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Efficacy of Using Retro Games in Multimodal Biofeedback Systems for Mental Relaxation

Kulbhushan Chand, Dr. B. R. Ambedkar National Institute of Technology, India*
https://orcid.org/0000-0001-6502-0748

Arun Khosla, Dr. B. R. Ambedkar National Institute of Technology, India
https://orcid.org/0000-0001-8571-7614

ABSTRACT

Video games are used to increase the engagement of biofeedback systems. For cost-effectiveness, the original Nintendo Entertainment System (NES) games can be used. Therefore, a multimodal biofeedback system was developed to leverage the NES games for biofeedback. This study aims to test the efficacy of the developed system, the motivation of participants, and the usability of the system. A within-group design study was conducted with 16 participants followed through four interventions: deep breathing, stress-test, non-biofeedback game (control), and biofeedback game (experiment), where their HRV was recorded. Participants showed significantly different HRV during interventions (F(1.60, 23.93) = 11.94, p < 0.001) and reported higher HRV when using biofeedback game than the non-biofeedback game (t(15) = 9.14, p < 0.0001). The motivation was reported to be the same with biofeedback and non-biofeedback version of the game, and the overall system was reported as usable. The results of this study support the efficacy of using original NES games in biofeedback for mental relaxation.

KEYWORDS

Biofeedback System, Graphical User Interface, Heart Rate Variability, MATLAB, Mental Relaxation, Nintendo Entertainment System Games, Open-Source Software, Physiological Signal Acquisition

1. INTRODUCTION

Mental stress has detrimental effects on one's mind and body (Lupien et al., 2009), and in the long run may lead to chronic diseases like cardiovascular problems (Larkin, 2005) and diabetes (S. Cohen et al., 2012). In developing countries like 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 (Murthy, 2017). Besides traditional interventions for stress management like Cognitive Behavioral Therapy, technological intervention like biofeedback is also becoming popular (L. Kennedy & Parker, 2019). In a biofeedback session, the physiological parameters (like heart rate)

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of an individual are shown in real-time and one can learn to better manage them by following some specific protocol (like paced breathing) (Schwartz, 2010).

However, the routine of a traditional biofeedback session can be quite monotonous and may offer a lesser appeal to the young participants (Pope & Palsson, 2001). One way to increase engagement with biofeedback sessions is to use video games as a biofeedback delivery mechanism (Bersak et al., 2001; Mandryk et al., 2013; Pope & Palsson, 2001; Wang et al., 2018; Zafar et al., 2020). In this case, the individual plays a game specially created/modified for biofeedback application. The physiological state of the individual is shown as a change of in-game elements or game-mechanics, instead of directly showing the physiological measures (Wang et al., 2018). In this way, the participant/player aims to control the game state by following the biofeedback protocol and thus have an engaging and fun experience during the biofeedback intervention.

There are some challenges with using video games for biofeedback. The lack of use of the same game or game genres across various studies creates difficulty with the replication and comparison of results. The non-availability of the game in the public domain and proprietary source code of the study further add to the challenges. Moreover, there is a higher cost associated with game development and maintenance which reduces the appeal of biofeedback research to groups with limited funding support.

The retro games developed for Nintendo Entertainment System (NES[1]) (Nintendo, Kyoto, JP) can address these issues. These are 8-bit games that run on NES hardware or NES emulator and are popular among people. The simple gameplay and meticulous level design of these games makes them excellent candidate for delivering biofeedback. Therefore, the authors have developed an open-source system to leverage NES games for multimodal[2] biofeedback. The system consists of data acquisition (DAQ) hardware (H/W), software (BioNES[3]), and a game system, which can be used to deliver heart rate (HR) and/or heart rate variability (HRV) biofeedback via any NES game. The player has to follow biofeedback protocol (like deep breathing) to keep the HRV deviation from baseline value at a minimum while simultaneously playing the biofeedback-enabled game. The in-game feedback continuously shows the current deviation of HRV to the player. Failing to keep up with the biofeedback protocol triggers additional game mechanics (like warning beep, change in player life) which brings about enhancements to the original gameplay of the NES game. The appeal of the system is that one does not need to know the proprietary source code of the NES games and the game mechanics can be modified and feedback can be displayed by using the support of the NES emulator. In this way, any available game created for the NES platform can be leveraged for delivering biofeedback.

In this paper, an attempt is made to understand the efficacy of the developed system in inducing mental relaxation. *Super Mario Bros.* (SMB) (*Super Mario Bros. - Super Mario Wiki, the Mario Encyclopedia*, n.d.), a popular NES game was used. The purpose of this study can be summarized in two steps.

- Firstly, to find the engagement of SMB, and what game mechanics of the game can be used for biofeedback. Authors have used Octalysis, a popular gamification analysis tool to disseminate the engagement core drives in the SMB game. Based on the results, the feedback delivery modality of the biofeedback is decided.
- Secondly, to test the hypotheses about the developed system. It was hypothesized that the biofeedback game (BF-Game) in the experiment group/intervention induces more relaxation than the non-biofeedback game (NBF-Game) in the control group/intervention. This will attempt to explain the efficacy of the developed system as well as the game used for biofeedback. Next, it was hypothesized that the participant's motivation towards playing the BF-Game is the same as towards the NBF-Game. Here, the intrinsic motivation to play the BF-Game is important, failing which defeats the purpose of using video games for biofeedback. It was also hypothesized that the participants find the overall biofeedback system usable, which is an important criterion for the continued use and acceptability of the system.

The paper is organized as follows. In related work, the literature and the research gaps focus on the use of biofeedback for mental relaxation, the use of video games, particularly NES games for biofeedback, and the use of off-the-shelf components for the biofeedback system. Next, the material and methods of the study are discussed with a detailed description of the biofeedback system. Then, the results are shown followed by detailed discussions on the obtained results and effect sizes. Limitations of the study are also discussed. Finally, the authors conclude the findings, and a link to the repository is provided where the code, data, and analysis scripts are made available with an open-source license.

2. RELATED WORK

2.1. Biofeedback for Mental Relaxation

Claude Bernard in 1865 introduced the concept of homeostasis (Bernard, 1865/1957). Later in 1885, J.R. Tarchanoff showed that one can voluntarily control his heart rate (Tarchanoff, 1885). In 1969 the biofeedback term was coined during the first meeting of Biofeedback Research Society. Over time, biofeedback has emerged as a popular alternative form of medication in the treatment of stress, anxiety, and achieving mental relaxation (Brinkmann et al., 2020; Dillon et al., 2016; Kotozaki et al., 2014). Mental stress arises due to imbalances in autonomic regulation (Malik & Camm, 2004, Chapter 7). HRV is a standard measure of stress, where lower HRV indicates higher stress and vice-versa (Malik et al., 1996). HRV is modulated during the respiration cycle, where heart rate increases with inhalation and decreases with exhalation and achieves its maximum at a breathing frequency of 6-cycles per min (Clark & Hirschman, 1990; Vaschillo et al., 2006). Thus, an individual can use paced breathing to increase the HRV and in turn reduce mental stress. Biofeedback can help individuals to acquire the necessary breathing skills through self-correction i.e. by monitoring their HRV response using real-time feedback and aiming to increase HRV via paced breathing (J. J. Kennedy & Pretorius, 2008; L. Kennedy & Parker, 2019; Sherlin et al., 2009).

