Creation of Galvanic Skin Response biofeedback in VR Unity Environment for enhancement of Mindfulness meditation

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Shareholder requirements

This project was driven by the idea of enhancing mindfulness meditation through immersive biofeedback. The core concept was to create a virtual reality (VR) environment that dynamically responds to a user's stress levels, thereby reinforcing mindfulness by providing real-time, intuitive feedback. The team was inspired by existing mindfulness practices and aimed to bridge them with physiological data to create a more effective training tool. The exploration focused on combining VR immersion with stress-sensing technology, particularly Galvanic Skin Response (GSR), to offer users tangible, environmental cues during meditation, rain when stress was detected and clear skies during calm periods.
The stakeholder asked us to develop an interactive system that could support mindfulness meditation using real-time biofeedback. The main requirements of the stakeholder was to create a functional VR environment which is able to visualise the GSR feedback in a way meaningful to the user. Specifically, they wanted a solution that would respond to the user's physiological state in a meaningful way, making internal changes, like stress, visible through environmental cues. The goal was to improve users' awareness during meditation by integrating sensor data into a virtual experience. The secondary requirements of the stakeholder included: finding the motivation and exploration of relevant literature, determining the functional and nonfunctional requirements of the system and the addition of an analysis to test the created system.

Exploration and Motivation

For this challenge, our group is focusing on creating a virtual environment that responds to biofeedback. This biofeedback comes from using a sensor that measures physiological changes within the individual. To specify, our group decided to create an environment that would respond to galvanic skin response (GSR) by providing the user with rain when stress was detected and no rain when no stress was detected. During the measurements, the participant would have to carry out a mindfulness task, where they would have to follow a guided meditation exercise. By adding the sensor, the participant would thus be presented with live feedback of how successful the task is going. By adding this feedback, we would hope to increase task performance. By adding virtual reality to the experiment, it allows a more innovative design that would otherwise not be possible in real-life settings.

To ensure both the validity of the sensor and the working of the environment the participants are asked to fill out the Meditation Depth Questionnaire (Piron,2022) after the experiment. This questionnaire consists of 30 questions about the feelings one has about the meditation exercise and one's emotions during this exercise. It answers the meditation on a 5 point likert scale ranging from "not at all" to "very much". An example includes "I found it difficult to relax".

Literature Background

Mindfulness

Didonna & Zinn (2009) describe mindfulness as remembering to be aware and to be attentive. In addition, they mentioned that the current mindfulness approach focuses on "awareness and acceptance first, change second". Another definition described by Didonna & Zinn (2009) of mindfulness included "self-regulation of attention so that it is maintained on immediate experience, thereby allowing for increased recognition of mental events in the present moment and adopting a particular orientation toward one's experience that is characterized by curiosity, openness and acceptance". The main aim of mindfulness is to transform how people relate to their internal experience, e.g., thoughts, emotions, and physical sensations (Didonna & Zinn, 2009). By practicing mindfulness one might be able to lower relapse rates from major depression.

As mentioned before mindfulness focuses on the ability of fully being aware and present. This is different from “normal” meditation which focuses on emptying the mind of thought. Instead, it focuses on training the mind to become aware of what we are thinking, and what we are doing at any time. This would be especially useful in the setting of our VR environment, where the real life feedback might help the individual to become even more aware.

Furthermore, a literature review of 106 studies on VR mindfulness was conducted and concluded that utilizing VR for mindfulness training is an effective technique for use within adult populations (Ma et. al., 2023). Therefore, we focus on potentially enhancing an already efficient technique.

Galvanic Skin Response

Because GSR signals differ greatly from one person to another, each participant's data was normalized using a mean normalization approach (Chao et al., 2014). The study itself utilizes Galvanic Skin Response (GSR) as a key physiological measure to assess drivers' mental workloads when using different navigation map formats. The fact that this study observed significant differences in galvanic skin responses across these different map formats directly supports the use of descriptive statistics to compare mean GSR values between different conditions. To minimize large variations in physiological responses, the analysis focused on how each participant's responses deviated from their baseline. The calculation for this deviation is expressed with the formula (Chao et. al., 2014):

$$\Delta X = (Mean\ value - Mean\ baseline/(Mean\ baseline)$$

As seen here , ΔX represents the deviation from the baseline, mean value is the average measurement taken during the driving experience, and mean baseline is the average recorded during the initial baseline measurement.

