Digital biomarkers reflect stress reduction after Augmented Reality guided meditation: a feasibility study

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ABSTRACT

Meditation, a mental and physical exercise which helps to focus attention and reduce stress has gained more popularity in recent years. However, meditation requires a concerted effort and regular practice. To explore the feasibility of using Augmented Reality(AR) Devices to assist in meditating, we recruited ten subjects to perform a five-minute meditation task integrated into AR devices. Heart Rate, Heart Rate Variability, and skin conductance response(SCR) are analyzed based on an Electrocardiogram(ECG), Electrodermal activity to monitor the physiological changes during and after a meditation session. Additionally, participants filled out surveys containing the Perceived Stress Questionnaire (PSQ), a clinically validated survey designed to evaluate stress levels before and after meditation to analyze the change in stress levels. Finally, we found significant differences in Heart Rate and Mean SCR Recovery Time for participants between the three study procedure periods (before, during, and after guided meditation).

CCS CONCEPTS

• Applied Computing---Life and medical sciences • Human-centered computing---Ubiquitous and mobile computing

KEYWORDS

Augmented reality, Digital biomarkers, Meditation

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1 Introduction

Meditation is a mental and sometimes physical exercise which helps to focus attention and reduce stress by encouraging mindfulness of one's self and surroundings [32]. According to data from the 2017 National Health Interview Survey (NHIS), the number of American adults and children using meditation techniques increased more than threefold between 2012 and 2017 [33]. Meditation has therapeutic effects on a range of physical ailments including chronic pain, high blood pressure, anxiety, depression and insomnia.[34] Meditation requires a concerted effort and improves with practice. However, regular practice can be difficult because people are often in distracting environments that do not facilitate relaxation. Augmented reality (AR), the overlaying of virtual content onto a view of the real world environment, may improve the ability for meditation in environments that are otherwise not conducive to relaxation. Additionally, AR devices can be used to improve attentiveness to the practice of meditation, for example by projecting a controllable virtual object on top of the real world that captures the users' attention. [3,7]. There is limited research that explores AR applications to assist meditation. InnerGarden[20], which presents an augmented sandbox using projected virtual content, is designed for self-reflection exercises and has been evaluated in combination with respiratory and electroencephalogram (EEG) monitoring. Another recent study integrated adjunctive neurofeedback (measuring brain wave activity through an EEG and using that information to monitor and modify mental processes [23]) into an AR meditation process[9]. Participants reported no significant mood difference as a result of the neurofeedback; however, this study did not monitor the cardiac and electrodermal signals, which eliminates the chance to observe the connection between AR and responses of heart and skin to meditation. In our study, we not only use AR devices to meditate, but we also employ wearable sensors to record digital biomarkers that can be used in the future to modify guided meditations in real time using physiological feedback systems.

Digital biomarkers are defined as objective, quantifiable physiological and behavioral data that are collected and measured by means of digital devices such as portables, wearables, implantables, or digestibles. [35] There is a variety of existing research which focuses on observing the effects of meditation on digital biomarkers. In [2,9,17], digital biomarkers which quantify sleep quality, such as total sleep time and sleep efficiency, are measured after meditation. In [13,29], heart rate variability (HRV) and respiratory rhythm are seen to be positively influenced by meditation exercises. In [12], it is indicated that body temperature can be controlled during meditation. In [36], the effects of meditation on heart rate and blood pressure are analyzed, where both are found to have a significant decrease. These studies demonstrate the feasibility of assessing the effects of meditation using digital biomarkers to reveal changes in underlying physiology.

In our study, we use AR to support meditation in settings that are not inherently relaxing, for example in an office or laboratory space. Selected digital biomarkers are monitored during the procedure to explore the physiological changes during and after a meditation session.

