RelaWorld: Neuroadaptive and Immersive Virtual Reality Meditation System

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ABSTRACT
Meditation in general and mindfulness in particular have been shown to be useful techniques in the treatment of a plethora of ailments, yet they can be challenging for novices. We present RelaWorld: a neuroadaptive virtual reality meditation system that combines virtual reality with neurofeedback to provide a tool that is easy for novices to use yet provides added value even for experienced meditators. Using a head-mounted display, users can levitate in a virtual world by doing meditation exercises. The system measures users' brain activity in real time via EEG and calculates estimates for the level of concentration and relaxation. These values are then mapped into the virtual reality. In a user study of 43 subjects, we were able to show that the RelaWorld system elicits deeper relaxation, feeling of presence and a deeper level of meditation when compared to a similar setup without head-mounted display or neurofeedback.

Author Keywords
Neurofeedback, Virtual Reality, Meditation, Mindfulness

ACM Classification Keywords
H.5.1. Multimedia Information Systems: Artificial, augmented, and virtual realities

INTRODUCTION
In recent years, meditation in its various forms has gained a lot of research attention, specifically mindfulness meditation. While the brain-level effects of meditation are numerous and complex (see e.g. [2]) and clearly in need of considerably more in-depth studying, the wide range of well-being benefits, such as stress reduction, are more well-known (for various meta-analyses, see e.g. [19] [8] [41] [17] [10]). It is suggested that naive meditators would benefit from a system / application, which would help in focusing their attention to the meditation task at hand and closing out all other visual and auditory distractors, especially in a noisy office environment.

Physiological computing [12] applied to develop symbiotic interaction between humans and computers [23], is still an open research area [44]. This includes identifying and recognising psychophysiological states through multidisciplinary investigations coupling machine learning, psychophysiology and human-computer interaction, as well as research on how to integrate such findings in useful applications [22]. Recent work, for example, includes identifying workload for safety in supervisory tasks or driving [5] [43], detecting relevance for implicit feedback in information retrieval[11] [4] [39], research and adaptation in computer games [28] [45] [46], interactive storytelling [16], training cognitive performance [32], and usability testing [20].

Neurofeedback has been proven to be a useful tool in the treatment of various disorders including ADHD [30], epilepsy [48], learning disabilities [13] and autism spectrum disorders [26], to name just a few. However, little research has been done on how neurofeedback could be used to enhance meditation, including mindfulness-based therapies.

Virtual reality technologies have been successfully used in many therapies, especially those that rely on mental imagery: patients with phobias who traditionally have attempted to desensitize themselves within their imagination can face their fears in a controllable virtual environment [36]. Similarly, patients with eating disorders who suffer from distorted body image can work on their self-image through a virtual body [14].

While all these technologies and techniques have been separately proven to be highly effective, and many have been used to treat the same disorders such as depression and stress, combining them all into a single system is still undone.

Our main contribution is a design for a system that combines neurofeedback and virtual reality into a computer-assisted meditation system. We also contribute a user study of 43 subjects that demonstrates that our system is able to generate a deeper level of meditation, greater relaxation and a higher level of felt presence.

IUI'16, March 07 - 10, 2016, Sonoma, CA, USA

ACM 978-1-4503-4137-0/16/03...$15.00.
DOI: http://dx.doi.org/10.1145/2856767.2856796

In the following we describe the related work before we introduce the design considerations and implementation of the RelaWorld system. Next, we present the user study, and conclude with a discussion.

RELATED WORK

Meditation and Mindfulness

Lutz and colleagues [31] define meditation as a set of complex emotional and attentional regulatory strategies developed for various ends, including the cultivation of well-being and emotional balance. Meditation as a concept covers a broad range of various practices, traditions and even religious belief-systems; it is thus important to always specify the exact meditation technique in question. Different meditation techniques have varying goals, ranging from relaxation to heightened sense of well-being [31]. Many of the currently practiced approaches to meditation, including the currently popular mindfulness-based stress reduction, draw from Buddhist tradition [31]. Lutz, Slagter, Dunne and Davidson [31] divided meditation exercises into two broad categories: focused attention and open monitoring. Later Travis and Shear [51] suggested a third category of automatic self-transcending.

Different meditation techniques and approaches have differing effects not only on self-reported experiences but also at the neural level. Focused attention has been characterized by EEG beta (13-30Hz) and gamma (30-50Hz) band activities, open monitoring by theta (4-8Hz) activation, and automatic self-transcending by alpha-1 (8-10Hz) band activity (for a review, see [51]).