Furthermore, while the Chao et al., 2014 study does not explicitly detail a "time-series analysis" the continuous measurement and subsequent analysis of physiological data over the course of the driving task, as well as the use of visualizations, suggest that examining the progression of responses over time is a recognized and valuable approach in this field.

One thing that should be taken into consideration is that the GSR sensor is very prone to noise. This might influence the outputs by showing inaccurate data, and in our case, creating inaccurate events.

Functional and Nonfunctional requirements of the system

In order to satisfy our shareholder, we created a full list of all the functional and nonfunctional requirements of our system, in order to be able to prioritise them and have a clearer development process. The main functional requirements of the system are to record the GSR signal, compute the relevant output and create a biofeedback within Unity. All these requirements can then be separated into smaller tasks. Namely, the recording of the GSR signal has the following requirements:

- Buffer to capture the GSR signal
- Buttons to start recording once Pico board is plugged in
- Recording function to allow for recording of GSR data within the buffer
- Send raw GSR data over the serial port

For computing the relevant output in Unity, we need the python script to contain the following functions:

- function to open and read the serial port
- function to calculate the baseline GSR measurement
- function to process the data (conduct normalised percentage change)
    - if the normalised percentage change is 5% or lower than the baseline, then the the output will be 0, otherwise the output will be 1

- function to read the newest filename
- function to write down each output into a new file containing either 1 or 0

In order to achieve true biofeedback, Unity contains its own functional requirements:

- function to get the latest Data file name
- function to read from the latest file
- function to update the rain according to the output read
- calling all functions in the Update() function to ensure the code is running in real-time along with the other codes

In terms of the nonfunctional requirements of the system, the main performance aspect of the system is for the users to get a somewhat real-time feedback of their mindfulness via the rain. Once the code is functional, the next steps should include to obviously validate the measures but also to minimise the computing time for all of the codes to ensure that the feedback is as ‘real-time’ as possible. From the user experience perspective, the system should facilitate better mindfulness for the user by providing feedback of their own biological measure, to make the user more aware that they are not in a state of mindfulness. The main focus of the system at this current stage is performance and usability as we are aiming for the creation of this biofeedback, with the subsequent gathering of data regarding how useful users find this feedback in trying to achieve mindfulness.

Description of our Codes

The following section contains a detailed description of all of the codes and other important aspects of our system. Firstly, the code that is running on the microcontroller is running the CircuitPython for the Maker Pi Pico board and receives the GSR data from the sensor and sends it to our second code via the serial port. The main aspects of this code, from now on referred to as main.py, were taken from the GSR code made during the Module 6 course. The main.py code contains the class buffer which contains various functions that together initialize, fill and empty the buffer. The class button creates buttons for starting, stopping and resuming recording, with the start function being the only relevant one in this system. The class sensor initializes and reads the data from the sensor. The main function continuously reads GSR data and sends it via the serial port at a 3 second interval to avoid any communication errors. In order to achieve smooth serial communication, it is very important to save this code as ‘main.py’ onto the microcontroller. Once that is finished, one needs to safely unplug and replug the microcontroller, and press the recording button (GP20) to start sending off the GSR data. It is really important to make sure that this code is running on the controller without Thonny being active as this disrupts the serial port communication and makes the transfer of data between the 2 programs impossible.

The second program that receives the GSR is a Python code running in Visual Code Studio, that is meant to compute the baseline and the normalised percentage change as well as save the output to a text file. This python code, named File_maker.py, contains the function read_serial_data which establishes a reading-only connection to the serial port, reads and parses through the data sent. The function calculate_baseline, uses the first 10 variables (changeable configuration called BASELINE_COUNT) for calculating the baseline measure of the individual. Afterwards, the process_data function creates a GSR buffer that collects every 5 variables (changeable configuration called GSR_BUFFER_SIZE) and averages them. These averages and the baseline are then used for the computation of the normalised percentage change, which is then compared to the baseline once again. If the normalised percentage change is lower than the baseline by 5% or more (Configuration PERCENT_CHANGE_THRESHOLD), the process data function returns 0, otherwise it returns a 1. The function get_next_filename looks at all the files in the directory and finds the one with the largest number in the name and adds plus 1 to it to get the newest file name. Finally,the main function runs all of the above mentioned functions in this order, with the addition of saving the data from the process_data function into a new text file, named by the output of the function get_next_file_name. The data gets saved into a text file named data[number].txt with the number starting with 0 and every subsequent file created receives a name with a +1 added to the number.