2.2. Video Games for Biofeedback

Video games have been used as a biofeedback delivery mechanism to increase the engagement of the traditional biofeedback routine and adherence to its long-term treatment. Conversely, the addition of biofeedback increases the level of immersion in the game (Nogueira et al., 2016). In the literature, researchers have used a range of video games in biofeedback for stress management (Bouchard et al., 2012; Zafar et al., 2020), reducing anxiety (Bossenbroek et al., 2020), changing stress mindset (Maarsingh et al., 2019), and physiological rehabilitation (Giggins et al., 2013). In context to the type of video game, researchers have either used open-source versions of popular games (Converse et al., 2013; Narducci et al., 2020; Othmer & Kaiser, 2000), off-the-shelf games (Dekker & Champion, 2007; Walther-Franks et al., 2013) or created their games from scratch (Bossenbroek et al., 2020; Lobel et al., 2016). One of the advantages of using video games is the availability of various modalities for feedback. In literature, studies have explored different modalities like visual, where the in-game visual bar, screen-tint or overlay is displayed (Bouchard et al., 2012; Dekker & Champion, 2007; Lobel et al., 2016; Mandryk et al., 2013; Nacke et al., 2011); auditory, where static noise or a warning beep is played (Bouchard et al., 2012; Lai et al., 2013); haptic, where vibration feedback is used (Asín-Prieto et al., 2020); and game mechanics, where the rules governing the game are manipulated (Dekker & Champion, 2007; Parnandi & Gutierrez-Osuna, 2017; Sonne & Jensen, 2016; Wang et al., 2018; Zafar et al., 2020). The direct physiological control (where player are given option to control their affective state directly by manipulating physiological signal like breathing rate) in the game is a preferred way of control in biofeedback (Nacke et al., 2011).

2.3. NES Games in Biofeedback

The use of retro/NES games for biofeedback is not a new concept. There is a successful commercial use of retro video games for biofeedback like Atari Mindlink (*The Atari Mindlink System*, n.d.), Tetris 64 (*Tetris 64*, n.d.), and Wii Vitality Sensor (*Wii Vitality Sensor*, n.d.). In literature, researchers have used the open-source clones of some popular retro/NES games like Pong (Converse et al., 2013; Emmen & Lampropoulos, 2014; Narducci et al., 2020), Pac-man (Othmer & Kaiser, 2000; Zafar et al., 2020), and Tetris (Braun et al., 2015; Narducci et al., 2020). Beyond biofeedback for relaxation, there are tailor-made Nintendo games used in healthcare research like *Packy and Marlon* (Brown et al., 1997) which aims at teaching children about diabetes self-management, and *Bronkie the Bronchiasaurus* (Lieberman, 2001) aimed at children for self-management of asthma, respectively. The popular Nintendo Gameboy handheld console was effectively used to reduce pediatric preoperative anxiety (Patel et al., 2006) and management of compulsive habits (Phillips, 1991). The Nintendo Wii platform was also used in literature for biofeedback applications like balance training (Barcala et al., 2013; Jorgensen et al., 2013; Travers et al., 2018) and gait improvement (Levinger et al., 2016).

2.4. Using Off-the-Shelf Components for Biofeedback

The out-of-lab experiments in biofeedback studies need affordable and quick to deploy data acquisition and feedback systems (Fortin-Côté et al., 2019; Nacke, 2011). On the other hand, the same challenge is experienced by the patients undergoing biofeedback therapy. Particularly in a developing country like India, the cost is a major factor for non-compliance with biofeedback treatment (Jain & Baijal, 2017). The resource challenges with biofeedback research can partially be alleviated by using off-the-shelf components. For the hardware part, open-source electronics platforms like Arduino have been used in biofeedback (Kim et al., 2011; Polo et al., 2018). These open-source hardware components can easily meet the relatively low sampling rate (~50Hz) requirement of biofeedback studies (Alhamid et al., 2012; Frey et al., 2018; Geršak & Drnovšek, 2020; Luo et al., 2017; Moeyersons et al., 2016; Moraveji et al., 2011). Likewise, hardware, the software development cost can be reduced by using open-source software like Instrumentino (Koenka et al., 2014) and Telemetry Viewer (Farahbod, 2016/2020) for data acquisition, FCEUX (*FCEUX*, 2018/2020), and snes9x (gocha, 2011/2020) for emulation of NES games. Hosting the project on popular code-sharing platforms like GitHub (*GitHub*, n.d.) can help with maintenance and support. The cost associated with the development of a biofeedback game from scratch is also nullified by leveraging the NES games for biofeedback delivery.

In summary, prior work has shown that biofeedback can be effectively used to achieve a state of mental relaxation and video games can be used to increase the engagement of biofeedback intervention. Several studies are conducted with different NES games sporadically across the various healthcare applications. However, few prior studies have used the existing pure entertainment-based original NES games for mental relaxation. This lack of use can be partly due to the closed source nature of NES games. The affordable open-source biofeedback system used in this study is thus developed to leverage NES games for biofeedback without modifying the source code of the games.

3. MATERIALS AND METHODS

3.1. Participants

To ascertain the sample size, a-priori power analysis using G*Power ver.3.1.9.6 (Faul et al., 2007) for the repeated measure, within factor ANOVA test is conducted. As detailed in section 3.4 the experiment is a within-group crossover randomized design study with 4 levels of measurement (deep breathing, stress test, control, and experiment). The significance level (α) is set at 5% and power (1-β) at 80%. The HRV biofeedback relaxation studies in the literature have obtained a large effect in their post-hoc analysis like eta-squared, $\eta^2 = 0.77$ (Aritzeta et al., 2017), eta-partial-squared, $\eta_p^2 = 0.698$ (Thurber et al., 2010), $d = 1.09 – 2.63$ (Parnandi & Gutierrez-Osuna, 2019), $d = 0.8$ (Loudon et al.,

2017) and $d = 0.54$ (Zafar et al., 2017). Using the most conservative of the above literature values of effect size ($d = 0.54$ (Zafar et al., 2017)), a sample size $N = 7$ is obtained. Also, using standard η^2 values (J. Cohen, 1988, pp. 286–287) or Cohen's f values[4], for medium ($\eta^2 = 0.06, f = 0.25$) to large effects ($\eta^2 = 0.14, f = 0.4$) we obtained a maximum and minimum sample size of 23 and 10 respectively. Although literature warrants the large effects in the HRV biofeedback for relaxation studies, the authors decided to choose the conservative value to have a better contrast among the control vs experiment. The mid-point at $\eta^2 = 0.1$ or $f = 0.33$, between medium to large effects is used which gives a minimum sample size of $N = 14$.

Therefore, for this study 16 healthy participants, between 13 and 34 years of age (20.88 ± 7.20, 9 males, 7 females) were recruited by word of mouth. The inclusion criteria for the participants is to be healthy individuals for their age and willing to play video games. Three exclusion criteria used were: any form of loco-motor and/or cognitive impairment that may hinder the efforts to play video games, any discomfort like headache and nausea from their prior experience with video games, and having a stress-is-enhancing (SMM(Heathcote et al., 2018) score of > 2.5) mindset which is used to exclude the participants who may perform well under stress. No other medical information was collected. All participants reported experience with video games but no prior experience with biofeedback methods, biofeedback enabled games, or exergames. Out of the final recruited participants, 12 play video games 5 times weekly, all know about the SMB game, 14 participants have prior experience with SMB game and none of them have played this game within the last 6 months.

The study was conducted following the principles embodied in the Declaration of Helsinki and is pre-registered[5] with Open Science Framework registries prior to the creation of data. All participants understood the purpose of the study and filled in a consent form. For the minor participants, informed consent is obtained from their caregivers, after fully explaining the study and procedure.

3.2. Biofeedback System Description

The participant/player interacting with the biofeedback system is shown in Figure 1 (a), where the Photoplethysmograph (PPG) sensor, Data Acquisition (DAQ) Hardware (H/W), and the in-game feedback are highlighted. During the gameplay, the goal is to achieve the highest possible score. Concurrently, the player has to keep the mental relaxation above a threshold level by deep breathing. The in-game bar at the top shows the mental relaxation which is the scaled value of the percentage deviation of HRV from the baseline values of the player.

The overall functional diagram of the biofeedback system used is shown in Figure 1 (b). At its core are the three main components: DAQ hardware, BioNES, and Game system. These independent components worked synchronously as a biofeedback system. At the left is the player, to whom biofeedback intervention is to be delivered. The player interacts with the game system i.e. to play an NES game using a gamepad and simultaneously received the in-game feedback. The DAQ H/W is responsible for the acquisition of the RR (time elapsed between successive heartbeats) intervals. At the core of the biofeedback system is BioNES, which is a MATLAB (MathWorks, Natick MA, USA) based software tool developed to act as data acquisition software and biofeedback controller. It acquires data from DAQ H/W, processes the data, displays real-time results, and drives feedback by communicating with the Game system.