Traditionally, meditation has been considered as something that needs to be exercised almost daily and for long periods. However, recently there has been a growing interest in short-duration meditation or mindfulness programs, which could give results quickly. Previous research has documented promising results of short-duration meditation interventions. Twenty-minute exercises during five consecutive days led to positive improvements in self-reported depression and anger in a sample of students [49]. A study by Zeidan and colleagues [52] hints that a brief mindfulness meditation intervention of only three sessions could also improve cardiovascular variables (heart rate), whereas Steffen and Larson [47] present evidence of reduced cardiovascular reactivity to a stressor during a single mindfulness meditation session.

While there is a multitude of different meditation traditions, practices and exercises, there are only a few prior studies on how well suited they are for VR implementation.

Computer-Assisted Meditation Systems

Various kinds of computer-assisted meditation systems have been proposed in the past. In a study by Baños et al. [3] a virtual environment was successfully used to induce positive moods in elderly people. The system simulated a walk in a park where the participants could stop to listen to relaxing melodies, nature sounds and guided meditation exercises. The participants reported both an increase in positive emotion and a decrease in negative emotions. The system was perceived to be easy to use. The system used a 21” touchscreen with integrated audio speakers.

Chittaro and Vianello [9] proposed a mobile application to help naive meditators practice mindfulness. In their application, called AEON, the users would enter their thoughts on a mobile device that would visualize them as ink on a parchment placed under water. The users can then use the touchscreen to produce waves on the water that progressively dissolve the written thoughts. In a user study with 22 participants that compared the AEON system to two traditional mindfulness exercises, they found the system to be more pleasant and easier than traditional meditation, yet still able to produce a higher level of decentering, an index of mindfulness.

Carissoli et al. [7] examined the effectiveness of a mobile app using a three-week mindfulness-inspired protocol for stress reduction. In a study with 56 participants, they compared a group using the mobile app with a group that listened to relaxing music and a control group. However, while the data showed a trend towards decreased stress levels for both meditation and music listener groups, the results failed to reach statistical significance.

Our work extends these types of meditation systems by adding the immersivity of virtual reality and the possibilities of neurofeedback.

Virtual Reality-Based Therapies

Virtual reality-based systems have been used in the treatment of a wide range of mental disorders, ranging from eating disorders [14], to erectile dysfunction [34]. Virtual reality systems have been especially successful in the treatment of various anxiety disorders including fear of flying, social phobia, PTSD, fear of spiders and fear of heights (for a review, see [36]). In fact, the meta-review concludes that these so,called virtual reality exposure therapies (VRET) are ”slightly but significantly more effective than exposure in vivo, the gold standard in the field.”

Shaw et al. [42] introduced the Meditation Chamber, an immersive virtual environment for meditation training. The system used skin conductance as the biofeedback mechanism in three guided meditation and relaxation exercises that used head-mounted display for stereoscopic imagery and sound. The system was installed in an exhibition where 411 users tested the system. The majority of the users reported an increase in relaxation, especially those who had little prior experience in meditation. While conceptually similar to our system, it used skin conductance, a measure of peripheral physiology for the biofeedback, while our system utilizes EEG to record brain activity directly.

Gromala et al.[18] combined virtual reality and biofeedback into a system that helps chronic pain patients to manage their pain with guided mindfulness meditation. Their system, the Virtual Meditative Walk, simulated a walking meditation through a forest with a biofeedback adaptation that modified the weather in the virtual world based on the user’s skin conductance: as the user relaxed the weather would clear, while anxiety would cause the user to be engulfed in a fog. In a user study of 13 participants, they were able to show that the virtual reality system was significantly more effective in reducing reported pain levels when compared to a control group that simply listened to a guided mindfulness audio track. This system differs from ours in that it used a mounted stereoscopic viewer instead of a head-mounted display for the VR, and skin conductance instead of EEG for the biofeedback.

Neurofeedback Therapies

Neurofeedback is a form of biofeedback where the brain activity, usually measured through EEG, is used for the feedback. Neurofeedback has been successfully used in the treatment of various disorders including ADHD [30], epilepsy [48], learning disabilities [13] and autism spectrum disorders [26].

Hinterberger [50] introduced the Sensorium, a neurofeedback environment that allowed the users to experience their physiological signals, brain waves and heart rate, as sounds and light effects. In a user study of 20 participants, almost all of the participants reported an increase in contentment, relaxation, happiness and inner harmony. Our work extends their idea by replacing the rather simple light effects with a virtual reality environment.