Finally, the Unity environment reads the newest text file in order to read the output and change the weather accordingly. The current VR environment utilizes the 'RelaxandMeditiationVR' open-source environment published by Berkcan Altungoz on github (Antungoz, 2021) with certain changes made to facilitate the aim of our project. Firstly, the original environment was built for the use of Google VR headset and controllers, so the entire player, its collisions and the main camera, along with the PlayerMovement script and the PlayerInteraction script had to be rebuilt to allow for mouse-and-keyboard controls. Due to these changes to the player, other accommodations had to be made such as changing the variables of the candle flames to allow the flames to rotate towards the new player and avoid looking 2-dimensional. Furthermore, a MeditationMatInteraction script was created to enable the participant to start an audio guided mindfulness exercise when they left-click on the pink meditation mat found in the middle of the environment. A study conducted by Call et. al. utilized a pre-recorded audio mindfulness exercise narrated by Jon Kabat-Zinn (Call et al., 2013), and we were able to find a version of this exercise on Youtube, which we utilized in our environment (Respirare Meditations, 2025). The downloaded environment already contained the RainMaker asset from the Unity Asset Store, which was utilised for the creation of rain for the biofeedback (Johnson, 2022). We added the rain Prefab from the Rainmaker assets before changing the RainScript attached to it so that the weather changes according to keyboard button presses, in order to test whether this weather asset is going to work. After establishing connection with the other codes, the RainScript was changed to read the newest text file. The RainScript initializes the entire weather including the falling particles, mist particle system, rain sounds and clouds. The ReadStressDataAndControlRain function does exactly what it says, it reads the newest text file to get the output 0 or 1 and if the output is 0, it sets the rain to null, otherwise it sets medium intensity rain along with its clouds and sounds. It's important to call the ReadStressDataAndControlRain function in the Update() event function, to ensure that this process is repeated continuously for every frame of the environment, rather than just at the beginning. The rain used is defined as medium as the Rain Script contains conditions for both light and heavy rain that can be added in future iterations to receive a more detailed form of biofeedback.

Methods

The following section describes the detailed process of how we tested our prototype system on participants. Due to time limitations and the small scale of this project, the participants were given a verbal version (with no signature) of the consent form provided in Appendix 1. We tested on 4 participants all of which were Psychology Master students from different specialisations, all of which were in the process of studying for their end of module exams, during the time of testing. First, the participants were first asked to sit without doing anything while wearing the GSR sensor for thirty seconds. During these thirty seconds, the program could establish a baseline value that was later used to recognize changes in the values during the experiment. Afterwards, the participants started the mindfulness meditation using the VR environment. Whenever the VR environment was opened the audio with the meditation guided started playing and the participants were instructed to explore the environment if they wanted and follow the guided meditation. This lasted for approximately five minutes. For half of the participants, that is Participant 2 and 4, they were asked to stress themselves out half-way through experiencing the environment. This was done to achieve a presence of biofeedback in the environment. The task for this was asking the participants about their upcoming exam and trying to get them to think of what would happen if they didn't pass this test and what kind of repercussions that would have for them. When the five minutes were over the participants had to fill out the meditation questionnaire (Appendix C). The output of the questionnaire was later computed by the researchers by adding up all the values to compute the total number.

Outcomes

Figure 1.

