Towards Affordable Biofeedback System for Mental Relaxation

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Abstract

The rising prevalence of stress-related mental health disorders highlights the need for accessible, non-pharmacological interventions. Biofeedback offers a promising approach by enabling individuals to regulate physiological processes for stress management and mental relaxation. This review examines 45 studies on biofeedback for mental relaxation detailing the core components of biofeedback systems (participant, data acquisition system, and feedback modalities) and discuss experimental protocols used in existing research. The understanding was that the key techniques include photoplethysmography (PPG), electrodermal activity (EDA), respiration (RSP), and electrocardiography (ECG), with visual feedback being the most common modality. Gamification is increasingly integrated to enhance user engagement. Despite their effectiveness, traditional biofeedback systems remain costly and complex, limiting accessibility. The lack of standardized biofeedback games and open-source research further restricts reproducibility. To address these challenges, this review advocates for cost-effective solutions using open-source hardware and software. Integrating retro gaming platforms, such as the Nintendo Entertainment System (NES), is proposed to improve engagement and accessibility. By identifying key challenges and opportunities, this review informs future research on affordable, replicable biofeedback systems, supporting their broader adoption in mental health care.

Keywords: Biofeedback, Mental relaxation, Stress management, Affordability, Reproducibility, Video Games

1. Introduction

1.1 Mental Health and Prevalent Statistics

The number of people affected directly or indirectly by stress and other psychological issue is increasing at an alarming rate. In India, for the productive population, stress from the number of contributing factors is responsible for mental disorders which contribute to greater morbidity and is a matter of serious concern. The National Mental Health Survey of India (2015-16) [1] revealed that 1 in 20 individuals in India suffers from depression. Alarmingly, nearly 80% of those afflicted with mental disorders had not received any treatment within 12 months of the onset of illness. The treatment gap for various mental disorders was reported to range between 70% and 92%. The number of people suffering from mental disorders in India is increasing at a rate much higher than what can be sustained by the country's healthcare system. Meanwhile, the government is actively ruling out healthcare policies, at the treatment level we can use one of the lesser-explored areas of alternate medical interventions like biofeedback.

1.2 Biofeedback for Mental Relaxation

Mental relaxation is a state where the mind is free from arousal caused by emotions such as anxiety, stress, anger, or fear. Achieving this state is essential for managing stress, which has become a global concern. Chronic stress can adversely affect both mental and physical health [2], potentially leading to conditions like cardiovascular diseases [3] and diabetes [4]. In 2015, cardiovascular diseases accounted for 31% of all deaths worldwide [5]. Therefore, attaining mental relaxation is crucial to counteract the negative effects of stress and maintain the body's internal balance, known as homeostasis.

While medications are available for stress management, they are not always recommended in the early stages due to possible side effects on other bodily functions and daily activities. Traditional interventions, such as Cognitive Behavioral Therapy, Music Therapy [6], [7] have been effective, but technological approaches like biofeedback are gaining popularity [8], [9], [10]. Biofeedback is a mind-body technique that enables individuals to gain control over certain physiological functions, like heart rate and breathing patterns. This method has shown promise in treating stress and anxiety, facilitating mental relaxation [8], [9], [11], [12], [13], [14]. As an alternative therapeutic approach, biofeedback can be used independently or alongside conventional medical treatments to effectively address certain mental health concerns.

1.3 Overview of Biofeedback Systems

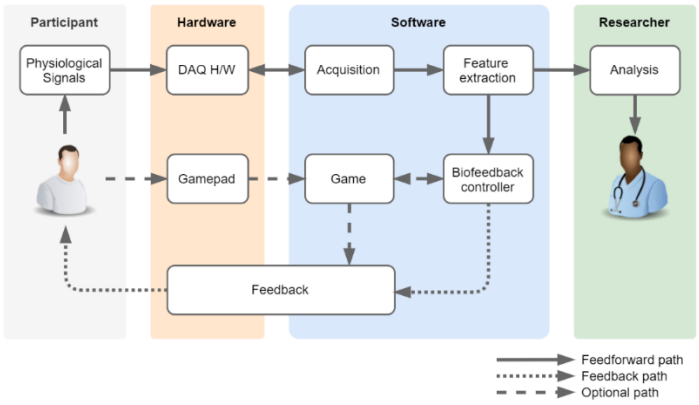

Figure 1: *Biofeedback loop*

Biofeedback is a technique that helps individuals gain control over certain involuntary bodily functions by providing real-time information about physiological activities [15]. By using sensors to monitor functions like heart rate, muscle tension, or skin temperature, individuals receive feedback—often through visual or auditory cues—that enables them to recognize and modify their body's responses. This process can lead to improved health and well-being.

Figure 1 shows a simplified overview of the biofeedback loop. First, sensors are attached to the body to detect specific physiological signals. These signals are then measured and processed by specialized equipment, which converts them into understandable feedback, such as a moving graph or sound. If video games are used for feedback delivery, the feedback can be the change in the game elements and game mechanics (rules). By observing this feedback, individuals can learn to make conscious adjustments to their physiological processes, such as practicing deep breathing to reduce heart rate. Over time, with guidance from trained practitioners, this practice can help individuals manage stress, anxiety, and other health conditions more effectively.

1.4 Traditional vs Modern Biofeedback

Biofeedback has evolved significantly with technological advancements, transitioning from traditional methods to modern, interactive approaches. Traditional biofeedback systems typically utilize limited signal modalities and provide basic feedback forms, such as simple charts and bar graphs [16], [17], [18], [19], [20]. However, traditional biofeedback systems face challenges in maintaining user engagement, particularly among younger participants. The necessity for multiple repetitive sessions [21] to master self-regulation of physiological and mental states can lead to monotony, reducing adherence and, consequently, treatment efficacy [22]. To address these issues, modern biofeedback methods have integrated video games as a delivery mechanism [13], [22], [23], [24], [25]. In this approach, individuals engage with specially designed or modified games that reflect their physiological states through in-game elements or mechanics, rather than displaying raw data. This gamified experience enhances motivation and adherence to biofeedback sessions [11], [26]. Additionally, modern systems often incorporate multimodal feedback, combining visual, auditory, and haptic cues to create a rich and immersive biofeedback experience [27], [28].

