Closing the Loop: The Effects of Biofeedback Awareness on Physiological Stress Response Using Electrodermal Activity in Virtual Reality

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ABSTRACT

This paper presents the results of a user study examining the impact of biofeedback awareness on the effectiveness of stress management, utilizing Electrodermal Activity (EDA) as the primary metric within an immersive Virtual Reality (VR). Employing a between-subjects design (N=30), we probed whether informing individuals of their capacity to manipulate the VR environment's weather impacts their physiological stress responses. Our results indicate lower EDA levels of participants who were informed of their biofeedback control than those participants who were not informed about their biofeedback control. Interestingly, the participants who were informed about the control over the environment also manifested variations in their EDA responses. Participants who were not informed of their ability to control the weather showed decreased EDA measures until the end of the biofeedback phase. This study enhances our comprehension of the significance of awareness in biofeedback in immersive settings and its potential to augment stress management techniques.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; Laboratory experiments; *Empirical studies in visualization.*

KEYWORDS

Biofeedback, Awareness, Electrodermal Activity, Virtual Reality, Stress

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1 INTRODUCTION & BACKGROUND

Biofeedback for stress management is important for enhancing individual well-being and health [1, 6, 12, 19, 46]. Biofeedback provides real-time feedback on physiological processes and empowers individuals to gain control over their stress responses and has been increasingly recognized for its potential in treating a variety of stress-related conditions [8, 28, 33]. When users are aware of their physiological responses related to stress, such as heart rate, muscle tension, or skin conductance, they can learn to control these responses deliberately [2, 4, 40]. By enabling individuals to monitor and adjust their physiological states, biofeedback offers a responsive and effective alternative to managing stress, potentially reducing the reliance on pharmacological interventions and promoting holistic health. To assess stress for biofeedback applications and in real-time, medical practitioners and researchers use electrodermal activity (EDA) – among others also known as galvanic skin response (GSR) or electrodermal response (EDR) – the skin's electrical conductance and sympathetic response, which varies due to sweat gland activity linked to stress and emotional arousal [3, 11, 34, 42, 45].

EDA is a non-invasive, sensitive, and reliable marker of the sympathetic nervous system's activity, making it an ideal metric for biofeedback in stress management in the field of human-computer interaction (HCI). Particularly using EDA in immersive environments, such as in Games [22, 27, 30] and immersive environments [5, 17, 20, 43], has gained increased interest for HCI researchers. Immersive environments offer a non-distracting platform for engaging users in stress management interventions by providing a controlled yet dynamic setting where physiological responses can be fully monitored and modulated in real-time. The immersive nature of virtual reality (VR) and interactive environments enhances the user's sense of presence, making the biofeedback experience more impactful [20]. The use of EDA in immersive settings also allows for a nuanced understanding of testing and even inducing stress interventions and how users respond to various stimuli and stressors within the virtual environment [9], enabling researchers and practitioners to tailor interventions more precisely to the user's needs and preferences with specialized interactive systems and applications [5].

"Closing the biofeedback loop" depends on the user's awareness of consciously perceiving the biofeedback process and the extent of feeling to directly control the physiological response. For example, researchers found an increased muscle activity in high-awareness tasks using electromyography (EMG) and a reduced activity where participants were not fully aware of the functional control [36–38, 41]. Thus, an increased or higher awareness about the physiological function may significantly alter the strategy to control the physiological response and could be used to enhance or decrease the effectiveness of biofeedback techniques. This is important for HCI researchers and healthcare practitioners utilizing a wide range of applications such as in virtual reality [23]. These applications do not only comprise measuring stress in VR [7, 29, 32], but also using the signal as biofeedback modality [44] such as for anxiety [24] or phobia treatment [21], trauma coping [25], emotion-adaptive games [10], skill training [31] or architectural feedback in VR [26], or for altered appearances of one's own avatar [39].