Sas and Chopra[40] described a system called MeditAid that used a special kind of aural neurofeedback to help meditators in a mindfulness practice. They recorded the users' brain activity with EEG and provided real-time audio feedback via binaural beats, a type of entrainment technique where two audio tones are played through headphones at a slightly different pitch. In a user study of 16 participants, all users were able to achieve a deeper level of meditation when using the system. While similar to our work, MeditAid was built around a special kind of audio feedback, while our system is designed to utilize the possibilities of full virtual reality immersion.

Presence

In the field of virtual reality research, the concept of presence has gained significant interest. In their book chapter titled "Presence-Inducing Media for Mental Health Applications" Riva et al. argue that "In general, what distinguishes VR from other media or communication systems is the sense of presence. [...] Specifically, we argue that the higher sense of presence induced by a VR may be used to elicit optimal experiences that will support the process of change." [38]

In a study by Freeman et al. [15] the effect of a virtual environment on the sense of presence was studied in the context of a relaxation exercise, and it was shown that the virtual environment, combined with a guided relaxation audio narrative produced a higher sense of presence than the narrative alone.

While the ability of virtual reality environments to generate the sense of presence is proven, to the best of our knowledge there is little research on how neurofeedback could enhance the sense of presence. Our experiment studies the added benefit of neurofeedback when combined with a virtual reality system.

SYSTEM OVERVIEW

The underlying motivation and design principle of the RelaWorld system was to combine the proven methods of neurofeedback and virtual reality into one package that would allow novice meditators to reap the full benefit of the meditative experience even in the middle of busy every day life. We aim to accomplish this by *immersing* the user into an alternative reality.

Immersion

What defines virtual reality as technology is its ability to *immerse* us into an alternative reality. Janet Horowitz Murray famously described immersion as

> "The experience of being transported to an elaborately simulated place is pleasurable in itself, regardless of the fantasy content. We refer to this experience as immersion. Immersion is a metaphorical term derived from the physical experience of being submerged in water. We seek the same feeling from a psychologically immersive experience that we do from a plunge in the ocean or swimming pool: the sensation of being surrounded by a completely other reality, as different as water is from air, that takes over all of our attention, our whole perceptual apparatus... in a participatory medium, immersion implies learning to swim, to do the things that the new environment makes possible... the enjoyment of immersion as a participatory activity."[33]

Taking cue from the above description, our system surrounds the user in a tropical island paradise. We harness the neurofeedback to generate a completely new type of participatory medium where users, instead of learning to swim, are able to fly utilizing parts of their psychophysiological whole hitherto unavailable for direct control. Instead of being submerged in water, the user is surrounded by an energy bubble that gets more opaque as the user relaxes.

Hardware

RelaWorld is a 3D-virtual reality environment designed for meditation practices. It utilizes the Oculus Rift DK2 head-mounted display, and it has been developed with the Unity3D game engine. See Figure 1.

Figure 1. The RelaWorld setup

Virtual world scenarios

In the virtual world, the user is placed sitting on a stone platform, oriented toward seaside scenery. The application has two modes of meditation practices: body scan and focused attention. Both modes use a graphical interface to guide the meditation. In body scan, an HUD-type UI is used to guide the focus (see Figure 2). Focused attention utilizes five focus objects shown floating in front of the user, one object always being highlighted (see Figure 3). As the practise progresses, the meditative performance is reflected with vertical movement of the user, and by varying the opacity of an energy bubble around the user.