2 Methods

2.1 Participants

This study was approved by the relevant IRB. Participants (n=10) chose a convenient time of day to perform the meditation to minimize disruption to their schedules. Eight of the participants were male, and all participants were over 18 with a mean age of 27.6 years (SD = 1.54). Five participants were Caucasian, four were Asian or Pacific Islander, and one participant did not report their race or ethnicity. Exclusion criteria included wearing glasses, as the AR headset does not fit over glasses, and sensitivity to flashing lights and/or images. All participants either did not require glasses to see or were wearing contact lenses, and none reported a history of sensitivity to flashing lights.

2.2 AR Devices and Software Design

Our AR-based meditation app was developed using Unity 2020.3.14f1. The app consists of three main components: our custom AR stimuli, a meditation audio track, and eye tracking functionality. It was built for and run on a Magic Leap One AR headset (Fig 2a), though the nature of our design would enable it to be implemented for other AR devices with minor changes. Some types of eye tracking data we capture are only available on the Magic Leap One headset, (e.g., pupil diameter), hence our choice to use this device.

First, our custom AR stimuli were designed with the goal of immersing the participant in a relaxing environment for their meditation exercise, similar to the approach taken in [5]. Upon app startup, we detect horizontal planes in the real environment and cover them with a virtual grass texture. Spatialized ambient audio is played using sound effects from a real forest environment [31]. We then instruct the participant to place a virtual tree in a place of their choosing on the plane generated by the desk in front of them, by looking at a spot on the desk and pulling the Magic Leap One control trigger. This will be the focus of the participant's visual attention during the exercise, so we allow them to adjust the tree position as many times as required until it is in a comfortable position for them to watch. The tree model is animated so that its branches and leaves appear to be swaying in a light wind. We also implement an experimental biofeedback feature, such that when a participant's exhalations are detected through the Magic Leap One's onboard microphone, the tree animation swaying speed increases then decays over a period of three seconds to imitate a gust of wind. An example screenshot of the participant's view through the Magic Leap One is shown in Figure 1.

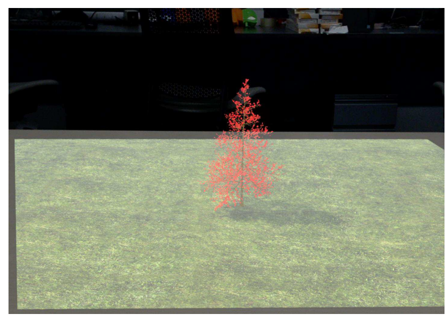

Figure 1: Participant's vista during meditation

The second component of our app design is a pre-recorded meditation audio track. Once the participant is comfortable in their AR environment, they start the meditation audio by pressing the Magic Leap One 'bumper' button on the control. This audio guides the participant through a deep breathing exercise; for this study we use the 5-minute 'Breathing Meditation' exercise made available by the Mindful Awareness Research Center at UCLA [37], which has been used in a variety of previous studies on the impact of meditation, including [25,30].

Finally, the third component of our app concerns the collection of eye tracking data using the video-oculography-based eye tracker onboard the Magic Leap One. From app startup until the participant removes the AR headset, we record the participant's 3D gaze position (in the coordinate space defined by the Magic Leap One), the pupil diameter of both eyes, and a 'gaze confidence' indicator provided by the eye tracker, which estimates the quality of eye tracking data, all at 60Hz.

2.3 Test Procedure

To collect physiological data, we utilized three distinct devices: the Bittium Faros 180, an FDA-approved 3-lead wearable electrocardiogram (ECG) device (Fig 2b), an Empatica E4 wristband (Fig 2c) that collects heart rate, skin temperature, electrodermal activity (EDA), and an Omron 7900K blood pressure cuff (Fig 2d).