However, it is currently unknown if increased or decreased awareness of being in a closed biofeedback loop changes the physiological response to stress in an immersive environment. This gap in knowledge actually addresses an important question in biofeedback research: Does the conscious recognition of biofeedback alter the effectiveness of stress management strategies? We hypothesized that the belief in controlling the body's function is not per se tied to the control of the body's function which could further reveal the role of secondary mediators of stress-coping skills [18, 34] or a person's stimulus-response specificity [13]. Therefore, we conducted a preliminary user study and presented initial results as a first step within a larger research effort investigating the mechanisms behind biofeedback awareness and the role of multimodal biofeedback in immersive VR settings.

In this paper, we present the study's results exploring the impact of biofeedback awareness on the efficacy of biofeedback in stress management, using EDA as a primary measure and biofeedback control using a VR weather control system. Although the measurement and rendering of the feedback occurred in real time, participants did not necessarily feel direct control over their skin conductivity, which allowed us to look at the definition of awareness in two different ways: informing participants about control (informed control) or asking if they feel control (control-aware). We found that the EDA measures of participants who were informed at the beginning of the biofeedback phase about their ability to control the weather were significantly higher at the end of the phase than those who were not informed. Participants who did not believe in their ability to control the weather showed decreased EDA measures until the end of the biofeedback phase. Our findings contribute to a better understanding of closing the biofeedback loop using immersive environments and fostering new research branches in that field.

2 METHOD

2.1 Study Design

To understand if biofeedback awareness affects the physiological response during stress management, we conducted a VR user study in which the EDA was used to control the weather in an immersive environment. Participants were either informed about their ability to control or not (INFORMED CONTROL), resulting in a between-subject study in which the participants (and experimenter) were blind to the conditions. In addition, we were interested if the participants felt control over the weather (CONTROL-AWARE), which was assessed posterior to the VR experience. As all participants experienced the same amount of time, we used TIME as a within-subject variable, assuming an interaction effect with INFORMED CONTROL or CONTROL-AWARE, indicating that the EDA will change during the biofeedback phase.

2.2 System and Biofeedback Control

The key biofeedback parameter in our study is the EDA. We used a PLUX Biosignals OpenBan[1] kit with skin conductance electrodes to measure the EDA. The electrodes were attached to the index and middle finger of the left hand. The sampling rate was 1,000 Hz with 16-bit resolution. To convert the raw values (ADC) into microsiemens (μS) as physical unit we used the following conversion formula as suggested by the openBan datasheet and with 3V for VCC:

$$EDA(\mu S) = \frac{\frac{ADC}{2^n} * VCC}{0.12} \quad (1)$$

We used the Unity game engine (2021.3.6f1) and the Biosignalsplux interface for Unity[2] to implement the VR application. For the visual representation of the animated weather in the biofeedback scene, we used the WeatherMaker asset[3] by Digital Ruby. The asset provides a realistic and smooth transition between volumetric cloud profiles with fluid animations. Animation transitions were set in a period of 10 seconds using linear interpolation. The asset also included suitable sound effects for the respective weather conditions. By leveraging the minimum and maximum values of the participant's EDA, each received value was transformed into a single weather variable transitioning between different weather profiles. Thus, the weather variable could take on values ranging from 0% to 100%, where 0% represented a very relaxed state on a sunny day, and 100% indicated a state of high stress using stormy cloud profiles.

The Unity application ran on an XMG Fusion 15 Laptop with Intel Core i7-9750H, GeForce RTX 2070 Max-Q, 16GB RAM, and Windows 10. While targeting frames per second (FPS) in Unity was set to 90, the application's average FPS was around 52 Hz. As VR head-mounted display (HMD) we used the HTC Vive Pro and SteamVR. The VR controller in the participant's right hand was only visible during the mental arithmetic task. We used the meadow environment from the Dynamic Nature Asset[4] from the Unity Asset Store for vegetation and animations in the nature scene during the relaxation and biofeedback phases. The system automatically calibrated the participant's skin conductance value during the relaxation and stress tasks for a (possible) full-range weather transition during the biofeedback phase. The application ran fully automatic to prevent any intervention from the experimenter.