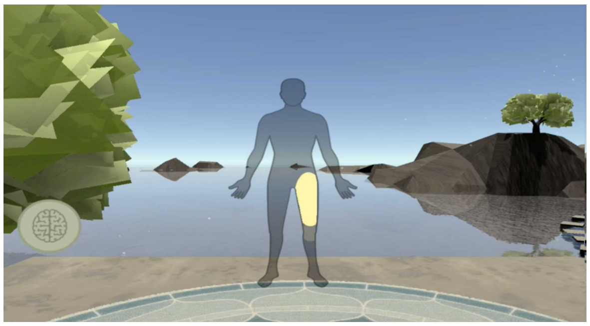

Figure 2. Body scan practice

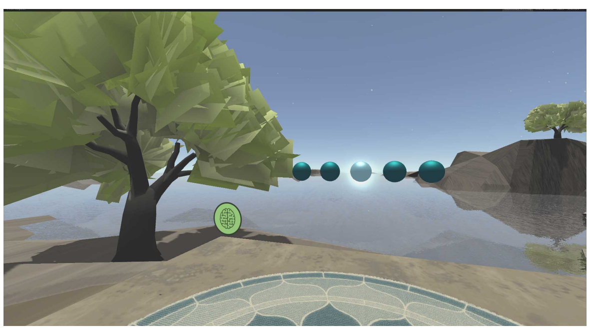

Figure 3. Focused attention practice

Scene design process

Beginning premise
As richness of detail, variety and motion of the visual signal might generate unwanted EEG artifacts, we decided that instead of aiming towards realism, to go for a minimalistic visual language in the scenery. A seaside scene was chosen, being a typical relaxation and meditation setting. A purposefully androgynous figure in the body scan guidance was chosen to take into account all genders.

Directing with details
A practice of level design in games is to guide the players' attention and direction by placing details and movement wherever the designer wants the player to focus. This combined with the design principles of visual hierarchy formed a guideline, by which we placed additional details to most relevant objects. The platform underneath had a detailed texture with a carpet pattern to both create a sense of comfort and to orient the user to the spot. To guide their attention to the meditation task at hand, focus object had a moving glow and highlighted color, body scan UI is visually detailed and bound to view to keep the players' attention at the guidance. The details of background objects are purposefully lesser. The ground is a low-poly with a simple striped texture, the trees have no trunk texture and instead of leaves, the foliage is presented with simple planes. Sky has no cloud coverage, and sun is positioned higher up from the immediate view. Only the waves of the sea have a rich detailing without an orienting purpose. Leaving it rich in detail was based on having a simple but strong immersive effect on the scene. The movement of pollen towards the sea serves a function of drawing the user towards the depth of the scenery; to look into the view, instead of the screen.

Preventing vertigo
As nausea is a common experience in VR, we saw it as important to design against from the get-go. While slow movement in one dimension was already on the safe side of VR-design, we took it a step further. Instead of levitating purely in the air, the user has a sturdy, heavy platform placed underneath the user's feet (see figure 4). That platform moves alongside the user to prevent possible experience of fear of heights and related vertigo. This was successful, as none of the testers reported nausea.

Figure 4. Platform without reference objects

Correcting the height perception
During early tests where the user was sitting on a plain beach just by the sea (see Figure 4), we noticed it was hard to estimate changes in vertical position without looking down. And even then it was hard, since the platform was blocking large part of the view underneath. To solve this, we moved the starting position more inwards from the shore, and added objects of known size around the meditation position and at varying distance: islands, a pathway of stepping stones, and most importantly, trees just next to the user. With their presence,

perception of vertical movement increased significantly (see Figure 5).

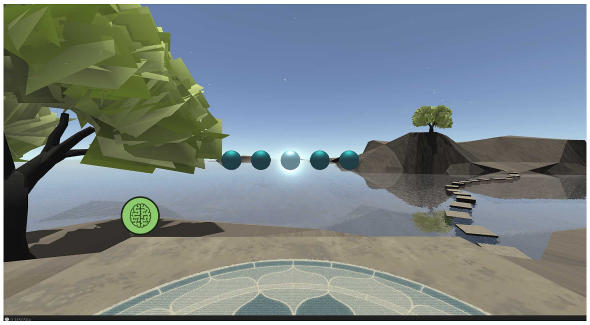

Figure 5. Vertical starting position with reference objects

Bringing the scene alive
With bare assets present, the scenery appeared lifeless and static. To make it more feel lively, we added subtle animations: gentle waves in the sea, a simulated wind that moves the trees gently pushing floating pollen towards the horizon. To the small pollen objects moving in depth, we applied the Oculus Rift chromatic aberration shader plugin, which added a sense of depth. An audio track of pink noise waves gushing to the shore added immersion, and served as a neutral noise based insulator from sounds of the outside world.

Adjusting the reactivity
When testing different parameters for live data, we found that too direct and immediate reactivity to the changes in the physiology made the experience nervous and jumpy. If the movement reacted fast to even the slightest changes, it was hard for the user to perceive connection between his state of mind and the changes in the adaptation of the environment. Also, the jagged and fast movement distracted concentration and relaxation. This was fixed by adjusting the thresholds and degree of change, so that the experience seemed to reflect a few seconds of change in state of mind, moving the direction smoothly and gently, feeling floaty.