2. The Objective of This Review

The increasing prevalence of mental health disorders necessitates accessible and effective interventions. Biofeedback has emerged as a promising technique, enabling individuals to gain control over physiological processes to enhance mental well-being. However, traditional biofeedback systems often involve high costs and complexity, limiting their widespread adoption, especially in resource-constrained settings. This review aims to explore the landscape of affordable biofeedback systems designed for mental relaxation. We systematically examine various biofeedback modalities and techniques employed for mental relaxation. Additionally, we analyze experimental designs utilized in studies to assess the efficacy of these interventions. By identifying the opportunities and challenges associated with implementing cost-effective biofeedback solutions, this review seeks to provide insights into their practical applications and potential integration into routine mental health care. Our goal is to inform future research and development efforts aimed at making biofeedback an accessible tool for mental relaxation across diverse populations.

3. Methodology

An exhaustive survey of existing literature was conducted and based on this review, we hope to identify the possible answers to whether the type of techniques, feedback modalities, and experiments are used in biofeedback for mental relaxation training? The literature review is primarily conducted in Jan 2025. We searched for the relevant studies in the review articles published in biofeedback studies for relaxation training and biofeedback devices [12], [29], [30], [31], [32], [33] and studies from the search results in the following electronic databases: PubMed, IEEE Xplore, ACM, and Google Scholar. For the search criteria, the various combinations of the following keywords are used: Biofeedback, mental relaxation, and stress management. Articles were sorted as per relevance in the search results and abstracts from the first 50 results for each search were scanned to select relevant studies. Further, the references in articles were also used to get to any relevant literature.

4. Results and Discussions

4.1 Search Results

Based on our search criteria, we narrowed down to 45 publications to review. Each study in the final selection was reviewed and information about the biofeedback techniques (e.g., ECG, EEG etc.), feedback delivery (e.g., Desktop game, Portable device etc.), feedback type (e.g., Visual, Auditory etc.), and experiment design was extracted and summarized (see **Table 1**).

Table 1: *Summary of the selected reviewed papers*

SN	References	Biofeedback technique	Feedback Delivery	Feedback Type	Experiment design
1	Larkin et al., 1992 [34]	ECG	Desktop game	Visual	BS (N=12)
2	Bersak et al., 2001 [23]	EDA	Desktop game	Visual, Game mechanics	NR
3	J. J. Kennedy & Pretorius, 2008 [35]	PPG	Portable device	Visual	BS (N=338)
4	Cutshall et al., 2011 [16]	EDA, PPG	Desktop app	Visual	WS (N=8)
5	Lemaire et al., 2011 [36]	PPG	Portable device	Visual, Auditory	BS, RCT (N=40)
6	Henriques et al., 2011 [37]	PPG	Desktop app	Visual	WS (N=9)
7	Moraveji et al., 2011 [38]	RSP	Desktop app	Visual	WS (N=13)
8	Bouchard et al., 2012 [11]	ECG, EDA	Desktop game	Visual, Auditory	BS, RCT (N=40)
9	Edvardsson et al., 2012 [17]	PPG, EDA	Desktop app	Visual	BS, RCT (N=29)
10	Sutarto et al., 2012 [39]	ECG, RSP	Desktop app	Visual	BS, RCT (N=36)
11	Vidyarthi et al., 2012 [40]	RSP	Environment	Auditory	OBS (N=15)
12	Wells et al., 2012 [41]	PPG	Desktop app	Visual	BS, RCT (N=46)
13	Sanchez et al., 2012 [42]	EDA, TEMP	Mobile app	Visual	WS (N=5)
14	Schnädelbach et al., 2012 [43]	ECG, EDA, RSP	Environment (Interactive space)	Visual, Auditory	WS (N=67)
15	Wu et al., 2012 [44]	ECG, PPG, RSP	Mobile app	Visual	QE (N=67)
16	Feijs et al., 2013 [18]	EDA	Desktop app	Visual	WS (N=12)
17	MacLean et al., 2013 [45]	EDA	Portable device	Visual	WS (N=11)
18	Prinsloo et al., 2013 [46]	PPG	Portable device	Visual	BS, RCT (N=18)
19	Chittaro & Sioni, 2014 [27]	EDA, PPG, EMG	Desktop game	Visual	WS (N=12)
20	De jonckheere et al., 2014 [47]	PPG	Mobile app	Visual	WS (N=19)
21	Gaggioli et al., 2014 [48]	ECG	Desktop app (VR)	Visual	BS, RCT (N=82)
22	Kotozaki et al., 2014 [10]	NIRS	Desktop app	Visual, Game mechanics	BS, RCT (N=30)
23	Whited et al., 2014 [49]	PPG	Desktop app	Visual	BS, RCT (N=28)
24	Bhandari et al., 2015 [50]	RSP	Environment (Ambient sound)	Auditory	BS, RCT (N=28)
25	Lee et al., 2015 [51]	PPG	Desktop app	Visual	BS, RCT (N=15)
26	Ratanasiripong et al., 2015 [52]	PPG	Portable device	Visual, Auditory	BS, RCT (N=60)
27	Sarabia-Cobo, 2015 [53]	PPG	Desktop app	Visual	QE (N=74)
28	van der Zwan et al., 2015 [54]	PPG	Portable device	Visual	BS, RCT (N=126)
29	Al Osman et al., 2016 [55]	ECG	Mobile app	Visual	WS (N=12)
30	Dillon et al., 2016 [9]	EDA	Mobile game	Visual, Game mechanics	BS (N=50)

31	Munafò et al., 2016 [56]	PPG, RSP	Desktop app	Visual	BS, RCT (N=40)
32	Sonne & Jensen, 2016 [57]	RSP	Desktop game	Visual, Game mechanics	WS (N=16)
33	van Rooij et al., 2016 [28]	RSP	Desktop game (VR)	Visual, Game mechanics	WS (N=86)
34	Parnandi & Gutierrez-Osuna, 2017 [26]	ECG, EDA, RSP	Mobile game	Visual, Game mechanics	BS (N=25)
35	Zafar et al., 2017 [14]	ECG, RSP	Mobile game	Visual, Game mechanics	BS (N=43)
36	Wang et al., 2018 [25]	ECG, EDA, RSP	Desktop game	Visual, Game mechanics	WS (N=86)
37	Brinkmann et al., 2020 [8]	PPG	Portable device	Visual	BS, RCT (N=52)
38	Jafarova et al., 2020 [58]	PPG	Desktop game	Visual, Game mechanics	BS (N=112)
39	Mazgelytė et al., 2021 [59]	EEG, EDA, RESP	Portable device	Visual	WS (N=43)
40	Kim et al., 2021 [60]	ECG, EDA, EMG, TEMP	Portable device	Visual	WS (N=74)
41	Chung et al., 2021 [61]	ECG	Portable device	Haptic	OBS (N=14)
42	Chand & Khosla, 2022 [62]	PPG	Desktop game	Visual, Game mechanics	WS (N=16)
43	Weibel et al., 2023 [63]	ECG	Desktop app	Visual, Auditory	BS, RCT (N=107)
44	Téllez et al., 2023 [64]	ECG	Mobile game	Visual, Game mechanics	WS (N=10)
45	Birk et al., 2024 [65]	ECG	Mobile app	Visual	OBS (N=10)