[1]https://www.pluxbiosignals.com/products/solo-kit
[2]https://github.com/pluxbiosignals/unity-sample
[3]https://assetstore.unity.com/packages/tools/particles-effects/weather-maker-volumetric-clouds-and-weather-system-for-unity-60955
[4]https://assetstore.unity.com/packages/3d/vegetation/meadow-environment-dynamic-nature-132195

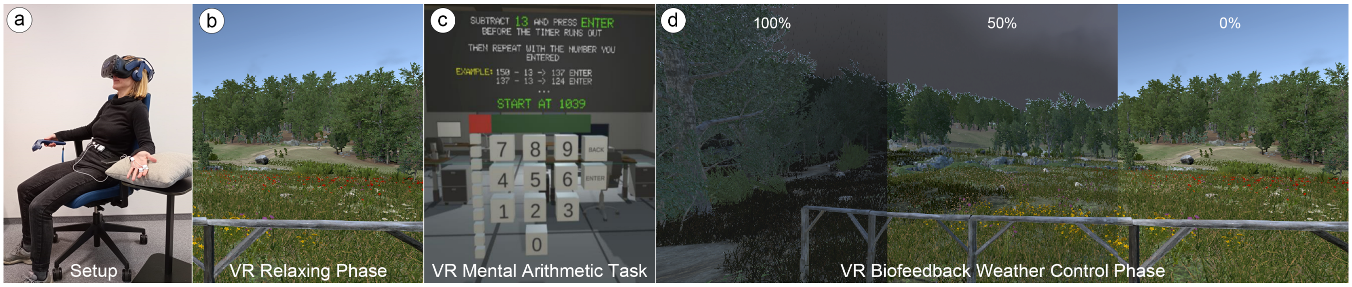

Figure 1: Photo of the experimental setup (a) and screenshots of the three phases in VR: Seven minutes in the Relaxation Phase (b) ensured a decreased EDA level as a minimum baseline for calibration. Maximal EDA levels were obtained in the Mental Arithmetic Task (c) based on the Trier Social Stress Test (TSST) paradigm to induce cognitive stress. In the biofeedback phase (d), the participants were able to control the weather activity from stormy (100% EDA) to sunny (0% EDA).

2.3 Procedure

After signing the informed consent and being briefed on the experimental setup, each participant was seated in our laboratory. Before launching the Unity application, the openBan device was attached to the fingers of the participant's left hand, and they were equipped with the HMD. The Unity application automatically assigned participants to an experimental condition, with the experimenter and the subject initially unaware of the condition. During the application's operation, participants received no further instructions other than those provided. The application's procedure was divided into three phases: Relaxation Phase, Stress Phase, and Biofeedback Phase (see Figure 1). The entire experimental procedure in VR lasted 24 minutes for all participants and was planned using the HCI studies toolkit [35].

2.3.1 Relaxation Phase. Participants were instructed using a visual prompt to relax (panel was visible for 20 sec). In this scene, a serene environment with natural sounds was displayed. This phase lasted exactly seven minutes (420 sec) to ensure full relaxation of the participants. The minimum EDA recorded in this phase was used to calibrate the weather conditions in the Biofeedback Phase.

2.3.2 Stress Phase. In this phase, participants solved a mental arithmetic challenge within seven minutes, based on the serial subtraction task from the TSST [14]. They were placed in a stressful office environment with loud noise and flickering lights. Participants had to continuously subtract thirteen from 1,039 and enter the result into a numerical field using a VR controller. Correct entries were acknowledged with a rewarding sound and a green cube lighting up. If time ran out or an incorrect entry was made, a loud horn sounded, and the number reset to 1,039. The remaining time was reduced by one second after each successful entry to increase stress. Additionally, at certain checkpoints, a false attempt was falsely attributed to the participant, resulting in the horn sounding and progress resetting. The participants' maximum EDA values were determined in this phase.