Unpleasantness of single focus
In an early version, focused attention followed strictly the along the lines of traditional meditation practice, and had a single point of focus. Only one of the balls was highlighted per session, and it stayed the same for the whole 10 minutes. This was found to be very straining and boring. Users reported starting to look at the grid of the LED screen, and finding the whiteness of the glow at a single point heavy on the eyes. As a solution, we decided to randomly change the location of the focus object between the balls every 30 seconds and lessened the glow. This made the experience enjoyable and provided the same pace of change in the guidance as in the body scan meditation.

Neurofeedback and Adaptations
We could have used several biofeedback options for the adaptation, such as the skin conductance used in the Meditation Chamber [42]. However, we thought observing the brain directly via technology like electroencephalograph (EEG) would make more sense than recording some index of peripheral physiology, such as heart rate or skin conductance, as meditation is inherently cognitive.

Several earlier studies have shown the connection between so-called ”brain waves” and cognitive processes, such as alertness. Klimesch et al. [25] showed that the lower alpha band (6.4Hz-8.4Hz) desynchronizes, that is the power decreases, when the subject is alert and expectant. Klimesch [24] also showed that the lower alpha power (6Hz-10Hz) decreases on all sides of the head. Conversely, the theta band power (defined as 4-6Hz, or sometimes as 6-7Hz) has been shown to increase with working memory requirements [21].

The brain activity has been measured during various meditation and relaxation exercises in several previous studies. The theta band (4-6Hz) power has been shown to increase during concentration (including meditative concentration) [1] [27]. Cahn and Polich [6] they concluded that the alpha band (8-12Hz), especially the lower alpha (8-10Hz), decreases during concentration and vigilance. Conversely, the alpha is increased during relaxation, including meditation. The theta band (4-6Hz), especially in the mid-frontal region, seems to increase during concentration and with tasks that employ working memory, but also during meditation.

Based on these findings we decided to design the neurofeedback of the RelaWorld system around the alpha-band and theta-band powers of the EEG. Increase in the power of the theta band (concentration) will produce floating; increase in the alpha band (relaxation) will increase the opacity of the energy bubble surrounding the user.

Adaptations and algorithms
The adaptation is based on theta-band and alpha-band activity of brain. The average of theta and alpha band activity from the six electrodes(F3, F4, C3, C4, P3, P4) generates a stream of two real numbers: one for the theta activity, and another for the alpha activity.

There are two visual adaptations representing the user's performance. Vertical platform movement shows user concentration, while relaxation appears as an energy bubble that becomes more visible the more the user relaxes. At near maximum relaxation level, a particle effect is shown to highlight exceptional performance and to stimulate the opaqueness of the view (see Figure 6).

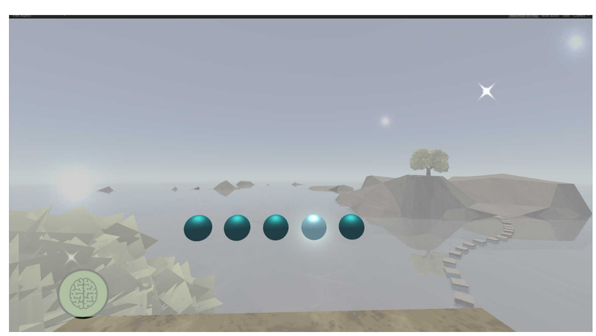

Figure 6. Bubble at maximum opacity, with star particles

EVALUATION

To evaluate the RelaWorld system, we designed a user study with two types of meditation exercises interspersed with mental tasks.

In this study we had a set of criteria for choosing the exercises for the experiment; they had to be 1) from the same category of meditation exercises, 2) previously studied (at least to a certain degree), 3) easy to learn and instruct to novices, 4) clearly theoretically distinct, 5) predictable in their main effect (even in short term practice with novices), 6) hypothetically more and less suited for VR. Based on these criteria, we chose Point Focus (PF) meditation and Body Scan (BS) meditation as forms of focused attention (FA) meditation for our study. In FA meditation, the task is to focus your attention to a certain single point and keep there, and when your attention starts to drift, bring it back gently (Lutz et al., 2008 [31]). FA may seem easy, but it is actually rather demanding, especially for novices. Its benefits have been associated with development of various attentional and emotional processes (see Lutz et al., 2008 [31]). In BS, the task is to focus on different parts of your own body, letting them relax, and then switching to the next until you have covered your whole body. In PF the task is to focus on a single point in front of you and not be distracted by anything else (this type of exercise is often also called focused attention meditation, but we want to reserve that term for the category of exercises to avoid confusion).

