their overall benefits (Navarro-Haro et al., 2017).

However, it is worth noting that while VR holds significant potential for mental well-being, there are also challenges to overcome, such as technological limitations, potential side effects like cyber sickness (Nichols & Patel, 2002). Therefore, it is important to investigate the comparative effectiveness of VR interventions with respect to other technology-mediated interventions, such as those facilitated via mobile platforms. This perspective is critical to ensure the selection of the most appropriate and efficacious digital tools for mental well-being.

3. Hypothesis development

3.1. VR-based Intervention for Mental Well-being

Mindfulness meditation originated in the Buddhist meditative tradition, and has been practiced in the form of interventions such as "mindfulness-based stress reduction" (Kabat-Zinn, 2003) and "mindfulness-based cognitive therapy" (Teasdale et al., 2000). Mindfulness meditation highlights being non-judgmental aware of the present moment by recognizing and accepting current experiences, feelings, thoughts and bodily sensations (Kabat-Zinn, 2003). Such intervention has considered as a valid means for improving individuals' mental well-being (Bostock et al., 2019; Lee et al., 2018).

The cognitive behavioral model (Roemer & Orsillo, 2002) postulates that maladaptive thoughts, beliefs, and attitudes can lead to negative emotional states and impair mental well-being. On the contrary, the modification of these cognitive constructs can result in improved mental health outcomes. VR-based mindfulness meditation offers an immersive environment that supports the development of adaptive cognitive behaviors, such as mindfulness. By immersing users in a distraction-free, calming environment, VR-based mindfulness meditation encourages a focus on the present moment, a key aspect of mindfulness. This presence in the present moment can facilitate a shift away from maladaptive thoughts towards more adaptive ones, resulting in enhanced mental well-being.

SWB, a dimension of mental well-being, is the pursuit of happiness and avoidance of pain, which is oriented toward pleasure associated with positive emotional experiences (Schueller & Seligman, 2010). The immersive nature of VR can support a heightened sense of presence, which is an essential component of mindfulness practices (Seabrook et al., 2020). This sense of presence, being fully "in the moment", can enhance life satisfaction and positive affect, key components of SWB. Therefore, we propose the following hypothesis:

H1a: *VR-based mindfulness meditation will positively influence SWB.*

VR holds potential in bolstering PWB by fostering self-acceptance, personal growth, and a sense of purpose (Malighetti et al., 2023). By creating a controllable and immersive environment for meditation, VR encourages introspective practices that enhance personal insights and growth (Riva et al., 2016). Furthermore, the mindfulness meditation cultivated via VR can foster emotional regulation skills that improve interpersonal relationships, contributing to PWB. Thus, VR-based mindfulness meditation, by providing immersive, tailor-made experiences, can potentially enhance several aspects of PWB. Thus, we propose the following hypothesis:

H1b: *VR-based mindfulness meditation will positively influence PWB.*

3.2. Mobile-based Intervention for Mental Well-being

Similar to the effect of VR on mental well-being, mobile-based mindfulness meditation is grounded in the principles of cognitive behavioral change. These interventions often employ mindfulness practices, progressive muscle relaxation, or other cognitive behavioral techniques that aim to change maladaptive thought patterns. Through consistent use, these interventions can help users develop more adaptive cognitive patterns, thereby improving mental well-being. Given the flexibility and accessibility of mobile platforms, users can easily incorporate these practices into their daily routines, providing regular cognitive behavioral change opportunities. Thus, a positive relationship between mobile-based mindfulness meditation and mental well-being can be posited.

H2a: *Mobile-based mindfulness meditation will positively influence SWB.*

H2b: *Mobile-based mindfulness meditation will positively influence PWB.*

3.3. Comparative Efficacy of VR and Mobile-based Intervention

While both VR and mobile-based mindfulness meditations can enhance mental well-being, VR, with its immersive, controlled, and sensory-stimulating environment, could potentially offer superior outcomes. VR allows users to feel completely engaged in the meditation process, providing a deeper state of mindfulness. Moreover, personalization features inherent in VR technology could facilitate tailored meditation experiences, further contributing to its potential superior efficacy.