GSR Values Participant 1

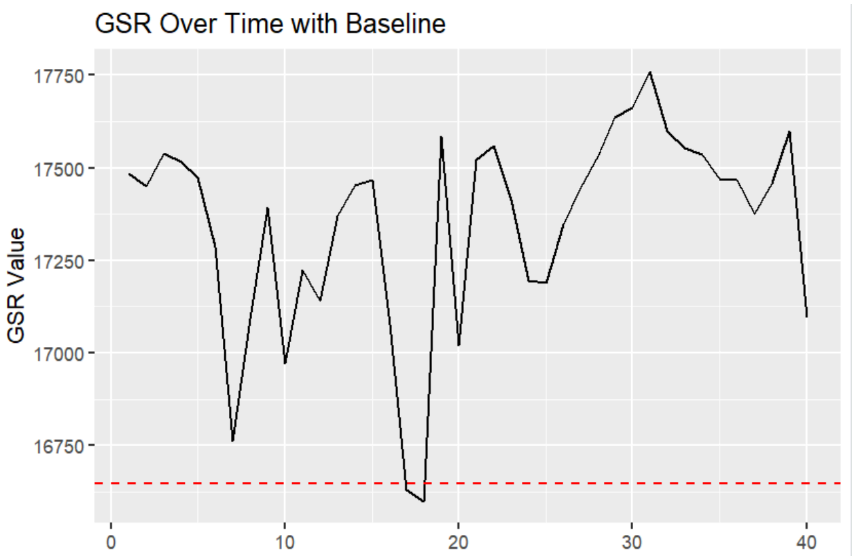


Figure 2.

GSR Values Participant 2

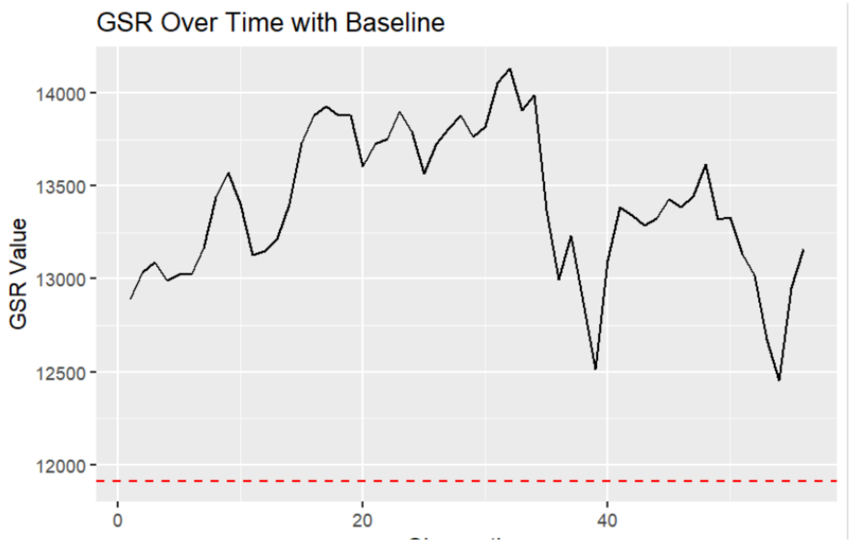


Figure 3.