3.2.1. Data Acquisition Hardware

The PPG signal is recorded from the player's left ear lobe using an ear clip sensor as shown in Figure 1 (a). A hardware interrupt on Arduino (Arduino LLC, Somerville, MA, US) is used to capture the real-time heartbeat followed by the elimination of high-frequency artifacts. The last RR interval value is stored till the time of the next heartbeat. The BioNES software and Arduino act in master-slave configuration respectively and custom-made commands were used to fetch data from the Arduino.

Figure 1. (a) Participant interacting with the system during biofeedback intervention. The acquisition hardware is attached to the ear-lobe to acquire the PPG signal. The GUI of the acquisition S/W is behind the game window and not visible to the player. The in-game visual feedback bar is displayed at the top of the in-game screen. In the figure, the feedback bar is at the 3rd level or 60%-70% deviation of current HRV from the baseline HRV value of the player, (b) System block diagram showing the various components of the developed biofeedback system.

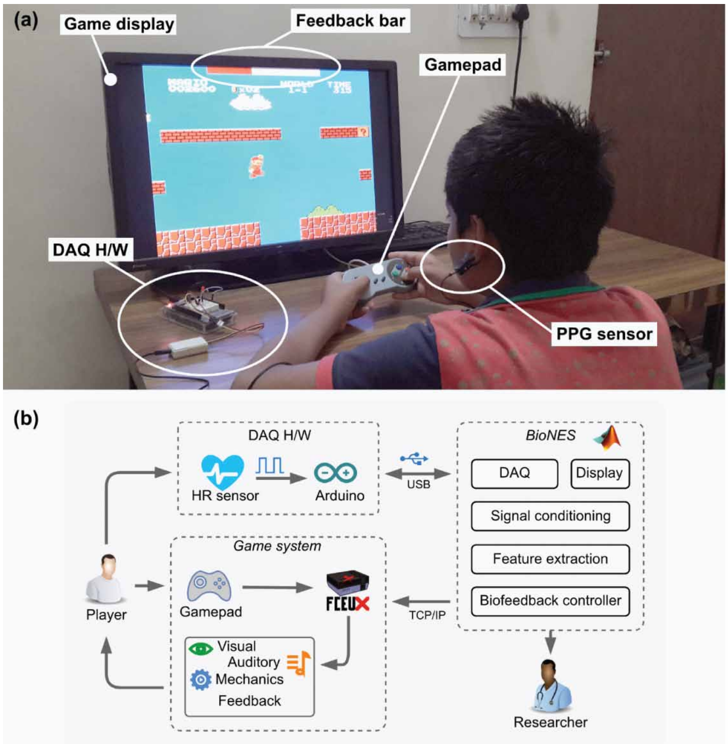
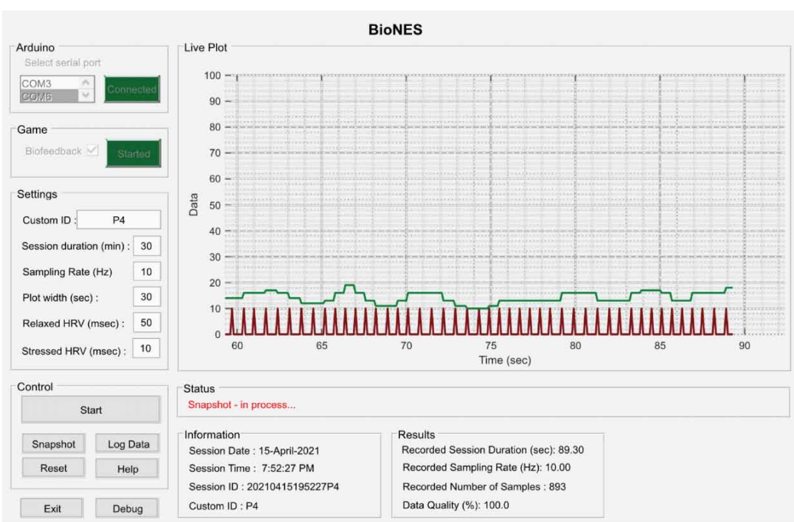


Figure 2. The frontend of BioNES. The sub-components of the graphical user interface are arranged into different panels as per their functionality. Real-time average HRV (in ms) and heartbeat (spikes) are shown in the live plot.



3.2.2. BioNES

The BioNES[6] software runs within MATLAB where data is received from the Arduino Mega via USB connection (Figure 2). After the acquisition, the real-time signal conditioning of the acquired RR intervals is performed using a custom algorithm adapted from the literature

(Rand et al., 2007). This is an important step because any significant player's movement can cause artifacts in PPG acquisition which can drastically alter the calculated HRV values (Berntson & Stowell, 1998; Porges & Byrne, 1992). HRV is calculated as the root mean square of successive differences (RMSSD) (ms) values of last N (=2) beats from successive RR intervals (Eqn. 1) and then median of RMSSD values, taken over a sliding window of length M (=30), is used as the current averaged HRV value:

$$RMSSD_i = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N-1}\left\{\left(RR\right)_{i+1} - \left(RR\right)_i\right\}^2} \quad (1)$$

A real-time plot of the features is also shown to the researcher. Since the HRV values strongly correlate with age (Zhang, 2007), the baseline HRV values of respective players are used for feedback in the biofeedback controller stage. These baseline values of HRV are $HRV_{R,}$ obtained while relaxing prior to biofeedback intervention, and HRV_S, obtained from the Stroop CWT test, for each player. The percentage deviation (HRV_D) of current HRV (HRV_C) from HRV_R is computed as:

$$HRV_D = \frac{HRV_C - HRV_R}{HRV_R - HRV_S} * 100 \quad (2)$$

For the in-game feedback, this deviation is displayed as a 9-level evenly-distributed horizontal top bar (Figure 3) and is calculated as:

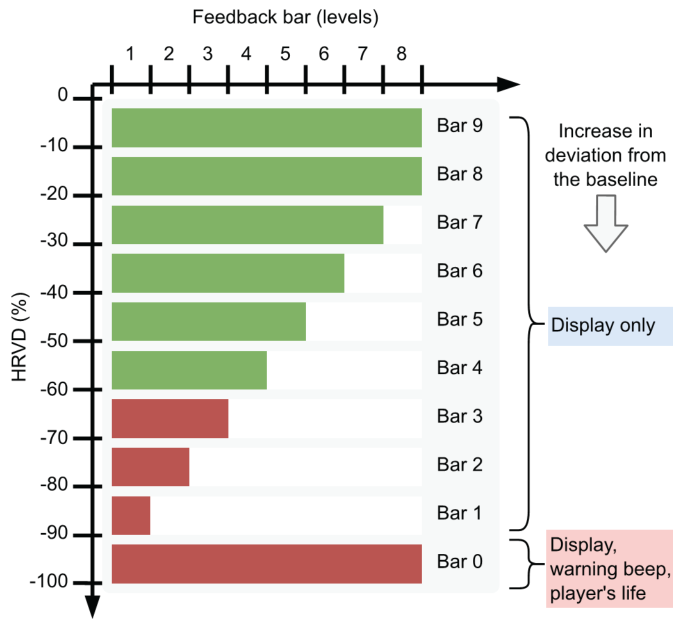
$$HRV_D^- = \begin{cases} -100, & HRV_D < -100 \\ HRV_D, & -100 \le HRV_D \ge 0 \\ 0, & HRV_D > 0 \end{cases} \quad (3)$$

$$Level\ of\ bar = \frac{\left|HRV_D^-\right|}{10} \quad (4)$$

3.2.3. Game-System

The game system consists of FCEUX (a third-party open-source NES emulator), a gamepad for playing, and in-game feedback mechanics. The emulator's capability to change in-game variables via LUA scripting was used to drive the in-game feedback (see relevant documentation (*Lua Scripting*, n.d.; *Super Mario Bros.:RAM Map - Data Crystal*, n.d.)). SMB game was used to deliver the biofeedback. The game is well-known among the sample population and offers engaging gameplay with simple game mechanics. The in-game biofeedback delivery was provided in three ways. Firstly, an in-game color-coded 9-level visual bar (Figure 3) was displayed at the top which indicates the current deviation of the player's HRV from the baseline value. Secondly, an in-game warning tone was played when the feedback bar reaches the lowest level. Thirdly, the player loses a life if the feedback bar stayed at

Figure 3. Translation of deviation (current HRV from baseline HRV) to different levels of in-game feedback bar. The increase in deviation of HRV from the baseline value corresponds to the descending order of bars. Bar 9 to bar 1, shows visual feedback only, whereas bar 0, shows visual feedback, audio feedback (after 10 seconds), and change in-game mechanics (loss of player life after 10 seconds).



the lowest level (Bar 0) for more than 10 consecutive seconds. Together these three additional game mechanics integrates the biofeedback gameplay in the SMB game.