H3a: *VR-based mindfulness meditation will be more effective than mobile-based mindfulness meditation in improving SWB.*

H3b: *VR-based mindfulness meditation will be more effective than mobile-based mindfulness meditation in improving PWB.*

4. Methods

4.1. Design

To empirically assess the proposed hypotheses, a between-subject experimental design was implemented, featuring a single factor: technology type (VR versus mobile). A total of 60 participants were enlisted from a large, private university located in Seoul, South Korea. The participants were divided into two groups through a random assignment procedure. Each group was instructed to engage with the same mindfulness meditation program, although delivered through different technological modalities. The VR-based mindfulness meditation group (henceforth referred to as the VR group) utilized Meta's Oculus Quest 2, while the mobile-based mindfulness meditation group (henceforth referred to as the mobile group) was furnished with Apple's iPad Pro 12.9. All experimental procedures executed in this study were endorsed by the institutional review board of the affiliated institution prior to initiation, thus ensuring ethical compliance.

4.2. Meditation Application

This study used "TRIPP", an application designed to provide experiences to promote relaxation, mindfulness, and personal well-being. This app offers meditation programs encompassing audio guidance, visual effects, and soft music on multiple devices such as VR, mobile, and web platforms. The meditation program adopted in this study was "How to meditate". The VR group could practice meditation with visual and auditory effects, featuring a "Nature" theme selected for the surrounding environment including a dark forest, aurora, open plain, and space. The mobile group could do meditation with voice guidance and some moving psychedelic imageries. Voiceover delivered by a female narrator introduced meditation techniques that focus on the breath. It also included instructions on perceptions and feelings. Through this voice guidance, participants could experience the process of focusing on their breathing, releasing unnecessary thoughts and tension.

4.3. Participants

There were 24 male and 36 female participants, with a mean age of 23.2 years (SD = 2.86). Of the total participant sample, 33 participants have used VR 1-2 times, a total of 6 people have used VR 3-5 times, and 1 person has used VR 6-10 times. There was a total of 3 participants who had multiple experiences of using VR more than 11 times. To the question about mindfulness or meditation experience within the last month, 46 participants answered that they had no experience, and the average number of times of meditation per week for participants who answered that they had mindfulness or meditation experience was 1.9 (SD = 1.41).

4.4. Procedure

After giving their informed consent to both participate in the experiment and allow the use of their data, participants began with a brief initial questionnaire. Once this was done, each participant was fitted with the EPOC X, an EEG apparatus. To ensure accurate and effective data recording, the device fitting was followed by a thorough check of its functioning. Next, we verbally confirmed their comfort and the visual clarity of their postures, offering assistance as needed to alleviate any discomfort. Subsequently, under the guidance of one of the authors, participants embarked on a mindfulness meditation program. Throughout the meditation program, the researchers stepped out of the lab room, returning only after its completion to assist in the removal of the equipment. Afterwards, participants filled out a post-experiment questionnaire. As a token of gratitude for their involvement in the study, all participants received a café merchandise gift certificate worth about US $10.

4.5. Measurement

To evaluate the perceived mental well-being of participants, this study employed the Warwick-Edinburgh Mental Well-being Scale (WEMWBS) (Tennant et al., 2007). This scale, composed of 14 items related to positive feelings and thoughts, broadly addresses mental well-being. Responses were obtained using a 5-point Likert scale, ranging from “1 = not at all” to “5 = very much so”. Higher scores suggest greater levels of mental well-being. A non-commercial research license was registered with Warwick Medical School to employ this scale in this study. It was utilized both pre- and post-engagement with the mindfulness meditation application. During the pre-assessment phase, participants’ experiences over the preceding two weeks were evaluated, while the post-assessment evaluated their “current experience” post-meditation.

Furthermore, to measure participants’ emotional responsiveness, the self-assessment manikin (SAM) (Bradley & Lang, 1994) was used. SAM, a pictorial assessment method, enables self-measurement of valence and arousal tied to emotions. Participants rated their emotional state using a 5-point Likert scale for two dimensions: valence (“1 = feeling very bad” to “5 = feeling very good”) and arousal (“1 = very calm” to “5 = very surprised and heart pounding”).