GSR Values Participant 3

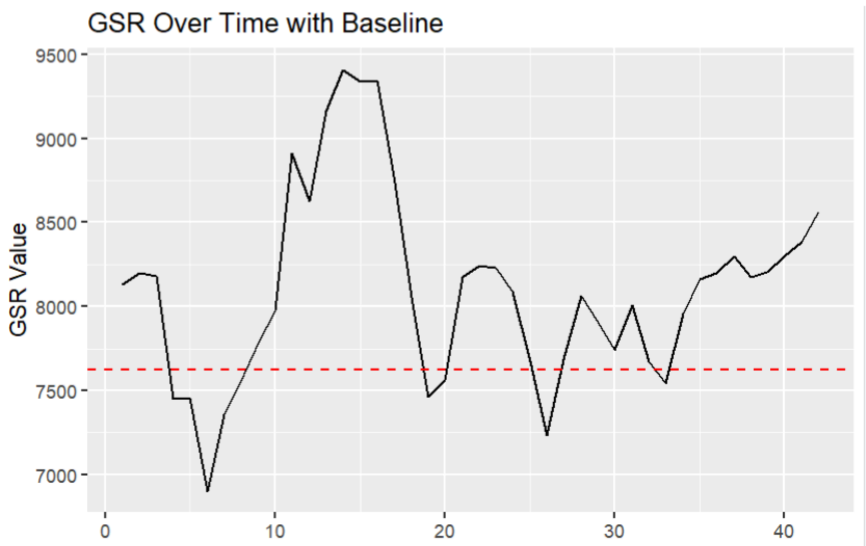
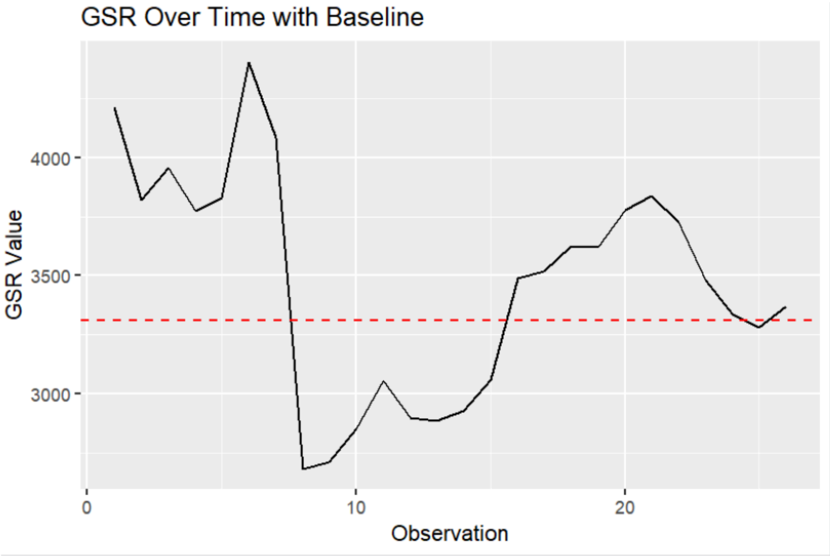


Figure 4.

GSR Values Participant 4



It is important to note that due to recurring coding problems and time limitations, we were unable to implement a way for the raw GSR data to be saved for the purposes of later Data analysis. That is why, the above-shown graphs and the following data analysis utilised the 5-point averages created within the process_data function of our python script, meaning each point on the graph actually represents an average of 5 values, instead of the raw data. Therefore, the following section is mostly concerned with whether participants saw the biofeedback in the environment and the scores from the mindfulness questionnaire.

The graphs represent the GSR (Galvanic Skin Response) values of four participants recorded during their mindfulness meditation sessions in the VR environment. These graphs help visualize how each participant's physiological state evolved over time and how this related to the presence or absence of biofeedback.

Figure 1:

This participant did not receive biofeedback (no rain triggered by GSR changes). The graph shows high variability and elevated GSR values, suggesting increased physiological arousal. According to qualitative feedback, this participant found the meditation guide’s voice irritating, which may explain the lack of relaxation during the session.

Figure 2:

Also in the no-biofeedback condition, Participant 2 shows a steady increase in GSR values. Without real-time feedback, the system could not provide any external cue to support stress regulation. This graph reflects the participant's internal physiological state without intervention.

Figure 3:

This participant experienced biofeedback. The graph shows a generally lower and more stable GSR trend throughout the session. The presence of rain in the VR environment, triggered when stress was detected, may have helped the participant become more aware of their state and adjust accordingly, contributing to improved mindfulness.

Figure 4:

Also in the biofeedback condition, Participant 4 shows similarly stable GSR values with slight fluctuations. The pattern indicates a potentially effective calming effect of the feedback loop, aligning with the aim of enhancing mindfulness through real-time environmental responses.

In Summary, participants who received biofeedback (Figures 3 and 4) demonstrated lower and more stable GSR values, suggesting that the rain visual feedback helped them manage their physiological arousal during meditation. In contrast, those without biofeedback (Figures 1 and 2) showed more erratic and elevated GSR patterns. These graphs support the system’s effectiveness in enhancing awareness and relaxation through biofeedback.

The outcomes of the study show that both participants experiencing the biofeedback gave higher scores on the MEDEQ questionnaire, as shown in Table 1, full questionnaire found in Appendix C. These higher scores would indicate more effective meditation.

Table 1.

Outcomes MEDEQ Questionnaire

Participant ID	Total Score MEDEQ
1	52
2	53
3	73
4	74

Another aspect of the outcomes that is worth mentioning is that both participants that were experiencing biofeedback had lower baseline scores. As percentage change was used, this would also mean that participants with lower baseline scores needed less change in measurements than participants with higher baseline scores.