3.3. Statistical Instruments

The Stress Mindset Measure (SMM) Youth version (Heathcote et al., 2018) was used to control for the participants with stress-is-enhancing mindset, who may exhibit greater cognitive flexibility (Crum et al., 2017) and performance (Crum et al., 2013) under stress than participants with stress-is-debilitating mindset. An Intrinsic Motivation Inventory (IMI) questionnaire (Table 1), adapted from the original IMI ("Intrinsic Motivation Inventory (IMI)," n.d.; Ryan, 1982) was administrated immediately after the biofeedback gameplay. Two subscales: Interest/Enjoyment, and Perceived Competence, consisting of 8 questions were used. The System Usability Scale (SUS) was used to evaluate the usability and learnability of the biofeedback-enabled game (Brooke, 1986). A score of >70 indicates the acceptability of the system by the participants (Miller, 2009).

3.4. Study Procedure

The experiment design was a within-subjects crossover randomized design with 1 factor (intervention), 4 levels (relaxation, stress-test, control, and experiment), and repeated measures (HRV). The details of the four groups/interventions are as follows:

- **Deep Breathing (DB):** In this group, the baseline measure of each participant was estimated in a relaxed state. The participants followed a visual cue to keep up with the paced breathing at 6 breaths per minute for 4 minutes.
- **Color Word Test (CWT):** In this group, the baseline measure of each participant was measured in a stressed state. The participants completed Stroop CWT (Stroop, 1935) for 4 minutes.

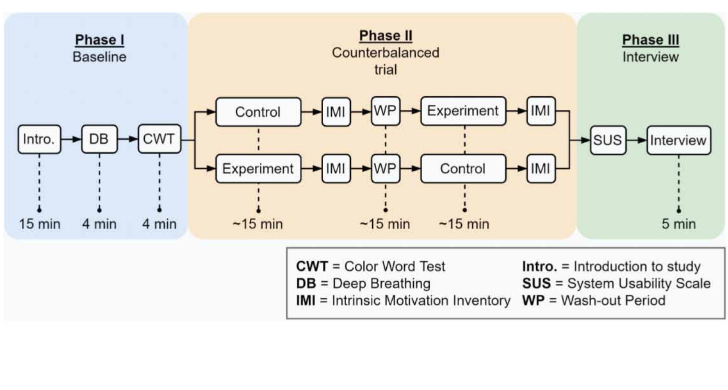
- **NBF-Game (Control):** In this group, the participants were run through the control conditions. The participants played the SMB game with no biofeedback but with deep breathing training. The controlled variable is the paced breathing training given to the participant prior to the intervention.
- **BF-Game (Experiment):** In this group, the participants were put through experimental conditions. The participants played a biofeedback version of the SMB game. Likewise, for the controlled variable, paced breathing training was given to the participant prior to the intervention. The instantaneous paced breathing is the manipulated variable which participants tried to control in order to increase their HRV during gameplay which is a requirement of the modified gameplay.

The participants were randomly assigned to either of the counterbalanced arms of the control group or the experiment group. The basic phase-wise structure of the experiment can be visualized as in Figure 4. Upon arrival, the participants were given basic information about the purpose of the experiment followed by filling out a simple questionnaire with background-specific information about their age, gender, gaming experience, and a consent form. Then SMM-Youth version questionnaire was filled and any participant scoring high value was excluded from the study. The experimental protocol consisted of three main phases as described below.

Phase I (Baseline): The unique baseline measures (baseline HRV and stressed HRV) for each participant were computed at this stage. For the baseline HRV, the participants were asked to relax and breathe in sync to a pacing signal, which was presented to them using an online service (*Breathe Slowly*, n.d.), set at 6 breaths per minute for 4 minutes with inhalation and exhalation time of 4 sec and 6 sec respectively. The longer exhalation to inhalation ratio (E:I > 1) without change in the breathing rate is known to increase the HRV (Bae et al., 2021; Strauss-Blasche et al., 2000). The average HRV value (HRV_R) obtained was used as the baseline and as an upper limit for driving feedback.

For the stressed HRV, the participants completed 4 min. of the Stroop Color-Word Test (CWT) (Stroop, 1935) which is widely used in the biofeedback literature to induce mental workload and stress. CWT was implemented and presented online using the PsyToolkit platform (Stoet, 2010, 2017). Instructions on how to use the CWT were provided to the participant prior to the beginning of the task. In this test, the participants were shown one of four words (red, blue, green, and yellow) displayed in different ink colors (red, blue, green, and yellow), and were asked to press the corresponding key (r, b, g, and y). A single trial of CWT spanned 3 seconds which consists of a fixation interval of 500 msec, stimulus of 2000 msec, and result of 500 msec. The participants had to answer within the stimulus interval. Both incorrect response and failure to respond within stimulus timeframe results,

Figure 4. The phase-wise experiment design for the study. The three main phases are the baseline measurements, counterbalanced trials between control and experiment groups, and the final interview.



shown as "INCORRECT" and the correct response was shown as "CORRECT" during the "result" interval. The number of trials was 100 which spanned approximately 4.5 min. To reduce the learning effects, the test switched between congruent (matched word and ink color) and incongruent mode (mismatched word and ink color). The average HRV value was used as the stressed value (HRV_S) and as a lower limit for driving feedback.

Phase II (Counterbalanced trial): In this stage, the trials were conducted for the control and experiment groups. The paced breathing relaxation training is the control variable that was already provided in Phase I to all the participants. To reduce the ordering effect, the trials were counterbalanced into two arms and half of the participants were randomly assigned to each of the arms. The randomization was carried out using a list randomizer from an online service (Haahr, 1998). The first half of the random list was assigned to the control and the latter to the experiment group. To reduce the learning effect a wash-out period of 15 min was added after the first intervention. To get a fresh response, the IMI questionnaire was executed immediately after the completion of any intervention. As a side benefit, the IMI questionnaire also extended the washout period.

For both the groups at the start of phase II, participants were made familiar with the game and gamepad controls after which they played a single try of the game. They were told that their maximum score will be evaluated against others. The control group played the original version (without the top biofeedback bar) of the SMB game, while the experiment group played the modified biofeedback version (with the top bar) of the game. Phase II spanned approximately 30 to 45 mins.

Phase III (Interview): In this phase, participants filled the SUS questionnaire regarding the biofeedback system, and any qualitative feedback regarding their involvement and the biofeedback system was taken. The entire session for a single participant lasted from 60 to 75 mins.

3.5. Analysis

The analysis was carried out using RStudio ver.1.4.1103 (RStudio Team, 2010/2021). The data were checked for normality and sphericity prior to applying statistical tests and a confidence interval of 95% was chosen for all comparisons. Firstly, Octalysis-analysis was carried out to find the engagement of the SMB game from a survey of 114 participants who were well-versed with the game. Next, hypothesis testing was carried out where the mean HRV for 4 different groups was compared using a one-way repeated measures ANOVA test, and the relaxation effects of the biofeedback system were analyzed by comparing, the player's HRV from the control versus experiment group using a paired

Table 1. Intrinsic motivation inventory subscales and questions

IMI subscale	Questions
Interest/ Enjoyment	1. I enjoyed doing this activity very much 2. This activity was fun to do. 3. This activity did not hold my attention at all.* 4. I would describe this activity as very interesting.
Perceived Competence	1. I think I am pretty good at this activity. 2. I am satisfied with my performance at this task. 3. I was pretty skilled at this activity. 4. This was an activity that I couldn't do very well.*

* To be reverse scored.
IMI, intrinsic motivation inventory

t-test. Also, the player's motivation towards biofeedback gameplay and system usability was analyzed by using a one-sample t-test on the obtained IMI and SUS scores respectively, against the set criteria. Finally, the post-hoc sensitivity and power analysis were carried out to estimate the obtained effect size and achieved power of the study respectively.