Abbreviations of physiological terms: *EEG = Electroencephalogram, ECG = Electrocardiogram, EDA = Electrodermal Activity, RSP = Respiration, EMG = Electromyogram, PPG = Photoplethysmogram, TEMP = Temperature*

Other abbreviations: *BS = Between Subjects, NR = Not Reported, OBS = Observational Study, QE = Quasi-Experimental, RCT = Randomized Controlled Trial, WS = Within Subjects*

4.2 Biofeedback Techniques

Biofeedback techniques are characterized by the specific physiological signals they monitor and the derived metrics used to assess mental relaxation. In our review of 45 studies, eight distinct physiological signals were identified: Photoplethysmogram (PPG), Respiration (RSP), Electrodermal Activity (EDA), Electrocardiogram (ECG), Electroencephalogram (EEG), Near-Infrared Spectroscopy (NIRS), Electromyogram (EMG), and Temperature (TEMP). **Figure 2**, illustrates the distribution of these signals across the reviewed studies. A one way ANOVA test on the on the biofeedback techniques revealed the significant diferrence amont the reveiwed 45 studies ($F(7, 352) = 9.79$, $p < 0.0001$, $\eta_p^2 = 0.16$). The PPG, ECG, EDA, and RSP were statistically equally and mostly used among the reviewed studies, in the order of their occurrences. In contrast, TEMP, EMG, NIRS, and EEG were statistically equally and least used among the reviewed studies, in the order of their occurrences.

PPG emerged as the most frequently utilized signal (n = 19), primarily measuring heart rate (HR) and heart rate variability (HRV) to evaluate mental stress levels. HRV derived from the PPG signal is a direct indicator of mental relaxation [66], [67], [68]. Its popularity is attributed to the low setup time and the availability of cost-effective sensors, making it accessible for various applications. ECG is the second most (n = 15) used technique as it can provide similar metrics to PPG, such as HR and HRV. ECG is equally used as compared to PPG in the studies ($t(352) = -1.17$, $p = 1$, $d_z = -0.25$).

EDA measurements, including skin conductance level (SCL) and skin conductance response (SCR), were also prevalent (n = 14), correlating with arousal and stress levels. RSP was the last (n = 13) among

mostly used techniques, with respiratory rate (RSP-R) serving as a stress indicator and facilitating paced breathing exercises. Voluntary control over respiration allows participants to directly modulate their breathing patterns, aiding stress management. Conversely, EEG and NIRS, despite offering valuable insights into brain activity, are less commonly employed in biofeedback for mental relaxation because of their high acquisition costs and extended setup times.

It's noteworthy that the cumulative count of signal usage (67 instances) exceeds the total number of studies reviewed (45) because several studies employed multiple physiological signals. These multimodal-signal systems integrate various biofeedback techniques to provide a comprehensive assessment of mental relaxation, distinguishing them from multimodal-feedback systems that utilize multiple feedback modalities.

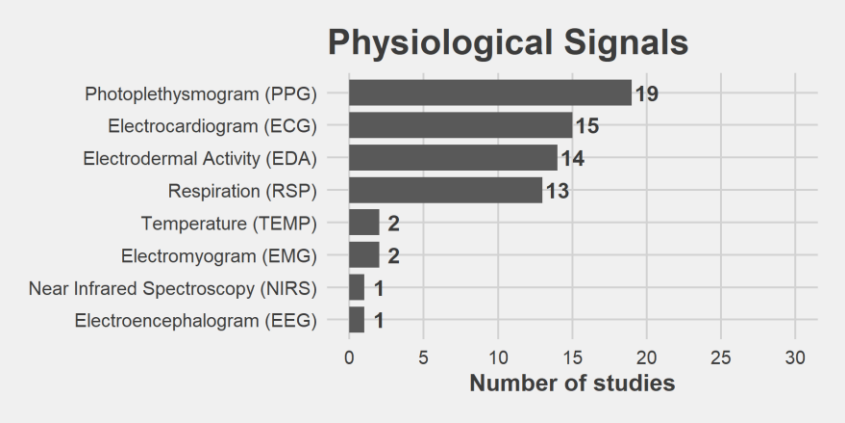

Figure 2: *Distribution proportion of physiological signal used in biofeedback studies for mental relaxation*

4.3 Feedback Systems

The feedback system consists of the feedback delivery system (like PC game or Mobile game), feedback modality (like visual or auditory), and feedback method (like animated graphs or change in brightness). As shown in **Figure 3 (a)**, 6 different feedback systems were employed in the literature review. The PC application is widely used which employs the feedback method in the form of animated strip time series charts, bar graphs with no use of gamification. Next, the PC game type system is catching up which leverages the of video games for feedback delivery with increased engagement among the participants. There are some kinds of portable devices (StressErasor [69], emWave [70], RESPeRATE [71], and Qiu [72]) that are made for ubiquitous biofeedback and can be easily integrated into everyday work. Further, with the recent advancements in smartphones, they are also being used for biofeedback delivery. The advantages of the latest smartphones are their adequate computational power, high fidelity multimedia content rendering, access to the internet, and portability. Besides, some studies have also explored the modification of the environment (sound, space, and light) around the participant for feedback delivery.

In addition to the delivery platforms, the modality of feedback plays a crucial role in biofeedback interventions. As shown in **Figure 3 (b)**, Visual feedback is the most commonly employed modality, providing real-time data through graphs, animations, or virtual reality environments to help users recognize and modulate their physiological responses. Auditory feedback, utilizing sounds or tones, serves as an alternative or complement to visual cues, aiding users in achieving desired physiological states. Haptic feedback, though less prevalent, offers tactile stimuli, such as vibrations, to convey

physiological information. The selection of feedback modality is often tailored to individual preferences and specific therapeutic goals, enhancing the effectiveness of biofeedback interventions.