4.6. EEG Data

Participants’ EEG data were collected during the entire meditation program. The device used in this study is Emotiv’s EPOC X, which can measure the ranges corresponding to the frontal lobe, prefrontal lobe, temporal lobe, parietal lobe, and occipital lobe. The device coverage of EPOC X is shown in Figure 1.

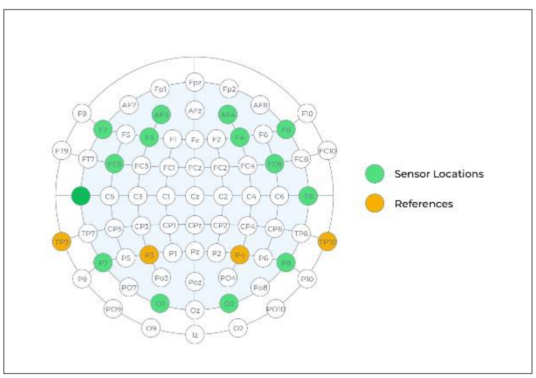

Figure 1. EEG device coverage

5. Results

5.1. Self-report Responses

All self-report data from the study were processed and analyzed using IBM SPSS Statistics version 27.0. As illustrated in Figure 2, emotions can be evaluated based on the magnitudes of arousal and valence values (Feldman Barrett & Russell, 1998). The y-axis represents arousal, while the x-axis signifies valence.

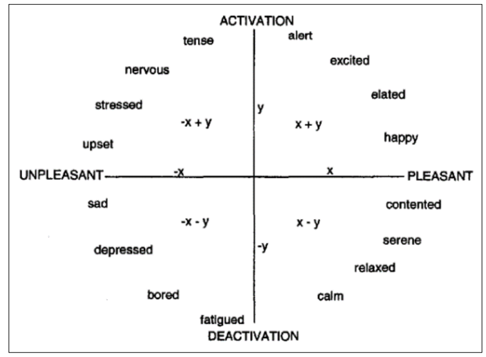

Figure 2. Arousal-valence 2D model

The valence score, ascertained immediately post-meditation program, was marginally higher in the VR group (M = 3.96, SD = 0.73) as compared to the mobile group (M = 3.79, SD = 0.56). The arousal score was slightly lower in the mobile group (M = 1.66, SD = 0.48) compared to the VR group (M = 2.04, SD = 0.73). As illustrated in Figure 3, the SAM results for both the VR and mobile groups are positioned within the fourth quadrant denoting low arousal and high valence, indicative of a relaxed state. These measurements were captured immediately subsequent to the mindfulness meditation.

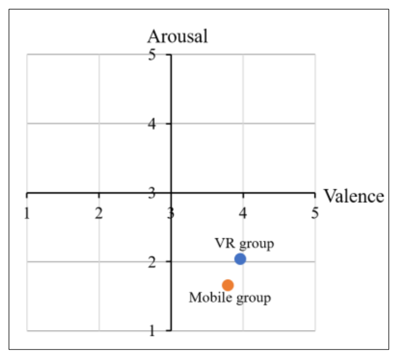

Figure 3. The SAM results

The outcomes suggest that participants in both groups experienced positive and low aroused emotions, such as calmness and relaxation, following the meditation session. This reflects the efficacy of both VR and mobile-based mindfulness meditation in inducing positive emotional states, thereby contributing to a subjective sense of mental well-being.

In order to evaluate the comparative impact of the technology-mediated meditation on overall mental well-being before and after the intervention, the scores derived from the WEMWBS were analyzed for each group. A paired t-test was conducted to compare the effect size (ES) of the VR and mobile groups. Both groups manifested t-values exceeding ±1.96 and a p-value of .000, underscoring the significant impact of both VR and mobile-based mindfulness meditation.

This demonstrated a significant augmentation in WEMWBS scores for both groups. The ES values for both VR and mobile groups surpassed 0.5, which implies a moderate effectiveness of the mindfulness meditation. Moreover, the mobile group's ES value of 0.838 exceeded that of the VR group, indicating a greater effectiveness.