2.3.3 Biofeedback Phase. In the experimental phase, participants controlled the weather using their stress levels as biofeedback. Through the relaxation and stress phase, we calibrated the user's response to map it linearly onto the weather conditions from stormy (maximal EDA) to sunny (minimal EDA). A task panel in the field-of-view (FoV) (visible for 20 sec) prompted the participants to relax while the informed group received the information that they could control the weather. High-stress levels were visualized by a fierce storm tossing trees and plants. The sky was covered with dark thunderclouds, heavy rainfall prevailed, and nature was shrouded in darker light. The more the participants relaxed, the less rain fell, the clouds dissipated, the wind animations calmed down, and the sun illuminated nature again, thus returning to the calm state of the relaxation phase. The biofeedback phase lasted ten minutes.

2.4 Participants

Thirty participants were recruited via social networks and mailing lists of our institution. The mean age of the participants was 23.333 (SD = 3.613), ranging from 18 to 34 years (6 female, 24 male). Twenty-one were computer science or mechanical engineering faculty students, and nine were our institution's staff members or in vocational training. Students were compensated with credit points for their lectures, and staff members with working hours. The study received ethical clearance according to the guidelines and hygienic instructions of our institution.

2.5 Data Analysis

Raw data were recorded throughout the experiment. We only considered the EDA for hypothesis testing in the biofeedback phase where participants controlled the weather (840 - 1440 seconds after application start). To reduce the noise in the data, we aggregated the raw values within each second using their median.

3 RESULTS

3.1 Objective Measures

Interestingly, the responses from the participants were markedly distinct. Among the informed participants, 8 out of 15 (53.3%) correctly surmised that they had the ability to control the weather. In contrast, 7 out of the 15 participants (46.6%) who were not informed also believed that they had control over the weather. Pearson Chi-squared test of independence was conducted to assess the relationship between the variables Informed Control and