4. RESULTS

From the exploratory analysis of the participant's preliminary data, the mean SMM score was 1.29 ± 0.38, which was significantly less than the requirement (mean < 2.5), $t(15) = -12.71$, $p < 0.001$. None of the participants reported any form of discomfort during gameplay. All the outliers were included in the data analysis.

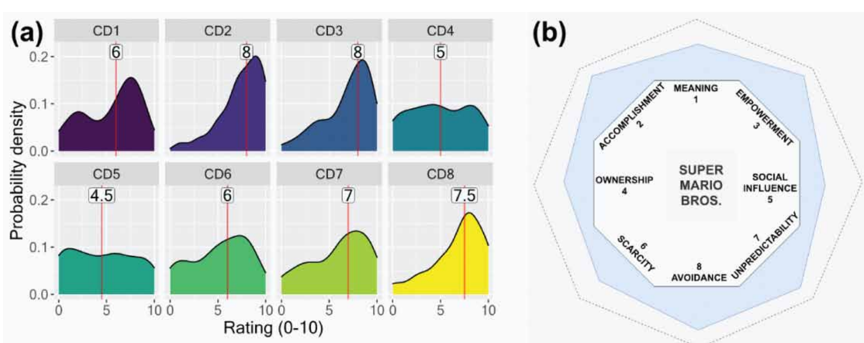
4.1. Octalysis Analysis of SMB

The descriptive statistics of the Octalysis analysis of SMB are summarized in Table 2. Each core drive is rated on a scale of 0 (No influence) to 10 (maximum influence). The density plot of obtained ratings comes out to be skewed (Figure 5 (a)), and thus median was used for scoring and plotting the Octalysis graph (Figure 5 (b)). The Octalysis analysis showed that the SMB game is well-balanced

Table 2. Descriptive results of the survey for Octalysis analysis

Core-drive	Mean ± SD	Median
CD1 – Epic meaning and calling	5.51 ± 2.86	6
CD2 – Development and accomplishment	7.49 ± 2.20	8
CD3 – Empowerment of creativity and feedback	6.88 ± 2.48	8
CD4 – Ownership and possession	4.87 ± 3.11	5
CD5 – Social influence and relatedness	4.59 ± 3.32	4.5
CD6 – Scarcity and impatience	5.22 ± 2.95	6
CD7 – Unpredictability and curiosity	5.95 ± 2.96	7
CD8 – Loss and avoidance	6.78 ± 2.67	7.5
CD, core drive; SD, standard deviation		

Figure 5. (a) Density plot of the Octalysis core-drive ratings (scale of 0-10), vertical line and label marks the median value for each core drive, (b) Octalysis graph (in the form of radar chart) of SMB, rated using the median average. The dotted line shows the maximum possible area and the blue region defines the computed area.



among its core drives with an Octalysis-score (calculated by the sum of squares of median ratings) of 350.5 out of 800.

4.2. Comparisons of Average HRVs Among Groups

HRV is the repeated measured variable across all the participants in the four groups/interventions: deep breathing (DB), stress-test (CWT), control (non-biofeedback-game or NBF-Game), and experiment (biofeedback-game or BF-Game). Figure 6 shows the modulation of Respiratory Sinus Arrhythmia (RSA) exhibited by participant 1 across all four conditions for the first 50 samples in each.

The descriptive statistics of the obtained HRV values for the four groups are listed in Table 3. The repeated measures (HRV) were compared using one-way repeated measures Analysis of Variance (ANOVA) with HRV as the repeated measure. Figure 7 (a), visualizes the descriptive analysis of the interventions along with the mean values and significant pairs. Mauchly's Test of Sphericity indicated that the assumption of sphericity had been violated.

$\chi^2(5) = 26.32$, $p < .001$, and therefore, a Greenhouse-Geisser correction ($\varepsilon = 0.53$) was used. The test determined that mean HRV differed statistically significantly between different interventions ($F(1.60, 23.93) = 11.94$, $p < 0.001$, $\eta_p^2 = 0.44$). To test among the interventions, post-hoc multiple pairwise paired t-tests with holms correction, between the levels of the within-subjects factor

Figure 6. Respiratory Sinus Arrhythmia (RSA) was exhibited by participant 1 during the 4 different interventions. The RSA is pronounced in the DB and Experiment conditions, whereas desynchronization occurs in both CWT and control conditions.

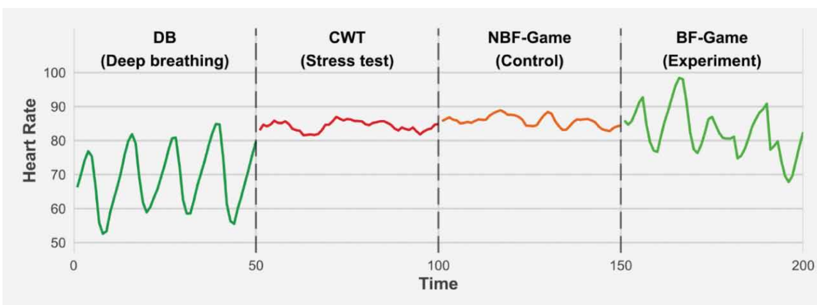


Figure 7. (a) Mean HRV during four interventions. Violin plot shows the distribution, box plot shows the quartiles, and a path joins the centrality (mean) of each intervention. (b) Comparison of mean HRV between NBF-Game (Control) and BF-Game (Experiment). Individual comparisons of the subjects are also shown with dotted lines.

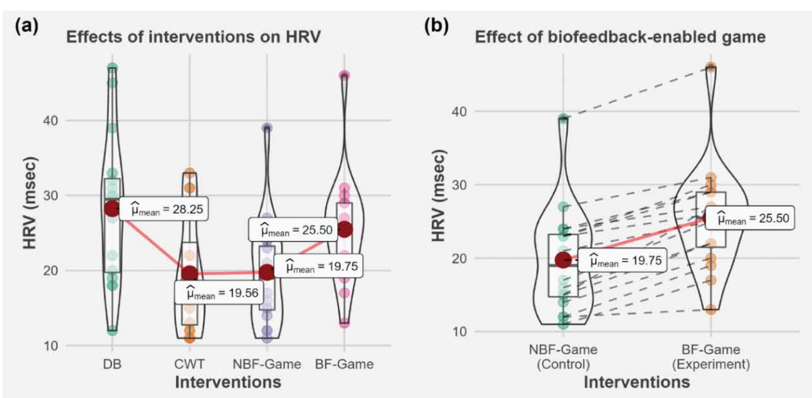


Table 3. Descriptive statistics of the HRV obtained during four interventions/groups

Intervention/Group	Mean ± SD	SE	Median	Range	Quartiles (Q_1, Q_3)	N
DB	28.25 ± 9.89	2.47	29.50	[12, 47]	[19.75, 32.25]	16
CWT	19.56 ± 7.65	1.91	18.50	[11, 33]	[12.75, 23.75]	16
NBF-Game (Control)	19.75 ± 7.25	1.81	19.00	[11, 39]	[14.75, 23.25]	16
BF-Game (Experiment)	25.50 ± 7.42	1.86	25.50	[13, 46]	[21.50, 29.00]	16

DB, deep breathing; CWT, color-word test; NBF-Game, non-biofeedback-game;
BF-Game, biofeedback-game; SD, standard deviation; SE, standard error;
Q1, first quartile or 25th percentile; Q3, third quartile or 75th percentile

(intervention) were conducted. Table 4, summarizes the results of the post-hoc tests. From the post-hoc tests, the participant's average HRV during the BF-Game (Experiment) was statistically significant than NBF-Game (Control) ($t(15) = 9.14$, $p < 0.0001$, 95% CI (3.84, 7.66), $d_z = 2.29$), and was also statistically significant than CWT (Stress Test) ($t(15) = 4.90$, $p < 0.001$, 95% CI (2.26, 9.62), $d_z = 1.22$). Figure 7 (b), shows the point-to-point comparison among the participants in the control v/s experiment group.