While seemingly different in many ways, these two meditation exercises share the same basic logic of actively controlling your attentional focus on a specific target. The main difference between them is what that focus is: in PF, it is external; in BS, it is internal. In VR, this turns into a difference whether the meditators attention is focused on something inside the virtual environment or outside it. One exploratory research question of our study was to see whether VR would support one type of attentional process better than the other, and consequently whether it would work better with certain types of meditation.

We used two set of questionnaires to evaluate the performance of the system:

(i) The ITC-Sense of Presence Inventory [29]

(ii)The meditation depth questionnaire (MEDEQ) [35]

From the ITC-Sense of Presence Inventory we chose a subset of questions from the full questionnaire so as to keep the experiment duration reasonable. The used the full version of the MEDEQ questionnaire.

Participants

The participants were 43 university students with various major subjects, aged between 20 and 48 years (M=28.7). There were 26 female participants. The participants were paid 40 euros as compensation.

Apparatus

A QuickAmp (BrainProducts GmbH., Germany) amplifier was used to record the EEG, which then went to the OpenVibe [37] framework for real-time analysis. Two frequency bands, the Theta (4-6Hz) and Alpha (8-12) were extracted using fourth order Butterworth bandpass filters. Then we calculated average band power for 100 ms epochs. The resulting values were then send to Unity3D via a TCP connection.

EEG was recorded with 6 electrodes (F3, F4, C3, C4, P3, P4) and the ground electrode was placed at FCz, selected so that the straps of the Oculus headset wouldn't interfere with them. A common reference montage was used during the recordings.

Procedure

When arriving to the lab, the participant at in a comfortable chair. After filling out written consent, the participant was attached to the electrodes. A 5-minute baseline recording took place before the actual experimental tasks, not only for the statistical analyses for controlling the differences in individual levels of the psychophysiological activity, but also to familiarize the participant with the recording apparatus. In the experiment there were 6 meditation exercises, each lasting 10 minutes. Following each exercise was a 3-minute 2-back working memory task for evoking stress and erasing the effects of the last meditation session. After the experiment, we removed the electrodes, thanked the participant and provided a short briefing about the purpose of the experiment. The whole experimental session took between 2 and 2.5 hours.

Design

The experiment employed a 2 (meditation type) X 2 (adaptation) X 2 (medium) design. The two meditation types were focused attention and body scanning, the EEG-based bio-adaptation was either on or off, and the medium was either the Oculus Rift VR-glasses or a computer screen. However, there were only 6 conditions in the experiment. There was no bio-adaptation combined with a computer screen. These two conditions were omitted to keep the total length of the experiment under 3 hours.

RESULTS

In the next sections we compared meditation and presence in the following three conditions with planned contrasts: (a) a control condition (CC) where the participants followed the meditation exercise on a computer screen without a head-mounted display or neurofeedback (NF), (b) a head-mounted display without neurofeedback, and (c) both a head-mounted display and neurofeedback.

We did the statistical analyses with the Linear Mixed Models (LMM) procedure with restricted maximum-likelihood estimation in SPSS (version 21). One at a time, we specified each outcome measure as the dependent variable and the model included the fixed effect for the condition (six different).

Perhaps surprisingly, no statistically significant difference emerged between the two exercises (FA and BS) in any of the outcome measures, except for the part of the meditation depth questionnaire that measures negative feelings, such as boredom. Respondents found FA more boring than BS, but only when they did not use the head-mounted display or neurofeedback. Therefore, the effect of meditation type will not

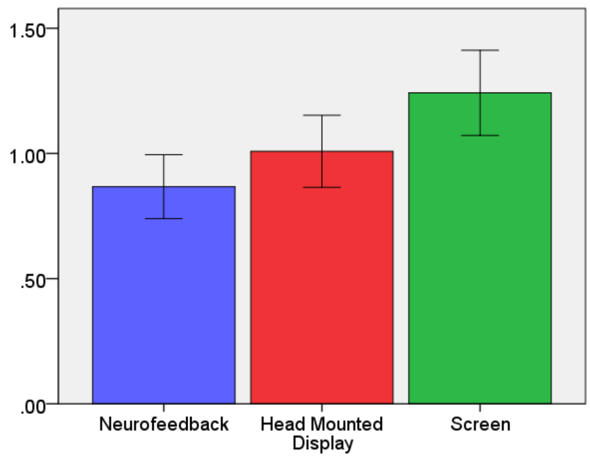

Figure 7. MEDEQ Hindrances: negative feelings during the meditation.