Each participant wore the E4 and the Faros for one hour before the meditation exercise to establish a baseline. During this time, participants were free to perform usual low-effort activities, but were asked not to eat or exercise. We additionally asked participants to complete a pre-study survey which assessed their level of perceived stress, as well as their perceived ability to perform mental visualization tasks. After this baseline period, blood pressure was measured with the Omron device according to the standard clinical protocol [28] and then the participant began the AR-assisted meditation exercise using the Magic Leap One AR headset. A visual calibration was completed first to ensure proper eye tracking, and then the participant opened the meditation app and was guided through instructions about the app's functionality. Once they felt comfortable using the app, the participant began the 5-minute meditation exercise. During this time, the participant was left alone in the conference room with the lights slightly dimmed to facilitate a calming experience. The meditation environment and devices are shown in Figure 2.

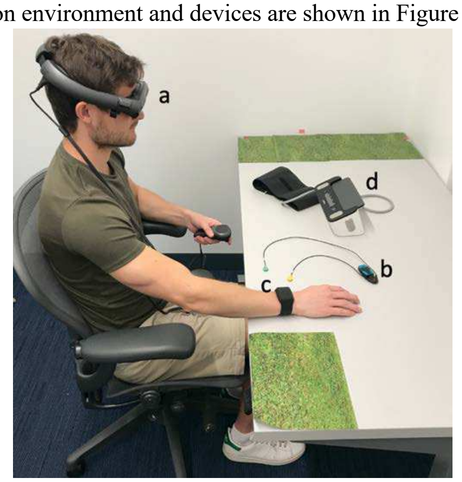

Figure 2: Meditation environment and devices

After the exercise had been completed, the participant removed the AR headset and the same blood pressure measurement procedure was repeated as before the meditation. The participant was asked to complete a post-meditation survey assessing stress levels after meditation, as well as their level of comprehension of the study procedures. The participant then continued to wear the Faros and the E4 for an additional hour after the exercise to measure physiology and activity in the period after the meditation.

2.4 Data Analysis Method

2.4.1 ECG Signal Processing Preprocessing of the Faros ECG data included signal filtering, peak detection, and metric calculation. First, a Butterworth filter (3rd order, 5Hz low-pass filtering frequency) was applied to remove high frequency noise. Then, a double-sided moving average window (width=0.75 seconds) was applied . R-peaks were searched for in regions where the signal amplitude exceeds the moving average[8,11]. Lastly, the RR intervals are calculated based on the position of the R-peaks. Heart rate, and two HRV parameters, RMSSD (the square root of the mean squared differences between adjacent normal RR intervals), and SDNN (the standard deviation of mean of all normal RR intervals), are calculated based on the peak-to-peak intervals.

2.4.2 EDA Signal Processing The E4 EDA preprocessing pipeline consisted of valid window selection, filtering, artifact removal, signal decomposition, and peak detection. During the study, we recorded when the participant started wearing the devices, as well as when the participant removed the device. Using these timestamps, we removed signals during non-use to ensure a valid window for data processing and analysis. The data is then filtered using a method adapted Taylor et al. [24] to reduce noise in the data while still preserving variations that represent physiological responses. Next, we removed motion artifacts using the Neurokit function eda_clean()[15]. The EDA signal is then decomposed into the fast varying phasic component and the slow varying tonic component using the Neurokit function eda_phasic(). Statistical features are calculated on each component, including maximum, mean, standard deviation and kurtosis. Lastly, peaks in the EDA recordings, deemed as skin conductance responses (SCRs), were detected through the Neurokit function eda_process(). Relevant features are calculated surrounding each SCR, including height, amplitude, rise time, and recovery time.

2.4.3 Statistical Analysis Differences in signal features between the three study procedure periods (before, during, and after guided meditation) were calculated individually for all 10 participants. Non-parametric Wilcoxon Rank Sum tests, which make no distributional assumptions and are robust to outliers, were used to determine whether these differences are sufficiently different from zero, indicating a change in the signal value between the procedure periods.