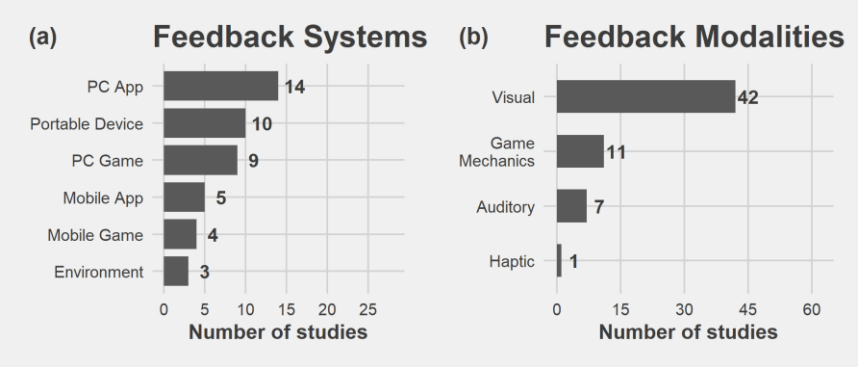

Figure 3: *Distribution proportion of (a) feedback systems, and (b) feedback modalities used in biofeedback studies for mental relaxation*

4.4 Experiment Design and Protocol

The biofeedback protocol defines the rules followed by the participants adhere to move forward in a successful biofeedback intervention. In literature, paced/resonant breathing is primarily used to achieve a state of mental relaxation. Participants either perform unaided paced breathing by using a box-breathing technique or mental counting to keep track of inhalation and exhalation times or follows a visual cue at the set breathing rate. Other protocols like positive mental imagery and emotions are also used. To validate the biofeedback varied types of experimental designs have been used. They can be broadly divided into 6 categories based on the approaches and the standards: Observational, Quasi-experimental, Between-subjects, Within-subjects, and Randomized Controlled Trial (RCT). As shown in **Figure 4**, a between-subjects study design is mostly used with 16 of them as RCT. While Randomized Controlled Trial is the best statistical design, it requires a greater number of participants, a control group, and higher resources. A within-group study can be an optimal choice if the number of participants is relatively less and are budget and time constraints, but one needs to have a balanced design or enough wash-out period between interventions. Another reason for a within-subject design is that the physiological signals and their variations during biofeedback intervention are specific to individuals, for which a within-group design is preferred. The exact reasons for using a particular study design are not reported in the studies.

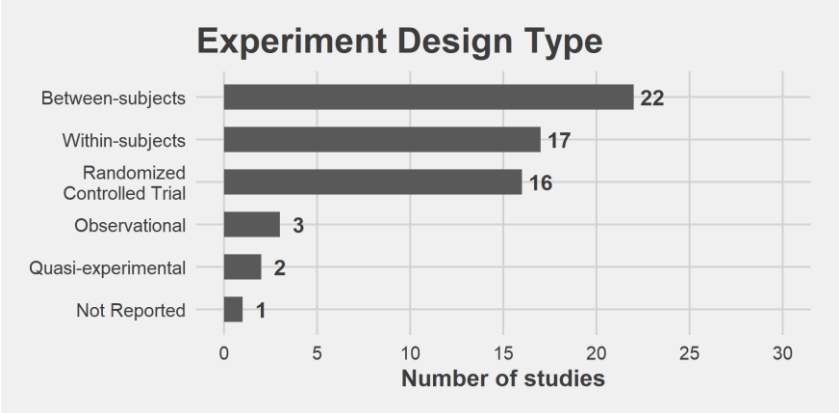

Figure 4: *Distribution proportion of experiment design type used in the evaluation of biofeedback studies*

5. Challenges and Opportunities

With the advancement in the biofeedback literature pointing towards the use of different biofeedback systems for mental relaxation and stress management, there are still some challenges regarding the biofeedback systems which bottleneck the widespread research and use of biofeedback devices. In this thesis, our work aims to address the two following main research challenges with the opportunity for research contributions in the same.

5.1 Lack of Simple and Affordable Biofeedback Systems

The high cost and complexity of traditional biofeedback devices pose significant barriers to accessibility, especially for individuals and institutions with limited financial resources. Researchers and practitioners often rely on proprietary hardware and software, which can be prohibitively expensive and require specialized training. This financial barrier limits the integration of biofeedback into routine mental health practices and restricts its benefits to a broader population [73], [74]. Particularly in a developing country like India, the cost is a major factor for non-compliance with biofeedback treatment [75].

Leveraging open-source hardware, such as Arduino and Raspberry Pi platforms, can significantly reduce the cost of biofeedback systems by providing flexible and affordable options for sensor modules and data acquisition. Additionally, integrating original Nintendo Entertainment System (NES) games offers an engaging and cost-effective solution for biofeedback applications [13], [62], [76], [77], [78]. Tools like BioNES facilitate the incorporation of NES games into multimodal biofeedback systems, enhancing user engagement while maintaining affordability [78]. Furthermore, adopting open-source software practices allows for collaborative development and maintenance, reducing overall costs and enabling researchers to customize biofeedback systems to their specific needs without significant financial investment.

5.2 Lack of Standardized Games for Biofeedback

Incorporating games into biofeedback therapy enhances user engagement. However, creating custom games is expensive, and modifying existing ones offers limited flexibility. Challenges include inconsistent game selection across studies, making it hard to compare results; proprietary games with restricted access; and high development costs, which deter research groups with limited funding.

Utilizing original Nintendo Entertainment System (NES) games can effectively address challenges in biofeedback research. These games are meticulously designed to maintain player engagement by balancing skill and challenge, aligning with the zone of proximal development (ZPD) [79]. Their diverse genres—such as platformers, puzzles, shooters, mazes, and racing—offer flexibility for various research applications. Moreover, open-source emulators enable real-time interaction and control of in-game parameters, facilitating seamless integration into biofeedback systems. While the concept of using retro games in biofeedback isn't new, previous studies have primarily employed open-source clones of classics like Pong, Pac-Man, and Tetris. However, recent research has demonstrated the efficacy of incorporating original NES games into biofeedback systems, enhancing mental relaxation and user engagement [62], [78].

5.3 Lack of Reproducible and Replicable Studies

In literature, there is a dearth of open-source and open-data studies. The custom biofeedback systems developed by researchers are not available in the public domain. Moreover, the data of clinical trials is

also not made available for replicability and comparison purposes. This severely limits the attempts to create and benchmark a biofeedback system and biofeedback trials.

The various components of biofeedback studies, including hardware and software elements of the biofeedback system, clinical trial data, and analysis scripts that support the findings of the studies, can be disseminated as an open-source project to facilitate the replicability and reproducibility of the research. To achieve this, reputable online repositories such as GitHub for sharing biofeedback systems and Open Science Framework (OSF) for sharing research methods and data can be utilized. These platforms provide long-term archival capabilities, persistent links, and opportunities for collaborative contributions from diverse developers and researchers for open-source projects.