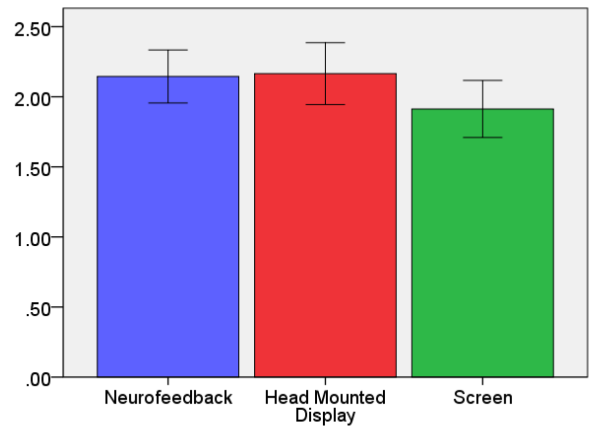

Figure 8. MEDEQ Relaxation: feeling of relaxation during the meditation.

be explored further in the analyses (the data were collapsed across the meditation types when presenting the results).

Meditation Depth Questionnaire

The meditation depth questionnaire showed a general trend: the combination of head-mounted display with neurofeedback was perceived to be the best, while the head-mounted display condition without neurofeedback was rated higher than the control. However, the difference between control condition and head-mounted display was greater, and always statistically significant, than the difference between head-mounted display and neurofeedback, which did not reach statistical significance.

Hindrances

The meditation depth questionnaire measures the meditation experience by dividing it into five stages or factors of increasing depth. The first factor, labeled "Hindrances", deals with the negative feelings associated with the meditation experience, such as boredom and anxiety, and is measured with questions such as "I found it difficult to relax" and "I felt bored." The results can be seen in figure 7. The CC elicited significantly more negative feelings than the head-mounted display condition ($p < 0.01$); while the HMD condition seemed to elicit higher negativity than the NF condition, the difference did not reach statistical significance ($p = 0.091$).

Relaxation

The second factor of the meditation depth questionnaire deals with relaxation and is measured with questions such as "I felt well" and "I became more and more calm and patient". See Figure 8. The CC was the least relaxing and rated significantly lower than the HMD ($p < 0.05$) The head-mounted display and neurofeedback condition elicited almost the same amount of relaxation.

Personal Self

The third factor is labeled "personal self" and deals with aspect of self-reflection elicited by the meditation practice. See Figure 9. It was measured with questions such as "I became aware of a center inside myself" and "I got intuitive insights or understand about my life." Again, the CC received significantly lower score than the HMD ($P < 0.01$) while there was no significant difference between neurofeedback and HMD.

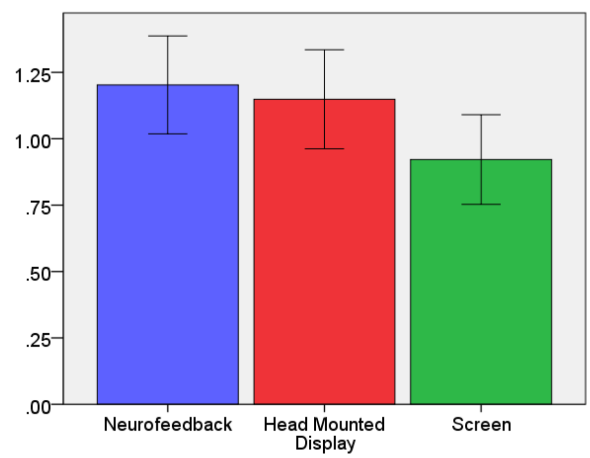

Figure 9. MEDEQ Personal Self: concentration and centeredness

Transpersonal Qualities

The fourth factor, labeled "transpersonal qualities" deals with essential qualities such as joy and love that may arise during meditation. See figure 10. The questions associated with this factor included "I felt love, surrender, connection" and "I experienced boundless joy". The CC was rated significantly lower than the HMD condition ($p < 0.01$) and no significant difference appeared between the neurofeedback and HMD condition.

Transpersonal Self

The final factor of the questionnaire dealt with the deepest levels of meditative experience: feeling of non-duality and infinity of consciousness. See Figure 11. It was measured with questions such as "there was no subject or object anymore" and "I felt myself at one with everything." The control condition again scored significantly lower than the HMD condition ($p < 0.05$) while no significant difference appeared between the NF and HMD conditions.