2.4.4 Pre & Post Survey Pre- and post-experiment surveys (administered electronically via Qualtrics [38]) were completed by each participant to determine study eligibility, record self-reported relaxation and stress levels, and examine the possible effects of prior experience with AR or VR and current levels of tiredness and stress on our results. To record self-reported relaxation and stress levels, in the post-experiment survey participants rated their level of relaxation relative to before the meditation exercise on a 5-point Likert scale, with the following responses: 'Much more relaxed", "A little more relaxed", "The same", "A little less relaxed", "Much less relaxed". Additionally, both the pre- and post-experiment surveys contained the Perceived Stress Questionnaire (PSQ), a clinically-validated survey designed to evaluate levels of stress in the participant's life [14]. The PSQ contains 30 descriptive statements such as "You feel rested", "You have too many things to do", and "You have many worries". Participants are asked to rate these statements using a 4-point Likert scale to indicate how frequently they feel the statement applies to their life. Scoring the PSQ yields a stress index between 0 and 1, with higher scores indicating higher levels of stress. To study the possible effects of prior AR or VR experience on our results, participants were asked to rate how frequently they have used AR and VR headsets, including the Magic Leap One specifically. To study the possible effects of tiredness and stress levels on our results, participants self-reported these levels prior to the experiment on two respective 5-point Likert scales, and for stress we also analyzed data from the aforementioned PSQ.

3 Results

We explored whether HR, HRV, and/or EDA changed between the baseline, meditation exercise, and post-meditation exercise periods. We also explored the correlation between the biosignals and the stress level in the survey. Based on the literature[13,19,21,22,27,36], we expected that HR would decrease and that HRV (both RMSSD and SDNN) would increase between baseline and meditation. Since lower SCR amplitude and recovery time indicate lower stress or emotional arousal levels [4], we also expected that EDA, as represented by the mean SCR recovery time, rise time, and amplitude, would decrease along with reported stress levels [16] [6].

We also hypothesized that post-meditation stress levels as reported through the PSQ would decrease. Finally, we explored the experience of wearing AR or VR headsets, hypothesizing that the effects of our meditation app would be weaker in participants who have less experience wearing AR or VR headsets, as relaxation effects may be diminished by stimulation related to a new or unfamiliar experience.

3.1 Statistical Analysis of Biosignals

To determine the effect of meditation on the body, Wilcoxon Rank Sum tests are performed for 18 hypotheses regarding the changes in digital biomarkers between the baseline, meditation, and post-meditation periods. The results are summarized in Table 1: bolded results indicate a p-value less than 0.05, and results highlighted in red have p-value less than the Bonferroni-corrected significance threshold of 0.00278. We observe statistically significant differences in two specific digital biomarkers: heart rate shows a significant difference between the baseline and meditation periods, and EDA mean SCR recovery time shows a significant difference between meditation and post- meditation periods.

Table 1: Changes of metrics pre-, during and post-meditation

Digital Biomarker	Post-meditation vs Baseline	Meditation vs Post-meditation	Meditation vs Baseline
Heart Rate (bpm)	**-5.051 ± 3.691 (p=0.006)**	**-3.596 ± 3.985 (p=0.037)**	**-8.646 ± 3.760 (p=0.002)**
RMSSD	**5.111 ± 4.773 (p=0.037)**	3.842 ± 10.311 (p=0.132)	**8.953 ± 9.437 (p=0.006)**
SDNN	5.269 ± 12.367 (p=0.193)	-14.768 ± 27.066 (p=0.131)	-9.499 ± 17.773 (p=0.193)
EDA Mean SCR Rise Time	-0.162 ± 0.252 (p=0.084)	-0.030 ± 0.298 (p=0.846)	-0.192 ± 0.367 (p=0.131)
EDA Mean SCR Recovery Time	-2.072 ± 14.457 (p=0.432)	**-9.352 ± 8.923 (p=0.002)**	**-11.424 ± 15.328 (p=0.027)**
EDA Mean SCR Amplitude	-0.013 ± 0.066 (p=0.770)	**-0.036 ± 0.045 (p=0.037)**	-0.049 ± 0.086 (p=0.160)