Furthermore, for both participant one and two, who did not experience biofeedback, their baseline values were much lower than the measures during the meditation exercise. For participant one this might be explained by the participant reporting to feel angry with the meditation guide, and finding its voice distracting rather than calming. This might have prevented the participant from both fully engaging with the meditation and the environment as well as its benefits.

In addition, for the participants that did experience the biofeedback both indicated that they found the rain helpful. Moreover, one participant explicitly mentioned thinking about a stressful event when it started raining.

Limitations

Our study already made a good starting point for future research, however, it also contains several limitations. Firstly, the normalization approach used to analyze the data might allow a more personal calibration, however, it might also introduce the issue of sensitivity. As the normalization approach makes use of percentage change it means that for individuals with higher baseline values, the change has to be greater than it has to be for individuals with a lower baseline. Additionally, as this analysis relies on mean values it might overlook short-term fluctuations that might be of relevance. This might result in the VR environment not being able to provide the participant with the most helpful feedback as it misses out on certain emotional changes.

Second, the GSR sensor is very prone to noise. More specifically, it easily alters the outputs when movement happens simultaneously. For this experiment, the participants were instructed that they were allowed to explore the environment freely during the task. However, as the sensor was placed on the participants' fingers and the movement was controlled by pressing keys, it often occurred that the participant moved the hand where the GSR was placed to move around in the environment. The movement of the sensor might have resulted in unreliable data as the sensor would have been more prone to detect noise.

Thirdly, the GSR is a valuable indicator of emotional arousal, however, it does not distinguish between emotional states. For example, the increase in emotional arousal, detected by the GSR, might be due to fear, but it might also be due to excitement. In our environment, the increase in sweat gland activity might be due to stress, and in turn, give the desired feedback, or be due to excitement elicited by the environment which would not require the biofeedback.

Fourth, A limitation of this report involves the consideration of a 5% normalized change in Galvanic Skin Response (GSR) as a potential threshold for indicating increased cognitive workload. While Chao et al. (2014) employed normalized ΔGSR in their study to interpret task-induced physiological changes related to drivers' mental workloads, the provided excerpts from their work do not specify or validate a 5% normalized change as a generally applicable threshold. The selection of a 5% normalized change threshold lacks explicit support within the reviewed literature, including the work of Chao et al. (2014). Other studies on GSR and cognitive load, such as those by Nourbakhsh et al. (2017) and Johannessen et al. (2020), used different methods for analyzing GSR and different metrics, highlighting the lack of a standardized approach and specific percentage thresholds across the field. This diversity in GSR analysis techniques and the absence of a consistent percentage-based threshold across these studies underscore the lack of a universally accepted standard.

Future research

As mentioned previously the study contains several limitations. Therefore, future research is needed to improve the accuracy, reliability, and immersion of the environment.

Firstly, a different type of analysis could be chosen to analyze the data. The current approach focuses on mean normalizations and baseline comparisons. Future research could make use of more sophisticated processing methods, for example, anomaly detection. Anomalies can be defined as the data points that differ significantly from most of the "normal" data (Musthyala et al.,). This type of analysis focuses on identifying these anomalies. In our setting this might allow for more appropriate feedback when detecting stress.

Furthermore, future research could focus on a design that reduces sensor noise. For example, by placing the sensor on a different part of the body that is less inclined to move or using a more passive experience where the participant is not asked to move around as much and is thus more able to keep the hand wearing the GSR sensor still. By reducing the noise more accurate and effective feedback can be given to the participant and in turn improve the effectiveness of the experiment.

In addition, to improve the reliability of the baseline readings of the GSR, future studies could investigate the effect of adding a standardized task within the VR environment while gathering the baseline. This might allow the researchers to collect the baseline for a time longer than 30 seconds, in order to get a more accurate baseline measurement. In addition, this would allow the participants to get familiar with the environment, if a tutorial was created during which the measurement would be taken.

Moreover, future studies might integrate additional biofeedback. At the current approach only two types of biofeedback are integrated, namely, rain or no rain. By for example making use of different types of rain, smaller changes could also be included in the presentation of feedback. Our current set-up actually includes code for the integration of 3 different types of rain and a no rain condition, however, we were unable to fully implement this due to coding problems and the instability of the baseline recording in its current state. In addition, other physiological data sources, e.g., heart rate, could be implemented to provide more accurate environmental responses.