6. Conclusion

Biofeedback is a technique that helps individuals manage stress and achieve mental relaxation by providing real-time information about their physiological processes. Among various physiological signals, Photoplethysmogram (PPG) sensor is commonly used due to its simplicity and cost-effectiveness. In biofeedback interventions, different feedback modalities are employed to convey information to users. Visual feedback, such as animated graphs, is widely used, providing intuitive representations of physiological data. Auditory feedback, using sounds or tones, offers an alternative or complement to visual cues. Additionally, incorporating game mechanics has been explored to enhance user engagement, making the process more interactive and enjoyable.

Despite the proven benefits of biofeedback, several challenges hinder its widespread adoption. Many developed tools for custom biofeedback are not publicly available, and those that often suffer from obsolescence and lack of maintenance, reducing their usability. Moreover, reliance on proprietary hardware and software makes these systems expensive, limiting accessibility for researchers and practitioners with limited resources. The development and maintenance of specialized video games for biofeedback further escalate costs. Some existing games are not usable due to proprietary code, expired links, or lack of public access, and the diversity in game genres complicates the comparison of results across studies. To address these issues, leveraging open-source hardware like Arduino and widely used platforms like MATLAB can offer cost-effective solutions. Integrating simple and engaging retro games, such as those from the Nintendo Entertainment System (NES), into biofeedback systems can reduce development overheads and enhance user engagement. By adopting these approaches, the accessibility and effectiveness of biofeedback interventions for mental relaxation can be significantly improved.

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8. Additional Information

8.1 Data availability statement

The raw data supporting the conclusions of this article will be made available upon request by the corresponding author, K.C., without any undue reservation.

8.2 Author Contribution

K.C. contributed to the conception and design of the study, data acquisition, analysis and interpretation of data, writing original draft, reviewing and editing of the manuscript, and critical revision of the manuscript. A.K. contributed to the supervision, resource acquisition, and critical revision of the manuscript. V.D. contributed to the resource acquisition and critical revision of the manuscript. All authors have read and agreed to the published version of the article.

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8.4 Competing interests/ Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

9. References

[1] R. S. Murthy, "National mental health survey of India 2015–2016," *Indian J. Psychiatry*, vol. 59, no. 1, p. 21, Jan. 2017, doi: 10.4103/psychiatry.IndianJPsychiatry_102_17.

[2] S. J. Lupien, B. S. McEwen, M. R. Gunnar, and C. Heim, "Effects of stress throughout the lifespan on the brain, behaviour and cognition," *Nat. Rev. Neurosci.*, vol. 10, no. 6, Art. no. 6, Jun. 2009, doi: 10.1038/nrn2639.

[3] K. T. Larkin, *Stress and Hypertension: Examining the Relation between Psychological Stress and High Blood Pressure*. Yale University Press, 2005. doi: 10.12987/yale/9780300106442.001.0001.

[4] S. Cohen *et al.*, "Chronic stress, glucocorticoid receptor resistance, inflammation, and disease risk," *Proc. Natl. Acad. Sci.*, vol. 109, no. 16, pp. 5995–5999, Apr. 2012, doi: 10.1073/pnas.1118355109.

[5] M. W. deVries and B. Wilkerson, "Stress, work and mental health: a global perspective," *Acta Neuropsychiatr.*, vol. 15, no. 1, pp. 44–53, Feb. 2003, doi: 10.1034/j.1601-5215.2003.00017.x.

[6] K. Chand, S. Chandra, and V. Dutt, "Raga Bhairavi in virtual reality reduces stress-related psychophysiological markers," *Sci. Rep.*, vol. 14, no. 1, p. 24816, Oct. 2024, doi: 10.1038/s41598-024-74932-1.

[7] S. Chandra, K. Chand, and V. Dutt, "Impact of Indian Classical Raga in Immersive Environments on Human Psycho-physiological Parameters," in *Proceedings of the 16th International Conference on PErvasive Technologies Related to Assistive Environments*, in PETRA '23. Corfu, Greece: Association for Computing Machinery, Aug. 2023, pp. 746–753. doi: 10.1145/3594806.3596555.

[8] A. E. Brinkmann, S. A. Press, E. Helmert, M. Hautzinger, I. Khazan, and J. Vagedes, "Comparing Effectiveness of HRV-Biofeedback and Mindfulness for Workplace Stress Reduction: A Randomized Controlled Trial," *Appl. Psychophysiol. Biofeedback*, vol. 45, no. 4, pp. 307–322, Dec. 2020, doi: 10.1007/s10484-020-09477-w.

[9] A. Dillon, M. Kelly, I. H. Robertson, and D. A. Robertson, "Smartphone Applications Utilizing Biofeedback Can Aid Stress Reduction," *Front. Psychol.*, vol. 7, 2016, doi: 10.3389/fpsyg.2016.00832.

[10] Y. Kotozaki *et al.*, "Biofeedback-based training for stress management in daily hassles: an intervention study," *Brain Behav.*, vol. 4, no. 4, pp. 566–579, 2014, doi: https://doi.org/10.1002/brb3.241.

[11] S. Bouchard, F. Bernier, É. Boivin, B. Morin, and G. Robillard, "Using Biofeedback while Immersed in a Stressful Videogame Increases the Effectiveness of Stress Management Skills in Soldiers," *PLOS ONE*, vol. 7, no. 4, p. e36169, Apr. 2012, doi: 10.1371/journal.pone.0036169.