Table 1. WEMWBS results (Mental well-being)

Mental well-being		Mean	SD	ES	t-value
VR group	Pre	51.67	7.76	0.643	-3.521
	Post	55.90	7.45		
Mobile group	Pre	51.87	7.79	0.838	-4.588
	Post	56.40	6.71		

The WEMWBS provides comprehensive measures of the feeling and function aspects of mental well-being, aligning with SWB and PWB respectively. We categorized the 14 items of the WEMWBS into their corresponding elements of overall mental well-being. To ensure the validity and reliability of the classification, three researchers with Ph.D. degrees or higher participated in this process. Consequently, six items were identified as related to feelings (i.e., SWB), while eight items were linked to function (i.e., PWB). The corresponding scores are displayed in Tables 2 and 3.

Table 2. WEMWBS results (SWB)

SWB		Mean	SD	ES	t-value
VR group	Pre	21.77	4.23	0.571	-3.128
	Post	24.37	3.53		
Mobile group	Pre	22.0	3.97	0.888	-4.865
	Post	24.23	3.13		

The outcomes demonstrate an enhancement in SWB for both the VR and mobile groups post-mindfulness meditation. Interestingly, the ES, which signifies the practical significance of the intervention, was found to be more substantial in the mobile group as compared to the VR group.

Table 3. WEMWBS results (PWB)

PWB		Mean	SD	ES	t-value
VR group	Pre	30.37	4.62	0.243	-1.329
	Post	31.63	4.25		
Mobile group	Pre	29.87	4.47	0.642	-3.516
	Post	32.17	3.79		

The findings pertaining to PWB exhibited contrasting patterns between the two groups. In the mobile group, the ES was observed to be 0.642, signifying a moderate effect of the intervention. On the other hand, the ES of the VR group fell below 0.5, suggesting an insubstantial impact of VR-based mindfulness meditation on PWB. Moreover, the t-value for the VR group did not meet the threshold of ±1.96, and as such, the result was deemed statistically insignificant. This implies that the VR-mediated intervention did not yield significant enhancements in the PWB of participants.

5.2. EEG Data Analysis

EEG data were processed and analyzed utilizing MATLAB R2003a. Prior to analysis, EEG data were subjected to preprocessing. This process leveraged EEGLAB, a MATLAB toolbox. Distinct brainwave patterns were extracted via frequency analysis utilizing a finite impulse response filter. Table 4 presents the frequencies of these extracted waveforms.

Table 4. Extracted brain wave frequencies

Brain wave	Frequency (Hz)
Theta	4Hz ~ 8Hz
Alpha	8Hz ~ 12Hz
Low beta	12Hz ~ 16Hz
High beta	16Hz ~ 25Hz
Gamma	25Hz ~ 45Hz

In order to optimize data quality, defective signals and data were excised from the extracted EEG data. Artifacts introduced by eye activity, brain activity, muscle movement, and heart rate were eliminated from the EEG data via independent component analysis. In this study, based on support vector machine (SVM) and k-nearest neighbor (kNN), bagging tree, pre-processing the EEG signals were classified in the experiment. The role of the classification algorithm in this study was to predict whether the valence and arousal levels, as previously recorded, belonged to a "High" or "Low" class. Table 5 provides a comparison of the actual and predicted classes.

Table 5. Actual and predicted classes

Arousal	Valence	Class	Valence-arousal 2D model
High	High	HAHV	Quadrant 1
High	Low	HALV	Quadrant 2
Low	Low	LALV	Quadrant 3
Low	High	LAHV	Quadrant 4

Table 6 shows the accuracies of each classifier, further illustrating the efficacy of the employed classification algorithms.

Table 6. Accuracies of the classifiers

Classifier	VR	Mobile
Bagging Tree	88.9%	93.5%
kNN	70.4%	67.7%
SVM	70.4%	67.7%

The emotion classification results derived by the classification algorithm can be compared with the self-reported results. The results also show that there is a difference between the predicted class and the actual class, which affects the classifier accuracy. As shown in Figure 3, both the SAM results of the VR and mobile groups correspond to the fourth quadrant, LAHV. However, as a result of the classification algorithm, 76% of LAHV in the VR group and 72.4% in the mobile group were confirmed. The results of classifying the EEG data of the VR and mobile groups are shown in Figures 4 and 5.