4.3. Comparisons of IMI Scores

The descriptive statistics of the score across questions of each IMI subscale and average total score for the IMI are presented in Table 5. Statistical test results revealed that mean scores for BF-Game in interest and enjoyment ($t(15) = 1.06$, $p = 0.30$) and perceived competence ($t(15) = -1.20$, $p = 0.25$) subscales were statistically same than those for NBF-Game. Figure 8, shows the comparison

Table 4. Statistical difference between the interventions in terms of average HRV

	DB	CWT	NBF-Game (Control)	BF-Game (Experiment)
DB	-	0.009**	0.009**	0.406
CWT	-	-	0.883	< 0.001***
NBF-Game (Control)	-	-	-	< 0.0001****
BF-Game (Experiment)	-	-	-	-

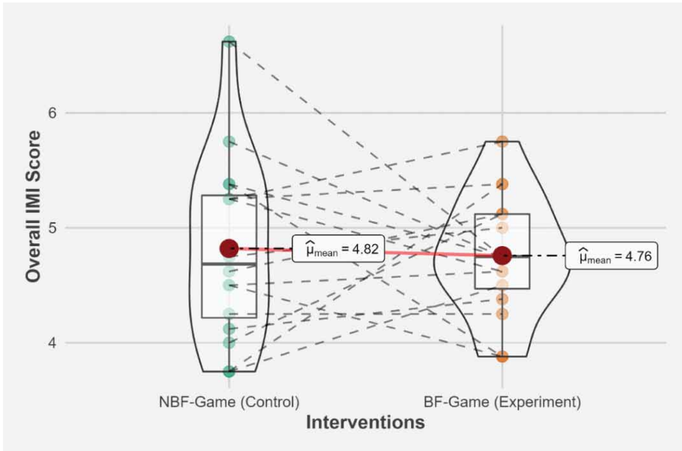
****$p < 0.0001$, ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$; df = 15; holm adjusted p values
DB, deep breathing; CWT, color-word test; NBF-Game, non-biofeedback-game; BF-Game, biofeedback-game

Table 5. Mean and standard deviation scores on two subscales of the intrinsic motivation inventory and overall intrinsic motivation for the two interventions

IMI subscale	Mean ± SD	
	NBF-Game (Control)	BF-Game (Experiment)
Interest/Enjoyment	5.94 ± 0.69	6.19 ± 0.59
Perceived Competence	3.70 ± 1.22	3.33 ± 0.68
Overall intrinsic motivation	4.82 ± 0.79	4.76 ± 0.52

IMI, intrinsic motivation inventory; NBF-Game, non-biofeedback-game; BF-Game, biofeedback-game; SD, standard deviation

Figure 8. Comparison of the Overall IMI Score rated by the NBF-Game (Control) and BF-Game (Experiment) groups



of mean overall intrinsic motivation between the NBF-Game and BF-Game which was statistically same ($t(15) = -0.27$, $p = 0.79$) for both the groups.

4.4. Comparison of SUS Score

The SUS ratings of all the participants for the biofeedback system are shown in Figure 9. The system obtained a mean rating of 74.69 ± 10.16, which was significantly greater ($t(15) = 1.85$, $p < 0.05$) than the acceptable criteria (>70) of the SUS scale (Miller, 2009).

4.5. Effect Sizes and Post-Hoc Power Analysis

The effect sizes were computed using JASP ver.0.16 (JASP Team, 2013/2021) for the ANOVA analysis and the post-hoc comparison of the different groups. The obtained effects during comparison of means for the four groups were eta-partial-squared (η_p^2) = 0.44, eta-generalized-squared (η_G^2) = 0.18, and omega-squared (ω^2) = 0.163, which all falls under large effects as per Cohen's recommendations (J. Cohen, 1988, pp. 286–287). Table 6, lists the effect sizes obtained during the post-hoc t-tests for multiple comparisons where large effects were obtained for the group pairs showing significant differences in the mean.

Figure 9. Comparison of SUS Score by the participants for the biofeedback system

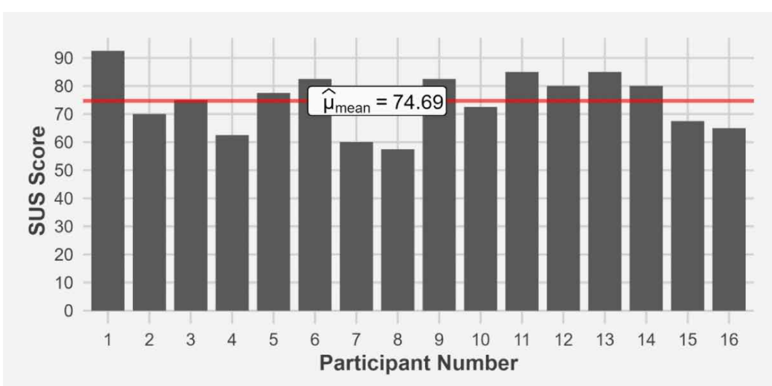


Table 6. Obtained effect sized during post-hoc comparisons of groups

Case	Mean Difference	95% CI of Mean Difference		SE	Cohen's $d^{\#}$
		Lower	Upper		
DB v/s CWT	8.69**	1.41	15.97	2.40	0.91
DB v/s NBF-Game	8.50**	1.52	15.49	2.30	0.92
DB v/s BF-Game	2.75	- 3.52	9.02	2.07	0.33
CWT v/s NBF-Game	- 0.19	- 3.98	3.61	1.25	- 0.04
CWT v/s BF-Game	- 5.94***	- 9.62	- 2.26	1.21	- 1.22
NBF-Game v/s BF-Game	- 5.75****	- 7.66	- 3.84	0.63	- 2.29

DB, deep breathing; CWT, color-word test; NBF-Game, non-biofeedback-game;
BF-Game, biofeedback-game; CI, confidence interval; SE, standard error
Cohen's *d* does not correct for multiple comparisons
****$p < 0.0001$, ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$; df = 15; holm adjusted p values

The post-hoc analysis for achieved power was computed using G*Power ver.3.1.9.7. From the mean and standard deviation from Table 3, the group effect size (d_z) of 0.78 was obtained for NBF-Game (Control) v/s BF-Game (Experiment). At a 5% significance level (α) and sample size of the present study, N = 16, this obtained effect yielded a 91.04% of achieved power.

5. DISCUSSION

The objective of this study was to test the efficacy, motivation, and system usability of a multimodal biofeedback system using NES games for achieving mental relaxation. A group of participants was tested under four different interventions and their average HRV was recorded. Later the motivation and system usability were determined from IMI and SUS questionnaire respectively.

5.1. Choice of Game and Game Mechanics for Driving Biofeedback

The Octalysis analysis of the SMB game showed the relatively high engagement with the quantitative game mechanics like score, number of lives, and level position. In Figure 5 (a), the participant's strong decisiveness can be seen while rating core drives 2, 3, 7, and 8. In contrast, while rating the core drives 4,5, and 6 participants gave a wider response with an interesting bi-modal graph with core-drive 2. The variability of the participant's ratings can be explained by the lack of knowledge about all the game mechanics, lack of knowledge about the game, and the experience of players (where the player may use anecdotal evidence while rating core drives). Our main aim was to identify the core drive with less variability in ratings which was shown by core drives 2,3, and 8. Therefore, two of these core drives, the development and accomplishment core drive (corresponding game mechanic: number of player's lives), and avoidance core drive (correspondence game mechanic: keep the health bar above 0th level) was chosen to modify during the biofeedback process. Using some other core drive's game-mechanic (especially with flat or bimodal curves with relatively larger variance among ratings) could result in relatively lower engagement with the BF-Game because participants are unsure about the engagement with the core drive.

5.2. Hypothesis 1: The BF-Game Induces More Relaxation Than the NBF-Game

As shown in Figure 6, the RSA was pronounced in the DB group where the participant was following the paced breathing relaxation protocol and subsides to a minimal value in the CWT group. The RSA is known to increase during paced breathing (Strauss-Blasche et al., 2000), which was also seen in the present study. The desynchronization of RSA in the control group suggests that the participants were unable to maintain the elevated HRV levels despite the relaxation training. However, the experiment group showed a significant effort by the participant to maintain the RSA amplitude. This visual inspection promises the relaxation effects of the biofeedback component in the game.