[12] L. Kennedy and S. H. Parker, “Biofeedback as a stress management tool: a systematic review,” *Cogn. Technol. Work*, vol. 21, no. 2, pp. 161–190, May 2019, doi: 10.1007/s10111-018-0487-x.
[13] M. A. Zafar, B. Ahmed, R. A. Rihawi, and R. Gutierrez-Osuna, “Gaming Away Stress: Using Biofeedback Games to Learn Paced Breathing,” *IEEE Trans. Affect. Comput.*, vol. 11, no. 3, pp. 519–531, Jul. 2020, doi: 10.1109/TAFFC.2018.2816945.
[14] M. A. Zafar, B. Ahmed, and R. Gutierrez-Osuna, “Playing with and without Biofeedback,” in *2017 IEEE 5th International Conference on Serious Games and Applications for Health (SeGAH)*, Apr. 2017, pp. 1–7. doi: 10.1109/SeGAH.2017.7939272.
[15] M. S. Schwartz, “A New Improved Universally Accepted Official Definition of Biofeedback: Where Did It Come From? Why? Who Did It? Who Is It for? What’s Next?,” *Biofeedback*, vol. 38, no. 3, pp. 88–90, Sep. 2010, doi: 10.5298/1081-5937-38.3.88.
[16] S. M. Cutshall *et al.*, “Evaluation of a Biofeedback-Assisted Meditation Program as a Stress Management Tool for Hospital Nurses: A Pilot Study,” *EXPLORE*, vol. 7, no. 2, pp. 110–112, Mar. 2011, doi: 10.1016/j.explore.2010.12.004.
[17] A. Edvardsson, A. Ivarsson, and U. Johnson, “Is a Cognitive-Behavioural Biofeedback Intervention Useful to Reduce Injury Risk in Junior Football Players?,” *J. Sports Sci. Med.*, vol. 11, no. 2, pp. 331–338, Jun. 2012.
[18] L. Feijs, J. Kierkels, N. H. van Schijndel, and M. van Lieshout, “Design for Relaxation during Milk Expression Using Biofeedback,” in *Design, User Experience, and Usability. User Experience in Novel Technological Environments*, A. Marcus, Ed., in Lecture Notes in Computer Science. Berlin, Heidelberg: Springer, 2013, pp. 494–503. doi: 10.1007/978-3-642-39238-2_54.
[19] R. McCraty, M. Atkinson, L. Lipsenthal, and L. Arguelles, “New Hope for Correctional Officers: An Innovative Program for Reducing Stress and Health Risks,” *Appl. Psychophysiol. Biofeedback*, vol. 34, no. 4, p. 251, May 2009, doi: 10.1007/s10484-009-9087-0.
[20] K. Yokoyama, J. Ushida, Y. Sugiura, M. Mizuno, Y. Mizuno, and K. Takata, “Heart rate indication using musical data,” *IEEE Trans. Biomed. Eng.*, vol. 49, no. 7, pp. 729–733, Jul. 2002, doi: 10.1109/TBME.2002.1010857.
[21] S. Othmer and D. Kaiser, “Implementation of Virtual Reality in EEG Biofeedback,” *Cyberpsychol. Behav.*, vol. 3, no. 3, pp. 415–420, Jun. 2000, doi: 10.1089/10949310050078878.
[22] A. T. Pope and O. S. Palsson, “Helping Video Games Rewire" Our Minds"," 2001, [Online]. Available: https://ntrs.nasa.gov/citations/20040086464
[23] D. Bersak *et al.*, “Intelligent biofeedback using an immersive competitive environment,” in *Paper at the designing ubiquitous computing games workshop at UbiComp*, 2001, pp. 1–6.
[24] R. L. Mandryk *et al.*, “Games as neurofeedback training for children with FASD,” in *Proceedings of the 12th International Conference on Interaction Design and Children*, in IDC ’13. New York, NY, USA: Association for Computing Machinery, Jun. 2013, pp. 165–172. doi: 10.1145/2485760.2485762.
[25] Z. Wang, A. Parnandi, and R. Gutierrez-Osuna, “BioPad: Leveraging off-the-Shelf Video Games for Stress Self-Regulation,” *IEEE J. Biomed. Health Inform.*, vol. 22, no. 1, pp. 47–55, Jan. 2018, doi: 10.1109/JBHI.2017.2671788.
[26] A. Parnandi and R. Gutierrez-Osuna, “Physiological Modalities for Relaxation Skill Transfer in Biofeedback Games,” *IEEE J. Biomed. Health Inform.*, vol. 21, no. 2, pp. 361–371, Mar. 2017, doi: 10.1109/JBHI.2015.2511665.
[27] L. Chittaro and R. Sioni, “Affective computing vs. affective placebo: Study of a biofeedback-controlled game for relaxation training,” *Int. J. Hum.-Comput. Stud.*, vol. 72, no. 8, pp. 663–673, Aug. 2014, doi: 10.1016/j.ijhcs.2014.01.007.
[28] M. van Rooij, A. Lobel, O. Harris, N. Smit, and I. Granic, “DEEP: A Biofeedback Virtual Reality Game for Children At-risk for Anxiety,” in *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, in CHI EA ’16. New York, NY, USA: Association for Computing Machinery, May 2016, pp. 1989–1997. doi: 10.1145/2851581.2892452.
[29] V. C. Goessl, J. E. Curtiss, and S. G. Hofmann, “The effect of heart rate variability biofeedback training on stress and anxiety: a meta-analysis,” *Psychol. Med.*, vol. 47, no. 15, pp. 2578–2586, Nov. 2017, doi: 10.1017/S0033291717001003.