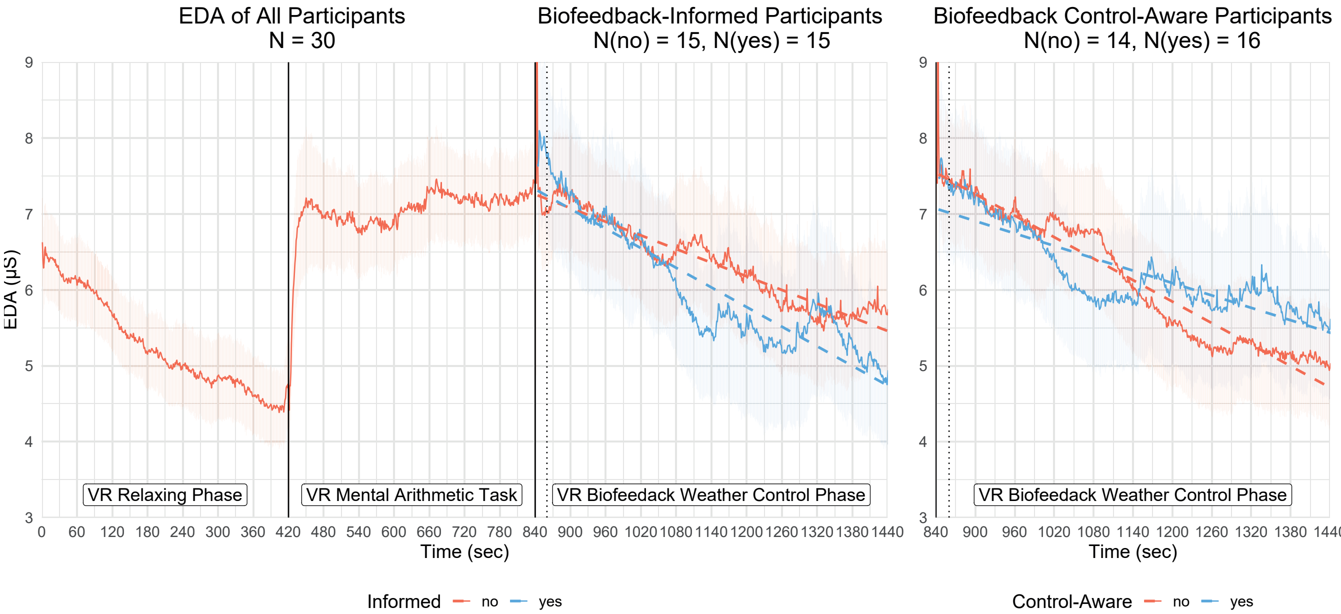

Figure 2: Electrodermal activity (EDA) of 30 participants, all of them controlling the weather in the VR Biofeedback Phase (Error bars show standard error). Fifteen participants were informed that their physiological responses will control the weather, while the other 15 were not provided with this information (the infopanel disappeared at the dotted vertical line). Additionally, post-experiment inquiries revealed that 16 participants found their physiological responses had influenced the weather, whereas 14 did not hold this belief. Their EDA measures are shown in the right graph. Linear regression model fit (dashed lines) using REML estimation on participant level showed significant interaction effects (both $p < .001$) indicating that the EDA measures of participants informed at the beginning of the biofeedback phase were significantly lower at the end of the phase than those who were not informed. Participants who believed in their ability to control the weather showed elevated EDA measures until the end of the biofeedback phase.

Control-Aware, which was not significant, $\chi^2 = 0$, $p = 1$. Therefore, we considered both groups independently and analyzed them separately using linear mixed model analysis.

3.1.1 Informed Control. We fitted a linear mixed model using restricted maximum likelihood (REML) and nloptwrap optimizer of the lme4 package[5] for R to predict the EDA (in μS) with Informed Control and Time as independent variables (IVs). Since all participants were in the VR for exactly the same amount of time, the time was treated as within-subject variable. The model included the subject as a random factor. The model showed substantial explanatory power, with a conditional R^2 of .91. The contribution from fixed effects alone (marginal R^2) is .03. The intercept of the model, representing the scenario of *non-informed* and *time* = 0, is at 9.78 ($CI95 = [8.040, 11.510]$), $t(17976) = 11.04$, $p < .001$. The main effect of being Informed Control is positive but statistically non-significant, $\beta = 1.170$ ($CI95 = [-1.280, 3.620]$), $Std.\beta = -0.090$ ($CI95 = [-1.280, 3.620]$), $t(17976) = 0.930$, $p = .350$. The effect of Time is statistically significant and negative, $\beta = -0.003$ ($CI95 = [-0.003, -0.003]$), $Std.\beta = -0.150$ ($CI95 = [-0.150, -0.140]$), $t(17976) = -45.400$, $p < .001$. However, also the interaction effect of Informed Control × Time is statistically significant and negative, $\beta = -0.001$ ($CI95 = [-0.002, -0.001]$), $Std.\beta = -0.060$ ($CI95 = [-0.070, -0.060]$), $t(17976) = -14.050$, $p < .001$. Standardized parameters were derived by fitting the model to a standardized version of the dataset. The 95% CIs and p-values were calculated using a Wald t-distribution approximation. Thus, that analysis confirmed the assumption that the EDA of participants being informed at the beginning of the biofeedback phase were significantly lower at the end of the phase than those who were not informed.