For the first hypothesis, the results suggest that the experiment group can maintain a higher mean HRV than the control group and also the CWT group. In other words, the biofeedback version of the SMB game was capable to induce higher relaxation among the players in comparison with the original SMB game and CWT. The significant statistical difference between the baseline measures (DB v/s CWT group) was as per the expectations. It is interesting to note that the participants showed a large variation among the DB intervention than CWT. This suggests the lack of interest and training for relaxation intervention (DB) among the participants. Also, worth noting is, the participant's mean HRV during the NBF-Game was comparable as in the CWT, which shows that the NBF-Game is equally capable of inducing mental stress to participants than a standardized stress test (CWT).

5.3. Hypothesis 2: The Participant's Motivation Towards Playing the BF-Game is the Same as Towards the NBF-Game

For the second hypothesis, the results indicate that overall, the participants were statistically equally motivated to play a BF-Game than an NBF-Game. As shown in Figure 8, the participants reported a slightly lower motivation for the biofeedback version of the SMB game as compared to the original SMB game. As quantified in Table 5, participants gave a higher mean rating for interest/enjoyment but a lower mean rating for perceived competence to the biofeedback game than the original game. This suggests that the participants were excited and motivated to try the new concept of biofeedback in the popular SMB game, but felt lower competence with the biofeedback game. Their lower competence can be attributed to the addition of extra biofeedback game mechanics into the game and the lack of biofeedback training for the participants. Overall, these results support the acceptability of the BF-Game by the participants for fun gameplay even with the additional biofeedback game mechanics.

5.4. Hypothesis 3: The Participants Find the Overall Biofeedback System Usable

For the third hypothesis, the results indicate that participants considered the developed biofeedback system to be usable. The SUS rating of >70 is defined as the good adjective rating or the acceptable range (Miller, 2009), which was statistically achieved by the developed system. During the feedback phase at the end of the session, all the participants gave positive and constructive feedback about the system. The participant's enjoyment for the biofeedback-enabled game is exemplified by comments like "It was fun to do" (P1), "I am very happy to play this game" (P3), and "It's a new and fun experience for me. I would love to use this in the future" (P6). The ease of system usability was mentioned by participants as, "there are few pieces of equipment involved, so the process is easy to follow" (P10). Additionally, the participants understand the health benefit of the biofeedback process and are evident from their comments like, "It's helpful to learn the breathing exercise and stays stress-free" (P12), and "I get aware of new thing like not taking stress while playing video-game" (P16). These results indicate the usability of the developed biofeedback system and participants are likely to actively use the biofeedback game in the future.

6. LIMITATIONS

There are a few limitations in this study that should be highlighted. At pre-registration, measures were taken to account for these limitations under the constraints of the study. Firstly, in this study only that participants which were self-motivated to play video games, were considered for the study. Therefore, the obtained results were more positive than would have been for a random sample. However, as the efficacy of a general biofeedback system using games was already proved in literature (Bouchard et al., 2012; Dekker & Champion, 2007; Parnandi & Gutierrez-Osuna, 2017; Walther-Franks et al., 2013; Zafar et al., 2020), this study aims to validate the developed system (specifically use of original NES games for biofeedback). Secondly, since the participants were aware of the purpose of the study, the results of the questionnaires may be biased.

7. CONCLUSION AND FUTURE WORK

This study highlights the efficacy of the developed multimodal biofeedback system for mental relaxation with the use of NES games. It was shown that the original video game, produces a stress response similar to a standardized stress test (CWT). However, the addition of the biofeedback component in the game encourages the participants to better manage their stress response using paced breathing. The results also show that the biofeedback enabled game was perceived as motivating and engaging when compared to the original non-biofeedback version of the game. Finally, the overall system was rated good for usability with some scope for improvement. The large effects obtained in the present study give promising directions to explore the NES games for biofeedback. While SMB game is used in this study, in the future, other popular NES games (like Tetris, Pac-man, etc.) can be used in this system with minor tweaking. Another line of work can be the study of different game mechanics and additional feedback modalities (like haptic feedback) to further increase the engagement of the biofeedback system.

8. DATA AVAILABILITY

This is open data, open code, and replicable research. The software tool, data, and analysis scripts that support the findings of this study are available as an open-source project, under the GPLv3 license, hosted at Open Science Framework repository, and can be accessed using DOI: 10.17605/OSF.IO/Q5EZ3 following an embargo period until the paper is accepted/published.

REFERENCES

Alhamid, M. F., Eid, M., Alshareef, A., & El Saddik, A. (2012). MMBIP: Biofeedback system design on Cloud-Oriented Architecture. *2012 IEEE International Symposium on Robotic and Sensors Environments Proceedings*, 79–84. doi:10.1109/ROSE.2012.6402610

Aritzeta, A., Soroa, G., Balluerka, N., Muela, A., Gorostiaga, A., & Aliri, J. (2017). Reducing Anxiety and Improving Academic Performance Through a Biofeedback Relaxation Training Program. *Applied Psychophysiology and Biofeedback*, *42*(3), 193–202. doi:10.1007/s10484-017-9367-z PMID:28623467

Asín-Prieto, G., Martínez-Expósito, A., Barroso, F. O., Urendes, E. J., Gonzalez-Vargas, J., Alnajjar, F. S., González-Alted, C., Shimoda, S., Pons, J. L., & Moreno, J. C. (2020). Haptic Adaptive Feedback to Promote Motor Learning With a Robotic Ankle Exoskeleton Integrated With a Video Game. *Frontiers in Bioengineering and Biotechnology*, *8*, 113. doi:10.3389/fbioe.2020.00113 PMID:32154239

Bae, D., Matthews, J. J. L., Chen, J. J., & Mah, L. (2021). Increased exhalation to inhalation ratio during breathing enhances high-frequency heart rate variability in healthy adults. *Psychophysiology*, *58*(11), e13905. doi:10.1111/psyp.13905 PMID:34289128

Barcala, L., Grecco, L. A. C., Colella, F., Lucareli, P. R. G., Salgado, A. S. I., & Oliveira, C. S. (2013). Visual Biofeedback Balance Training Using Wii Fit after Stroke: A Randomized Controlled Trial. *Journal of Physical Therapy Science*, *25*(8), 1027–1032. doi:10.1589/jpts.25.1027 PMID:24259909

Bernard, C. (1957). *An Introduction to the Study of Experimental Medicine* (H. C. Greene, Trans.). Dover Publications. https://books.google.co.in/books?id=MIx8D61JlboC (Original work published 1865)

Berntson, G. G., & Stowell, J. R. (1998). ECG artifacts and heart period variability: Don't miss a beat! *Psychophysiology*, *35*(1), 127–132. doi:10.1111/1469-8986.3510127 PMID:9499713

Bersak, D., McDarby, G., Augenblick, N., McDarby, P., McDonnell, D., McDonald, B., & Karkun, R. (2001). *Intelligent biofeedback using an immersive competitive environment.* Paper at the Designing Ubiquitous Computing Games Workshop at UbiComp.

Bossenbroek, R., Wols, A., Weerdmeester, J., Lichtwarck-Aschoff, A., Granic, I., & van Rooij, M. M. J. W. (2020). Efficacy of a Virtual Reality Biofeedback Game (DEEP) to Reduce Anxiety and Disruptive Classroom Behavior: Single-Case Study. *JMIR Mental Health*, *7*(3), e16066. Advance online publication. doi:10.2196/16066 PMID:32207697

Bouchard, S., Bernier, F., Boivin, É., Morin, B., & Robillard, G. (2012). Using Biofeedback while Immersed in a Stressful Videogame Increases the Effectiveness of Stress Management Skills in Soldiers. *PLoS One*, *7*(4), e36169. doi:10.1371/journal.pone.0036169 PMID:22558370

Braun, N., Debener, S., Sölle, A., Kranczioch, C., & Hildebrandt, H. (2015). Biofeedback-based self-alert training reduces alpha activity and stabilizes accuracy in the Sustained Attention to Response Task. *Journal of Clinical and Experimental Neuropsychology*, *37*(1), 16–26. doi:10.1080/13803395.2014.977232 PMID:25658671

Breathe Slowly. (n.d.). Retrieved April 10, 2021, from https://xhalr.com/

Brinkmann, A. E., Press, S. A., Helmert, E., Hautzinger, M., Khazan, I., & Vagedes, J. (2020). Comparing Effectiveness of HRV-Biofeedback and Mindfulness for Workplace Stress Reduction: A Randomized Controlled Trial. *Applied Psychophysiology and Biofeedback*, *45*(4), 307–322. doi:10.1007/s10484-020-09477-w PMID:32556709

Brooke, J. (1986). System usability scale (SUS): A quick-and-dirty method of system evaluation user information. *Reading, UK. Digital Equipment Co Ltd*, *43*, 1–7.