Figure 4 shows the classification results for the VR group. 24% of the VR group can be interpreted as feeling HAHV emotions, which are emotions corresponding to 'happy' or 'excited' according to Figure 2.

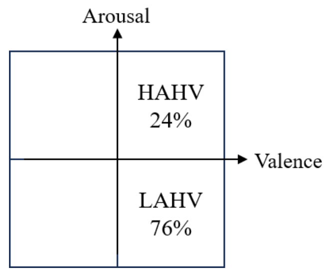

Figure 4. EEG emotion classification of the VR group

On the other hand, Figure 5 confirms that 27.6% of LALV was classified as a result of classification for the mobile group. This is an emotion corresponding to 'bored' according to Figure 2, which contrasts with the VR group.

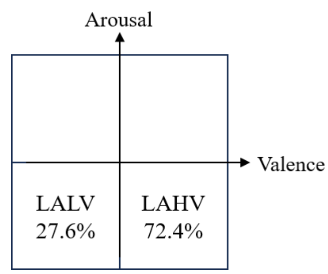

Figure 5. EEG emotion classification of the mobile group

To investigate the neural activities of participants during the meditation exercise in both the VR and mobile groups, band power of specific brainwave frequencies, namely alpha and high beta waves, were analyzed at the onset and termination of the meditation session. Alpha waves are typically linked to a state of relaxation and tranquility (Puzi et al., 2013), whereas beta waves are associated with alertness and conscious awareness. High beta waves are specifically associated with states of anxiety and nervoursness (Díaz et al., 2019; Ossebaard, 2000). For the purpose of this study, high beta waves were specifically chosen for comparison with alpha waves to provide a more comprehensive understanding of the users' mental states during the meditation session.

Figure 6 shows the band power comparison of alpha waves. The alpha wave power of the VR group was weakened, and the alpha wave power of the mobile group was slightly enhanced. Alpha waves are highly influenced by vision and are more induced in situations where the eyes are closed and rested (Chapman et al., 1970). Both groups were instructed to close their eyes within the meditation program, but the VR group was instructed to stare at a screen for progression after every breathing exercise. It is interpreted that the visual stimulation in the VR environment may have influenced the alpha waves of users in the VR group.

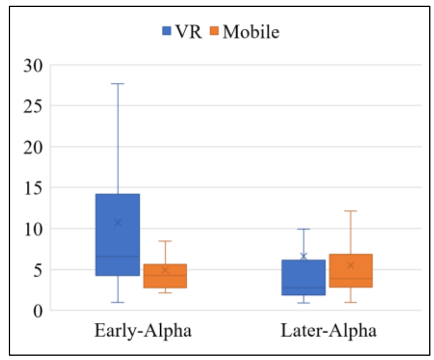

Figure 6. Alpha band power

Figure 7 shows the comparison of the band power of high beta waves between the two groups. High beta waves in the mobile group increased slightly, and high beta waves in the VR group decreased noticeably.

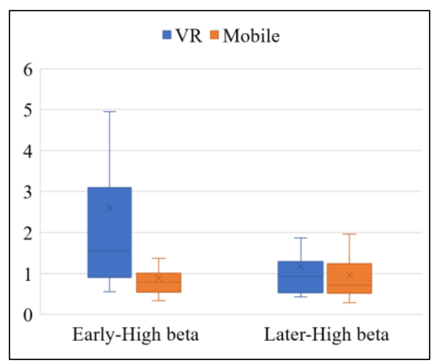

Figure 7. High beta band power

This is interpreted as the fact that the VR group was greatly helped in reducing anxiety and nervousness than the mobile group.

6. Discussion

The aim of this study was to compare the effects of VR and mobile-based mindfulness meditation interventions on mental well-being. Our results revealed that both VR and mobile-based mindfulness meditation had a positive effect on SWB, specifically by increasing positive emotions such as calmness and relaxation.

Interestingly, contrary to our expectations, participants in the mobile group reported a more significant increase in their SWB compared to the VR group. We conjecture that this discrepancy may be due to the immersive and interactive virtual environment rendered by VR, which could lead to heightened arousal among users. Our machine learning classification of EEG data supported this, indicating that VR-based mindfulness meditation tends to induce higher arousal in users compared to mobile-based mindfulness meditation. High arousal, when paired with positive valence, can trigger strong positive emotions, such as excitement, elation, and happiness. While these emotions can reflect one's SWB, the WEMWBS that we used to assess SWB does not include such emotions in its measurement items, which may have influenced the results.