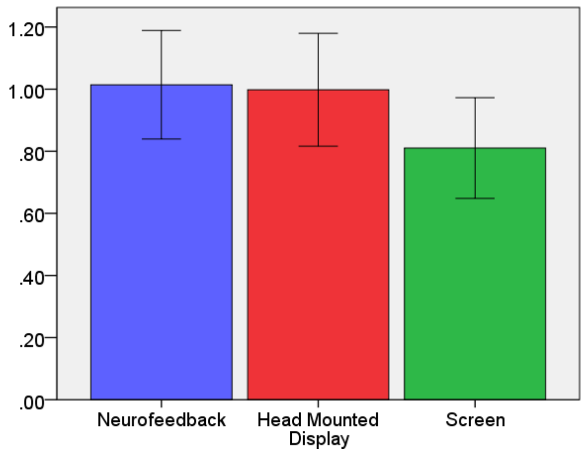

Figure 10. MEDEQ Transpersonal Qualities: experience of essential qualities such as joy and love.

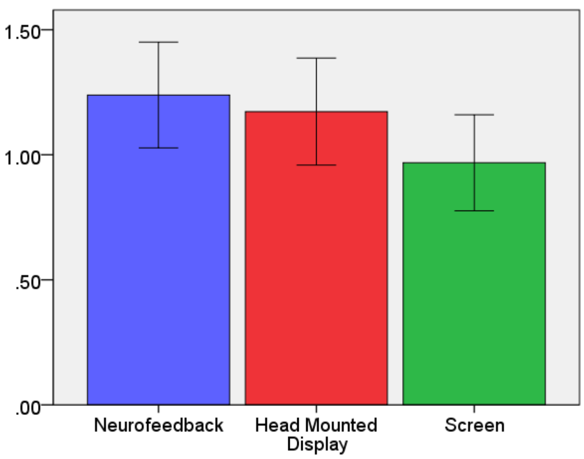

Figure 11. MEDEQ Transpersonal Self: Deepest meditative states of non-duality and infinity of consciousness

Presence

We measured the perceived level of presence using the The ITC-Sense of Presence Inventory [29]. The results show that the combination of neurofeedback and head-mounted display produced the highest level of presence, followed by the head-mounted display without neurofeedback. The screen condition elicited lowest level of presence. See figure 12. These results follow the same trend as those of the meditation depth questionnaire.

DISCUSSION AND CONCLUSIONS

It is well known that VR technology can elicit higher presence than a monitor screen; however, the fact that neurofeedback can increase the feeling of presence even further is something not previously shown (to the best of our knowledge). The results of the meditation depth questionnaire indicate that the system is able to provide added value on all levels of the meditative experience: from the mundane feeling of boredom to the more esoteric states of non-duality, the system was rated better than the control condition. It is also interesting to note that while neurofeedback induced a higher level of presence, it did not directly reflect in the meditation depth questionnaire

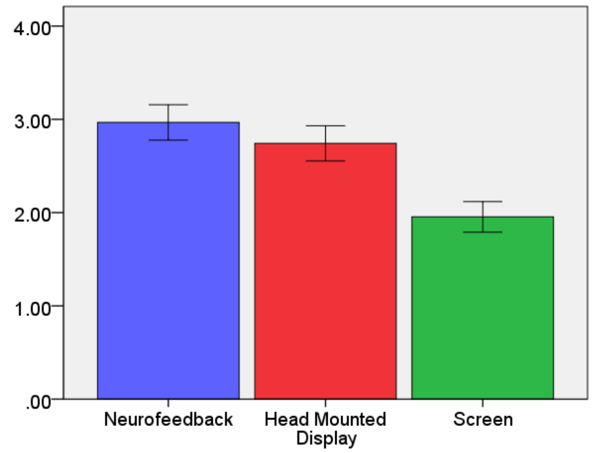

Figure 12. Presence

results. As there was a clear trend of higher ratings for the neurofeedback, this might just be due to the limited sample size.

In this paper we have presented a neurofeedback virtual reality meditation system. The system measures user's brain waves in real time and maps them into levitation and visual effects inside a virtual environment, displayed using a head-mounted device. Our user study shows that the head-mounted display generates higher meditative states when compared to the same system displayed on a normal screen. Neurofeedback further enhances the experience, providing higher levels of presence as reported by the users.

In the next version of the system, we intend to implement individually defined alpha and theta frequency bands (see, for example, [1]) that adapt automatically to each user. In addition to fully using the possibilities of modern VR technology, we plan to implement a walking meditation scenario.

ACKNOWLEDGEMENTS

This work has been partly supported by Academy of Finland (Academy project number 268999) and by the European Commission FP7 framework through the MindSee project (FP7 - ICT; Grant Agreement # 611570).

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