[30] J. M. Peake, G. Kerr, and J. P. Sullivan, "A Critical Review of Consumer Wearables, Mobile Applications, and Equipment for Providing Biofeedback, Monitoring Stress, and Sleep in Physically Active Populations," *Front. Physiol.*, vol. 9, 2018, doi: 10.3389/fphys.2018.00743.
[31] C. J. Schneider, "Cost effectiveness of biofeedback and behavioral medicine treatments: A review of the literature," *Biofeedback Self-Regul.*, vol. 12, no. 2, pp. 71–92, Jun. 1987, doi: 10.1007/BF01000010.
[32] L. Tarler-Benlolo, "The role of relaxation in biofeedback training: A critical review of the literature.," *Psychol. Bull.*, vol. 85, no. 4, pp. 727–755, 1978, doi: 10.1037/0033-2909.85.4.727.
[33] B. Yu, M. Funk, J. Hu, Q. Wang, and L. Feijs, "Biofeedback for Everyday Stress Management: A Systematic Review," *Front. ICT*, vol. 5, 2018, doi: 10.3389/fict.2018.00023.
[34] K. T. Larkin, C. Zayfert, J. L. Abel, and L. G. Veltum, "Reducing Heart Rate Reactivity to Stress with Feedback Generalization Across Task and Time," *Behav. Modif.*, vol. 16, no. 1, pp. 118–131, Jan. 1992, doi: 10.1177/01454455920161006.
[35] J. J. Kennedy and M. Pretorius, "Integrating a Portable Biofeedback Device into Call Centre Environments to Reduce Employee Stress: Results from Two Pilot Studies," *J. Workplace Behav. Health*, vol. 23, no. 3, pp. 295–307, Aug. 2008, doi: 10.1080/15555240802243096.
[36] J. B. Lemaire, J. E. Wallace, A. M. Lewin, J. de Grood, and J. P. Schaefer, "The effect of a biofeedback-based stress management tool on physician stress: a randomized controlled clinical trial," *Open Med.*, vol. 5, no. 4, pp. e154–e165, Oct. 2011.
[37] G. Henriques, S. Keffer, C. Abrahamson, and S. Jeanne Horst, "Exploring the Effectiveness of a Computer-Based Heart Rate Variability Biofeedback Program in Reducing Anxiety in College Students," *Appl. Psychophysiol. Biofeedback*, vol. 36, no. 2, pp. 101–112, Jun. 2011, doi: 10.1007/s10484-011-9151-4.
[38] N. Moraveji *et al.*, "Peripheral paced respiration: influencing user physiology during information work," in *Proceedings of the 24th annual ACM symposium on User interface software and technology*, in UIST '11. New York, NY, USA: Association for Computing Machinery, Oct. 2011, pp. 423–428. doi: 10.1145/2047196.2047250.
[39] A. P. Sutarto, M. N. A. Wahab, and N. M. Zin, "Resonant Breathing Biofeedback Training for Stress Reduction Among Manufacturing Operators," *Int. J. Occup. Saf. Ergon.*, vol. 18, no. 4, pp. 549–561, Jan. 2012, doi: 10.1080/10803548.2012.11076959.
[40] J. Vidyarthi, B. E. Riecke, and D. Gromala, "Sonic Cradle: designing for an immersive experience of meditation by connecting respiration to music," in *Proceedings of the Designing Interactive Systems Conference*, in DIS '12. New York, NY, USA: Association for Computing Machinery, Jun. 2012, pp. 408–417. doi: 10.1145/2317956.2318017.
[41] R. Wells, T. Outhred, J. A. J. Heathers, D. S. Quintana, and A. H. Kemp, "Matter Over Mind: A Randomised-Controlled Trial of Single-Session Biofeedback Training on Performance Anxiety and Heart Rate Variability in Musicians," *PLOS ONE*, vol. 7, no. 10, p. e46597, Oct. 2012, doi: 10.1371/journal.pone.0046597.
[42] D. I. Sanchez, T. Collins, R. Stone, and S. I. Woolley, "Cellular phone-based Biofeedback to treat physical and mental disorders," in *2012 IEEE 14th International Conference on e-Health Networking, Applications and Services (Healthcom)*, Oct. 2012, pp. 411–414. doi: 10.1109/HealthCom.2012.6379449.
[43] H. Schnädelbach, A. Irune, D. Kirk, K. Glover, and P. Brundell, "ExoBuilding: Physiologically Driven Adaptive Architecture," *ACM Trans. Comput.-Hum. Interact.*, vol. 19, no. 4, p. 25:1-25:22, Dec. 2012, doi: 10.1145/2395131.2395132.
[44] W. Wu, Y. Gil, and J. Lee, "Combination of Wearable Multi-Biosensor Platform and Resonance Frequency Training for Stress Management of the Unemployed Population," *Sensors*, vol. 12, no. 10, Art. no. 10, Oct. 2012, doi: 10.3390/s121013225.
[45] D. MacLean, A. Roseway, and M. Czerwinski, "MoodWings: a wearable biofeedback device for real-time stress intervention," in *Proceedings of the 6th International Conference on PErvasive Technologies Related to Assistive Environments*, in PETRA '13. New York, NY, USA: Association for Computing Machinery, May 2013, pp. 1–8. doi: 10.1145/2504335.2504406.
[46] G. E. Prinsloo, W. E. Derman, M. I. Lambert, and H. G. Laurie Rauch, "The Effect of a Single Session of Short Duration Biofeedback-Induced Deep Breathing on Measures of Heart Rate

Variability During Laboratory-Induced Cognitive Stress: A Pilot Study," *Appl. Psychophysiol. Biofeedback*, vol. 38, no. 2, pp. 81–90, Jun. 2013, doi: 10.1007/s10484-013-9210-0.
[47] J. De jonckheere, I. Ibarissene, M. Flocteil, and R. Logier, "A smartphone based cardiac coherence biofeedback system," in *2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Aug. 2014, pp. 4791–4794. doi: 10.1109/EMBC.2014.6944695.
[48] A. Gaggioli *et al.*, "Experiential Virtual Scenarios With Real-Time Monitoring (Interreality) for the Management of Psychological Stress: A Block Randomized Controlled Trial," *J. Med. Internet Res.*, vol. 16, no. 7, p. e3235, Jul. 2014, doi: 10.2196/jmir.3235.
[49] A. Whited, K. T. Larkin, and M. Whited, "Effectiveness of emWave Biofeedback in Improving Heart Rate Variability Reactivity to and Recovery from Stress," *Appl. Psychophysiol. Biofeedback*, vol. 39, no. 2, pp. 75–88, Jun. 2014, doi: 10.1007/s10484-014-9243-z.
[50] R. Bhandari, A. Parnandi, E. Shipp, B. Ahmed, and R. Gutierrez-Osuna, "Music-Based Respiratory Biofeedback in Visually-Demanding Tasks," in *Proceedings of the international conference on New Interfaces for Musical Expression*, in NIME 2015. Baton Rouge, Louisiana, USA: The School of Music and the Center for Computation and Technology (CCT), Louisiana State University, May 2015, pp. 78–82.
[51] J. Lee, J. K. Kim, and A. Wachholtz, "The benefit of heart rate variability biofeedback and relaxation training in reducing trait anxiety," *Hanguk Simni Hakhoe Chi Kongang Korean J. Health Psychol.*, vol. 20, no. 2, pp. 391–408, 2015, doi: 10.17315/kjhp.2015.20.2.002.
[52] P. Ratanasiripong, O. Kaewboonchoo, N. Ratanasiripong, S. Hanklang, and P. Chumchai, "Biofeedback Intervention for Stress, Anxiety, and Depression among Graduate Students in Public Health Nursing," *Nurs. Res. Pract.*, vol. 2015, p. e160746, Apr. 2015, doi: 10.1155/2015/160746.
[53] C. M. Sarabia-Cobo, "Heart Coherence: A New Tool in the Management of Stress on Professionals and Family Caregivers of Patients with Dementia," *Appl. Psychophysiol. Biofeedback*, vol. 40, no. 2, pp. 75–83, Jun. 2015, doi: 10.1007/s10484-015-9276-y.
[54] J. E. van der Zwan, W. de Vente, A. C. Huizink, S. M. Bögels, and E. I. de Bruin, "Physical Activity, Mindfulness Meditation, or Heart Rate Variability Biofeedback for Stress Reduction: A Randomized Controlled Trial," *Appl. Psychophysiol. Biofeedback*, vol. 40, no. 4, pp. 257–268, Dec. 2015, doi: 10.1007/s10484-015-9293-x.
[55] H. Al Osman, H. Dong, and A. El Saddik, "Ubiquitous Biofeedback Serious Game for Stress Management," *IEEE Access*, vol. 4, pp. 1274–1286, 2016, doi: 10.1109/ACCESS.2016.2548980.
[56] M. Munafò, E. Patron, and D. Palomba, "Improving Managers' Psychophysical Well-Being: Effectiveness of Respiratory Sinus Arrhythmia Biofeedback," *Appl. Psychophysiol. Biofeedback*, vol. 41, no. 2, pp. 129–139, Jun. 2016, doi: 10.1007/s10484-015-9320-y.
[57] T. Sonne and M. M. Jensen, "ChillFish: A Respiration Game for Children with ADHD," in *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*, Eindhoven Netherlands: ACM, Feb. 2016, pp. 271–278. doi: 10.1145/2839462.2839480.
[58] O. Jafarova, K. Mazhirina, E. Sokhadze, and M. Shtark, "Self-regulation Strategies and Heart Rate Biofeedback Training," *Appl. Psychophysiol. Biofeedback*, vol. 45, no. 2, pp. 87–98, Jun. 2020, doi: 10.1007/s10484-020-09460-5.
[59] E. Mazgelytė *et al.*, "Effects of Virtual Reality-Based Relaxation Techniques on Psychological, Physiological, and Biochemical Stress Indicators," *Healthcare*, vol. 9, no. 12, Art. no. 12, Dec. 2021, doi: 10.3390/healthcare9121729.
[60] H. Kim *et al.*, "Effect of Virtual Reality on Stress Reduction and Change of Physiological Parameters Including Heart Rate Variability in People With High Stress: An Open Randomized Crossover Trial," *Front. Psychiatry*, vol. 12, 2021, Accessed: Sep. 12, 2023. [Online]. Available: https://www.frontiersin.org/articles/10.3389/fpsyt.2021.614539
[61] A. H. Chung, R. N. Gevirtz, R. S. Gharbo, M. A. Thiam, and J. P. (Jack) Ginsberg, "Pilot Study on Reducing Symptoms of Anxiety with a Heart Rate Variability Biofeedback Wearable and Remote Stress Management Coach," *Appl. Psychophysiol. Biofeedback*, vol. 46, no. 4, pp. 347–358, Dec. 2021, doi: 10.1007/s10484-021-09519-x.