Our results also showed that VR-based mindfulness meditation did not significantly enhance PWB, while mobile-based mindfulness meditation did. We attribute the lack of significant impact of VR-based mindfulness meditation on PWB to the heightened emotions among VR users. This suggests that while VR's immersive experience can be highly engaging, the accompanying emotional intensity could disrupt the tranquility often associated with mindfulness meditation, potentially undermining its effectiveness in improving PWB. Conversely, mobile-based mindfulness meditation, with its less immersive but more familiar interface, may offer a more relaxed environment conducive to a deeper, more focused meditative state, thus enhancing PWB.

Our EEG data analysis revealed another notable finding: VR-based mindfulness meditation significantly reduced high beta band power, whereas mobile-based mindfulness meditation did not. This suggests that VR-based mindfulness meditation might be more effective for SWB in terms of reducing negative emotions such as heightened anxiety and nervousness. Its significant reduction after VR-based mindfulness meditation suggests that despite not impacting overall PWB, this approach might be particularly effective in diminishing negative emotional states. This paints an intriguing picture of the distinct impacts VR and mobile-based mindfulness meditation can have on brain wave patterns.

6.1. Academic Implications

The findings of this study present several pertinent implications for academia. First, the differential impacts of VR and mobile-based mindfulness meditation on SWB and PWB necessitate further examination of the role of platforms in digital well-being interventions. Second, our finding of reduced high beta band power in VR-based mindfulness meditation illustrates the importance of neuroimaging techniques in evaluating therapeutic effectiveness. This underlines the need for objective neurobiological markers to supplement self-report measures in mental health research. Third, despite VR-based mindfulness meditation not significantly increasing PWB, its effectiveness in reducing negative emotions signals potential for its use in specific therapeutic contexts. Further research on optimizing VR-based interventions is crucial, including aspects like interface design, session duration, and VR environment nature. Fourth, distinct strengths of both VR and mobile-based interventions suggest potential of a hybrid approach in digital therapies. Future research could investigate how these platforms can be combined to provide more comprehensive, personalized mental health interventions.

6.2. Practical Implications

The results of this study offer significant insights for therapists, app developers, and users. First, the different impacts of VR and mobile-based mindfulness meditation on SBW and PWB highlight the potential for tailoring mindfulness interventions to individuals' needs. VR might be used for immediate anxiety reduction, while mobile-based methods may be more suitable for holistic PWB enhancement. Second, the effectiveness of mobile-based mindfulness meditation on PWB emphasizes the importance of accessibility and familiarity in digital therapy design. Developers should prioritize these factors to improve user engagement and therapy adherence. Third, EEG data could be utilized in therapeutic contexts to track progress and adjust interventions based on neurological responses, providing a more objective measure of therapy effectiveness. Fourth, the VR-based mindfulness meditation's success in reducing negative emotions, despite no significant effect on PWB, suggests potential for its use with some refinements to improve comfort and effectiveness. Finally, the distinct benefits of VR and mobile-based mindfulness meditations may encourage a hybrid approach to provide comprehensive, personalized mental health care. These findings can guide the design, implementation, and selection of digital mental health interventions, potentially enhancing the effectiveness of such therapeutic strategies.

6.3. Limitations

While we believe our efforts contribute to a better understanding of mental well-being through VR-based interventions, there are still some limitations. First, although the study's sample was sufficient for statistical analysis, a larger and more diverse sample could provide more robust findings. Second, it is possible that the mindfulness meditation results of this study were influenced by the novelty of technology used by people who are new to technology. Additionally, it is plausible to consider the prospect that the devices employed during the measurement procedure could have induced unaccustomed circumstances for the participants, potentially resulting in a degree of discomfort. Thus, the user may have had difficulty reaching a fully meditative state. This study only focused on mindfulness meditation. The results might differ with other forms of digital therapy, so further studies are necessary to broaden the implications of our findings.

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