3.1.2 Control-Aware Biofeedback. For Control-Aware, we fitted a second linear mixed model with subject as a random effect factor. The model's total explanatory power is substantial (conditional $R^2 = 0.91$) and the part related to the fixed effects alone (marginal R^2) is 0.03. The model's intercept, corresponding to *not aware* and time = 0, is at 11.51 ($CI95 = [9.710, 13.310]$), $t(17976) = 12.55$, $p < .001$. The main effect of Control-Aware is negative but statistically non-significant, $\beta = -2.150$ ($CI95 = [-4.610, 0.310]$), $Std.\beta = 0.04$ ($CI95 = [-0.660, 0.730]$), $t(17976) = -1.71$, $p = 0.087$. The effect of Control-Aware is statistically significant and negative, $\beta = -0.005$ ($CI95 = [-0.005, -0.005]$), $Std.\beta = -0.23$ ($CI95 = [-0.240, -0.220]$), $t(17976) = -69.56$, $p < .001$. The interaction effect of Control-Aware × Time is statistically significant and positive, $\beta = 0.002$ ($CI95 = [0.002, 0.002]$), $Std.\beta = 0.10$

[5]https://cran.r-project.org/web/packages/lme4/index.html

($CI95 = [0.090, 0.110]$), $t(17976) = 21.48$, $p < .001$. Thus, participants who believed in their ability to control the weather showed higher EDA values until the end of the biofeedback phase. We also analyzed the data under one single model and considering the hypothesis if there is a three-way interaction between Informed Control × Control-Aware × Time, which was, however, not significant ($p = .914$). We note that the rank deficiency in the model due the limited samples size causes a chance of type III errors and does not allow valid conclusions about if the EDA of informed and control-aware participants (or other combinations) were different. The same applies to the effect of gender.

3.2 Subjective Feedback and Observations

As already mentioned, only eight participants from the group informed about the biofeedback actually believed that it was biofeedback that caused the weather change. After the experiment, seven participants believed that the weather has been controlled by their stress level, even though they were not informed. Consequently, 14 participants, almost evenly distributed in both groups, were strongly convinced that the weather was not manipulated by their stress or relaxation obtained from their EDA. While all of them observed that the weather changed over time, only ten of them cited as a reason that they were not convinced that the weather was being manipulated by them did not feel stressed or relaxed at all. However, a decrease in the EDA data of all participants was noticed. Thus, we suspect that not all participants can accurately assess their level of cognitive load.

The participants who believed that their body controlled the weather stated that they felt connected with the environment. "When I breathed in and out, the weather improved. When I was getting excited, the weather worsened," (P20). Every third participant experienced boredom during the relaxation scene. However, most of them reported positive feelings, including relaxation or a state of serenity during that first phase. Only two participants were annoyed during the experiment due to restricted movement caused by the sensor attached. In total, 25 participants described in their own words that they felt particularly stressed, frustrated, or angry during the arithmetic task. Three stated that they felt challenged, one felt competent enough, and only one participant (P8) reported feeling good after the task. Indeed, his EDA reflected this, as despite a significant increase during the transition to the stress scene, his EDA quickly recovered after the beginning after starting the task. Generally, most participants praised the VR environment, even though the graphics and resolution were criticized. Generally, the biofeedback itself was positively received by the participants. The arithmetic task, however, was mostly negatively recognized and as being too stressful.

4 DISCUSSION

In this study, we explored the impact of biofeedback awareness on physiological responses during stress management in VR. Thirty participants were involved in a between-subject design, where they were either informed or not informed about their ability to control the weather using EDA. The VR application allowed participants to control the weather based on their EDA levels, with a range from sunny (low EDA) to stormy (high EDA) conditions. After the experiment, we surveyed the participants to see if they felt control over the weather, which was additionally analyzed. Two linear mixed models revealed significant interaction effects between the investigated groups and their time while experiencing biofeedback. The biofeedback mechanism worked exactly the same for all participants.