3.2 Pre & Post Survey Analysis

The range of self-reported tiredness and stress levels (with 1 being the least and 5 being most) in the pre-experiment survey spanned four out of five tiredness levels (1:1 participant, 2:5 participants, 3:3 participants, 4:1 participant) and all five stress levels (1:2 participants, 2:1 participant, 3:4 participants, 4:1 participant, 5:2 participants). In our post-meditation survey, when asked to rate how relaxed participants felt compared to before the meditation exercise on a 5-point Likert scale, 9 out of 10 responded 'A little more relaxed' and one participant responded 'Much more relaxed'. The majority of participants (7 out of 10) had no previous experience with headset AR (with four of those having no experience with VR either), while two participants had used it once or twice for a brief period, and one participant used it frequently. These results indicate that our approach can help users with varying levels of tiredness and stress, as well as those new to headset AR, to increase their level of relaxation. The fact that we found no statistically significant differences between pre-and post-meditation stress levels reported in the PSQ was expected because many PSQ questions are focused on longer-term sources of stress, while our meditation session was designed to alleviate short-term stressors. Finally, we observe that the greatest reduction in heart rate, which is the biomarker most strongly impacted by meditation, occurred in two of the three subjects who had prior experience with AR. This supports our hypothesis that the effects of AR-based meditation are strongest for users who are already familiar with AR.

4 Discussion

Biofeedback works by providing a perceptible, real-time metric indicating the physiological state of the body, which allows the subject to make a conscious effort to improve that metric [39]. By providing visual or auditory cues to the subject about the state of their body, such as how happy, focused or relaxed they are, meditation outcomes can be improved [23,26]. In this study, the only biofeedback mechanism that was implemented was associating the swaying of the AR tree with the participant's breaths. While the study included physiological signal analysis to determine the effect of meditation on the body, we did not use any of these signals to provide feedback to the subjects during meditation. In future work, we will further explore whether using biosignals such as eye movement, heart rate, heart rate variability and EEG for biofeedback, can positively impact the effectiveness of meditation in an AR environment.

As detailed in Section 2.2, we also captured eye tracking data while participants were using our AR app using the video-oculography tracker onboard the Magic Leap One headset. Our hypothesis was that pupil diameter would decrease during the relaxing meditation exercise based on previous work showing positive correlations between stress level and pupil diameter [1][18], including within virtual environments[10]. While we did not find a statistically significant difference between pupil diameter at the start and end of the exercise, pupil diameter did reduce for 5 of the 8 participants for which data was available (recorded eye tracking data was invalid for 2 participants who reported myopia, but were not wearing contact lenses). In future work we will further examine the effects of AR-based meditation exercises on pupil diameter, as well as its impact on other eye tracking metrics such as the length and number of fixations and the speed of eye movements.

While we did see differences in heart rate and HRV, two metrics which are expected to correspond with effective meditation, pre- and post-meditation, neither difference was statistically significant. This is possibly due to the small population size and the need for multiple hypothesis correction, for which we used the most conservative method. In future studies, a larger participant population and fewer metrics of focus for statistical testing will improve the statistical power of this study. To remove the effects from the order of experiments(baseline-meditation-baseline), we will add another pair of baseline and mediation task (baseline-meditation-baseline-meditation-baseline). In this way, the activities of subjects will not affect the second and third baseline period.

5 Conclusion

In this work, we collected biosignals from subjects who performed a guided meditation using an AR headset. We compared the biosignals between the baseline, meditation, and post-meditation periods and discovered a statistically significant decreases in heart rate during the meditation period as compared to the baseline and mean SCR recovery time during the post-meditation period compared to the meditation period, as well as a trend toward decreased self-reported stress. Our work indicates that biosignals recorded during AR-based meditation warrant further study to examine physiological changes resulting from meditation, and to determine how AR can play a role in improving meditation outcomes.

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