[62] K. Chand and A. Khosla, “Efficacy of Using Retro Games in Multimodal Biofeedback Systems for Mental Relaxation,” *Int. J. Gaming Comput.-Mediat. Simul. IJGCMS*, vol. 14, no. 1, pp. 1–23, Jan. 2022, doi: 10.4018/IJGCMS.295874.
[63] R. P. Weibel *et al.*, “Virtual reality-supported biofeedback for stress management: Beneficial effects on heart rate variability and user experience,” *Comput. Hum. Behav.*, vol. 141, p. 107607, Apr. 2023, doi: 10.1016/j.chb.2022.107607.
[64] A. M. Téllez, L. A. Castro, and M. Tentori, “Developing and Evaluating a Virtual Reality Videogame Using Biofeedback for Stress Management in Sports,” *Interact. Comput.*, p. iwad025, Mar. 2023, doi: 10.1093/iwc/iwad025.
[65] J. L. Birk, R. Cumella, D. Lopez-Veneros, S. Agarwal, and I. M. Kronish, “Feasibility of a remote heart rate variability biofeedback intervention for reducing anxiety in cardiac arrest survivors: A pilot trial,” *Contemp. Clin. Trials Commun.*, vol. 37, p. 101251, Feb. 2024, doi: 10.1016/j.conctc.2023.101251.
[66] K. Chand, S. Chandra, and V. Dutt, “A comprehensive evaluation of linear and non-linear HRV parameters between paced breathing and stressful mental state,” *Heliyon*, vol. 10, no. 11, p. e32195, Jun. 2024, doi: 10.1016/j.heliyon.2024.e32195.
[67] K. Chand, S. Chandra, and V. Dutt, “Effects of Relaxed and Stressful Mental States on the Heart Rate Variability Parameters,” in *Mind, Brain, and Consciousness Conference (MBCC)*, IIT Mandi, India, Dec. 2023. [Online]. Available: https://iksmha.iitmandi.ac.in/mbcc/2023/ProceedingsMBCC_10May.pdf
[68] F. Shaffer and J. P. Ginsberg, “An Overview of Heart Rate Variability Metrics and Norms,” *Front. Public Health*, vol. 5, 2017, doi: 10.3389/fpubh.2017.00258.
[69] “StressEraser Pro.” Accessed: Jul. 10, 2021. [Online]. Available: https://www.stresseraserpro.com/home
[70] “HeartMath,” HeartMath. Accessed: Oct. 08, 2020. [Online]. Available: https://www.heartmath.com/
[71] “RESPeRATE.” Accessed: Jul. 20, 2021. [Online]. Available: https://www.resperate.com/d-resperate/
[72] “BioSign.” Accessed: Jul. 22, 2021. [Online]. Available: https://www.biosign.de/?lang=en
[73] A. Fortin-Côté, N. Beaudin-Gagnon, A. Campeau-Lecours, S. Tremblay, and P. L. Jackson, “Affective Computing Out-of-The-Lab: The Cost of Low Cost,” in *2019 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, Oct. 2019, pp. 4137–4142. doi: 10.1109/SMC.2019.8914646.
[74] L. E. Nacke, “Directions in Physiological Game Evaluation and Interaction,” in *In CHI 2011 BBI Workshop Proceedings*, 2011.
[75] M. Jain and R. Baijal, “Biofeedback therapy—Challenges in Indian setting,” *Indian J. Gastroenterol.*, vol. 36, no. 2, pp. 160–160, Mar. 2017, doi: 10.1007/s12664-017-0738-4.
[76] N. Braun, S. Debener, A. Sölle, C. Kranczioch, and H. Hildebrandt, “Biofeedback-based self-alert training reduces alpha activity and stabilizes accuracy in the Sustained Attention to Response Task,” *J. Clin. Exp. Neuropsychol.*, vol. 37, no. 1, pp. 16–26, Jan. 2015, doi: 10.1080/13803395.2014.977232.
[77] E. Narducci, K. Mouttet, A. Shahbazi, D. Pool, and T. Tan, “A Study of the Safety and Functionality of Gamified Electromyographic Biofeedback for Children with Cerebral Palsy,” in *2020 42nd Annual International Conference of the IEEE Engineering in Medicine Biology Society (EMBC)*, Jul. 2020, pp. 5180–5183. doi: 10.1109/EMBC44109.2020.9175654.
[78] K. Chand and A. Khosla, “BioNES: A plug-and-play MATLAB-based tool to use NES games for multimodal biofeedback,” *SoftwareX*, vol. 19, p. 101184, Jul. 2022, doi: 10.1016/j.softx.2022.101184.
[79] L. S. Vygotsky, *Mind in Society: The Development of Higher Psychological Processes*, Revised ed. edition; Original works published 1930–1935. Cambridge, Mass.: Harvard Univ Pr, 1978.