The EDA of informed participants was significantly lower at the end of the biofeedback phase than those who were not informed. This suggests that knowing that their stress levels and their body could control the weather promotes their relaxation, which is generally in line with the principle of biofeedback using EDA [24, 26, 29, 31, 44]. However, higher EDA values of participants that recognized that they also gained control were probably higher due to their ability to test and "play around" with their influence on the weather in the biofeedback phase. This becomes probably evident in an initially similar progression to that in the informed group, with the EDA measurements changing and increasing after a certain time (between second 1020 and 1080). Participants who were not able to control it showed lower values, indicating that they just waited and relaxed until the end of the experiment. This finding indicates that being informed about the biofeedback loop does promote relaxation but not necessarily due to their ability to control the weather.

These findings are important for a number of research branches such as HCI, healthcare, psychology, game, and immersive application design. While in HCI the awareness and belief in control can be used for more effective and user-centered interactive systems dealing with stress, in medical healthcare, the findings are significant for practitioners focusing on non-pharmacological stress management techniques. Understanding how awareness and belief in control influence physiological responses can inform psychological theories and therapeutic practices, particularly in the context of biofeedback and stress-coping mechanisms using placebo or control groups. For cognitive researchers of interactive systems, the research offers valuable insights into the mental aspects of stress management and even could mean a methodological revision of typical stress tests or study designs [9, 14, 16]. In the field of game design, particularly in the development of emotion-adaptive games and playful experiences [22], this research also provides a first step for understanding game control mechanisms when integrating biofeedback.

4.1 Future Work

A deeper investigation into the psychological mechanisms underlying the observed effects of information for biofeedback awareness is warranted. This could involve a more nuanced exploration of the cognitive processes that participants engage in when they are informed about their control over the biofeedback loop. The lack of a significant three-way interaction between informed control, control awareness, and time suggests caution in interpreting these results and further highlights the need for more research. Particularly, the role of perceived and informed control in biofeedback effectiveness merits further exploration. For example, believing in the benefits of a biofeedback system that is not functional may change the EDA signals since the participants believe in physiological control [15]. Similar to the study by Segreto [36], future studies could manipulate the level of control participants have over the biofeedback system, examining how varying degrees of control influence EDA. Subjective experiences of stress and relaxation could further help to understand the phenomenon. This could be complemented by measuring additional physiological markers of stress and relaxation, such as heart rate (HR), heart rate variability (HRV), breathing, or cortisol levels, to provide a more comprehensive understanding of the process of closing the biofeedback loop.

The temporal dynamics of EDA responses indicate the need for a more granular analysis of EDA fluctuations over time. Subsequent research could also employ time-series analysis or subsequent methodologies to examine dynamics over time in greater detail, potentially revealing more patterns or other predictors of participant responses to biofeedback. Both control-awareness groups asked after the experiment to assess their belief of control happened to be two almost equally sized group split of a perceiving a system that worked the same for all participants. Future research should specifically control this factor in further studies. Additionally, the impact of individual differences on biofeedback outcomes is an area ripe for investigation. Factors such as personality traits, gender, prior experience with biofeedback or meditation, and individual stress levels could be examined to determine their influence on the effectiveness of biofeedback interventions. As our sample skew toward male computer science or mechanical engineering students, we also recommend to further consider a more diverse and heterogeneous group of participants.

4.2 Conclusion

The study's findings with 30 participants offer early insights into our research investigating the interplay between information, belief of control, and physiological responses in a biofeedback experiment using EDA within immersive environments. The results indicate that being informed about the biofeedback loop's control over the environment significantly influences participants' EDA, leading to lower stress levels. An effect is also notable when considering that the belief in control, irrespective of actual information provided, also impacts EDA, albeit in a different manner. Regardless of being informed, participants who believed they had control exhibited higher EDA levels, probably due to their engagement or will for experimentation with the perceived control over the environment. The subjective feedback further underscores this complexity, revealing a disparity between participants' perceived stress or relaxation and their actual physiological responses. This difference also suggests that individuals may not always accurately assess their cognitive load or stress levels. More research is needed to understand the underlying mechanisms.

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