Finally, future studies could make use of a VR headset to increase immersion. The current approach solely makes use of a desktop and keyboard which might fail to create full engagement with the environment. By increasing the immersion it might improve both the realism and the effects of the mindfulness training.

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Appendix

Appendix A: Informed Consent

Biofeedback in VR environment

Brief Summary of Project:

The research is about the investigation of biofeedback in a VR environment. The participant will be asked to follow a guided mindfulness meditation exercise in a VR environment while wearing a GSR sensor to measure stress. This stress measurement will be used to add real-time biofeedback to the environment and measure the impact of this feedback.

In order to participate in this study, we need to ensure that you understand the nature of the nature of the research, as outlined in the participant information sheet. Please tick the boxes to indicate that you understand and agree to the following conditions:

· I confirm that I have read the participant information sheet for this study. I have had the opportunity to consider the information and have had these answered satisfactorily.

· I understand that in order to take part in this study, I should be at least 18 years old and have a sufficient level of English and be a UT student. Furthermore, I should not be deaf and/or mute.

· I understand that personal data about me will be collected for the purposes of the research study including gender and nationality, and that these will be processed in accordance with data protection regulations.

· I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without my rights being affected.

· I understand that my data is anonymous and will be stored on secure university servers. I understand that it will only be used by the investigators for research purposes and that there is a possibility this research will be presented at conferences or published in journal publications.

· I agree to take part in this study.

Date, Signature: ___________________________

Appendix B: AI Statement

During the preparation of this work, the AI programme Grammarly and the automated correction in Google Docs was used to reduce grammatical and spelling errors. After using this tool/service, the content was thoroughly reviewed and edited as needed, taking full responsibility for the final outcome. In addition, AI programs ChatGPT, and Gemini's coding partner were used to help create several lines of code.

Appendix C: MEDEQ Questionnaire

MEDEQ © Dr. Harald Piron Please mark how much the following descriptions fit your meditation experiences of the last week. The following key is meant as a support for orientation: 0 = not at all 1 = a little bit 2 =mediocre 3 =much 4 = very much					
1) I found it difficult to relax.	0	1	2	3	4
2) I experienced equanimity and inner peace.	0	1	2	3	4
3) My body was relaxed.	0	1	2	3	4
4) There was a constantly change of thoughts in my mind.	0	1	2	3	4
5) I became aware of a center inside myself.	0	1	2	3	4
6) I felt myself at one with everything.	0	1	2	3	4
7) There was no subject and no object anymore.	0	1	2	3	4
8) I became more and more calm and patient.	0	1	2	3	4
9) I was very busy in order to use the recommended method properly.	0	1	2	3	4
10) I experienced some control over my mind; I could observe my thoughts from a distance	0	1	2	3	4
11) My mind was alert and clear.	0	1	2	3	4
12) Mainly I was more in a state of dozing or sleeping.	0	1	2	3	4
13) I felt bored.	0	1	2	3	4
14) I sensed a field of energy around me.	0	1	2	3	4
15) I felt love, surrender, connection.	0	1	2	3	4
16) Thoughts had come completely to rest.	0	1	2	3	4
17) I felt well.	0	1	2	3	4
18) I was glad that the meditation had finished.	0	1	2	3	4
19) The feeling of time disappeared.	0	1	2	3	4
20) I sensed my breathing comfortably calm and fluent.	0	1	2	3	4
21) Sometimes I sensed my body as very light.	0	1	2	3	4
22) I experienced boundless joy.	0	1	2	3	4
23) My mind/consciousness expanded to an infinite space.	0	1	2	3	4
24) I felt being accepted unconditionally.	0	1	2	3	4
25) There was no differentiation, comparison or judgment anymore. Everything could be as it was.	0	1	2	3	4
26) My mind, the field of consciousness and awareness was empty from thoughts, emotions and sensations.	0	1	2	3	4
27) I experienced humility, grace, gratitude.	0	1	2	3	4
28) There was no meaning of any meditation techniques anymore.	0	1	2	3	4
29) I felt a strong energy or power within myself.	0	1	2	3	4
30) I sensed myself as formless energy.	0	1	2	3	4