Brown, S. J., Lieberman, D. A., Gemeny, B. A., Fan, Y. C., Wilson, D. M., & Pasta, D. J. (1997). Educational video game for juvenile diabetes: Results of a controlled trial. *Medical Informatics*, *22*(1), 77–89. doi:10.3109/14639239709089835 PMID:9183781

Clark, M. E., & Hirschman, R. (1990). Effects of paced respiration on anxiety reduction in a clinical population. *Biofeedback and Self-Regulation*, *15*(3), 273–284. doi:10.1007/BF01011109 PMID:2223892

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences* (2nd ed.). Routledge. doi:10.4324/9780203771587

Cohen, S., Janicki-Deverts, D., Doyle, W. J., Miller, G. E., Frank, E., Rabin, B. S., & Turner, R. B. (2012). Chronic stress, glucocorticoid receptor resistance, inflammation, and disease risk. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(16), 5995–5999. doi:10.1073/pnas.1118355109 PMID:22474371

Converse, H., Ferraro, T., Jean, D., Jones, L., Mendhiratta, V., Naviasky, E., Par, M., Rimlinger, T., Southall, S., Sprenkle, J., & Abshire, P. (2013). An EMG biofeedback device for video game use in forearm physiotherapy. *2013 IEEE SENSORS*, 1–4. 10.1109/ICSENS.2013.6688474

Crum, A. J., Akinola, M., Martin, A., & Fath, S. (2017). The role of stress mindset in shaping cognitive, emotional, and physiological responses to challenging and threatening stress. *Anxiety, Stress, and Coping*, *30*(4), 379–395. doi:10.1080/10615806.2016.1275585 PMID:28120622

Crum, A. J., Salovey, P., & Achor, S. (2013). Rethinking stress: The role of mindsets in determining the stress response. *Journal of Personality and Social Psychology*, *104*(4), 716–733. doi:10.1037/a0031201 PMID:23437923

Dekker, A., & Champion, E. (2007). *Please biofeed the zombies: Enhancing the gameplay and display of a horror game using biofeedback*. 10.25917/5d1443e8af4a0

Dillon, A., Kelly, M., Robertson, I. H., & Robertson, D. A. (2016). Smartphone Applications Utilizing Biofeedback Can Aid Stress Reduction. *Frontiers in Psychology*, *7*. Advance online publication. doi:10.3389/fpsyg.2016.00832 PMID:27378963

Emmen, D. H., & Lampropoulos, G. (2014). BioPong: Adaptive Gaming Using Biofeedback. *Creating the Difference*, 100–103. http://chi-sparks.nl/2014/session/kidsplay-2/

Farahbod, F. (2020). *TelemetryViewer*. https://github.com/farrellf/TelemetryViewer

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. doi:10.3758/BF03193146 PMID:17695343

FCEUX. (2020). *TASVideos on GitHub*. https://github.com/TASVideos/fceux

Fortin-Côté, A., Beaudin-Gagnon, N., Campeau-Lecours, A., Tremblay, S., & Jackson, P. L. (2019). Affective Computing Out-of-The-Lab: The Cost of Low Cost. *2019 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, 4137–4142. doi:10.1109/SMC.2019.8914646

Frey, J., Grabli, M., Slyper, R., & Cauchard, J. R. (2018). Breeze: Sharing Biofeedback through Wearable Technologies. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 1–12. doi:10.1145/3173574.3174219

Geršak, G., & Drnovšek, J. (2020). Electrodermal activity patient simulator. *PLoS One*, *15*(2), e0228949. doi:10.1371/journal.pone.0228949 PMID:32023317

Giggins, O. M., Persson, U. M., & Caulfield, B. (2013). Biofeedback in rehabilitation. *Journal of Neuroengineering and Rehabilitation*, *10*(1), 60. doi:10.1186/1743-0003-10-60 PMID:23777436

GitHub. (n.d.). Retrieved December 9, 2021, from https://github.com/

gocha. (2020). *Snes9x-rr*. https://github.com/gocha/snes9x-rr

Haahr, M. (1998). *RANDOM.ORG: True Random Number Service*. https://www.random.org

Heathcote, L., Hernandez, J., Kronman, C., Mahmud, F., Crum, A., & Simons, L. (2018). 'Stress helps me learn and grow': Does stress mindset matter for children and young adults with chronic pain? *The Journal of Pain*, *19*(3), S56. https://doi.org/10.1016/j.jpain.2017.12.137

Intrinsic Motivation Inventory (IMI). (n.d.). *Center for Self-Determination Theory (CSDT)*. Retrieved February 5, 2021, from https://selfdeterminationtheory.org/intrinsic-motivation-inventory/

Jain, M., & Baijal, R. (2017). Biofeedback therapy—Challenges in Indian setting. *Indian Journal of Gastroenterology*, *36*(2), 160–160. https://doi.org/10.1007/s12664-017-0738-4

JASP Team. (2021). *JASP* (0.16) [Computer software]. The JASP Statistics Project. https://jasp-stats.org/

Jorgensen, M. G., Laessoe, U., Hendriksen, C., Nielsen, O. B. F., & Aagaard, P. (2013). Efficacy of Nintendo Wii Training on Mechanical Leg Muscle Function and Postural Balance in Community-Dwelling Older Adults: A Randomized Controlled Trial. *The Journals of Gerontology: Series A, 68*(7), 845–852. 10.1093/gerona/gls222

Kennedy, J. J., & Pretorius, M. (2008). Integrating a Portable Biofeedback Device into Call Centre Environments to Reduce Employee Stress: Results from Two Pilot Studies. *Journal of Workplace Behavioral Health*, *23*(3), 295–307. https://doi.org/10.1080/15555240802243096

Kennedy, L., & Parker, S. H. (2019). Biofeedback as a stress management tool: A systematic review. *Cognition Technology and Work*, *21*(2), 161–190. https://doi.org/10.1007/s10111-018-0487-x

Kim, D. K., Kim, J., Lee, E. C., Whang, M., & Cho, Y. (2011). Interactive emotional content communications system using portable wireless biofeedback device. *IEEE Transactions on Consumer Electronics*, *57*(4), 1929–1936. https://doi.org/10.1109/TCE.2011.6131173

Koenka, I. J., Sáiz, J., & Hauser, P. C. (2014). Instrumentino: An open-source modular Python framework for controlling Arduino based experimental instruments. *Computer Physics Communications*, *185*(10), 2724–2729. https://doi.org/10.1016/j.cpc.2014.06.007

Kotozaki, Y., Takeuchi, H., Sekiguchi, A., Yamamoto, Y., Shinada, T., Araki, T., Takahashi, K., Taki, Y., Ogino, T., Kiguchi, M., & Kawashima, R. (2014). Biofeedback-based training for stress management in daily hassles: An intervention study. *Brain and Behavior*, *4*(4), 566–579. https://doi.org/10.1002/brb3.241

Lai, C.-H., Peng, C.-W., Chen, Y.-L., Huang, C.-P., Hsiao, Y.-L., & Chen, S.-C. (2013). Effects of interactive video-game based system exercise on the balance of the elderly. *Gait & Posture*, *37*(4), 511–515. https://doi.org/10.1016/j.gaitpost.2012.09.003

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

Levinger, P., Zeina, D., Teshome, A. K., Skinner, E., Begg, R., & Abbott, J. H. (2016). A real time biofeedback using Kinect and Wii to improve gait for post-total knee replacement rehabilitation: A case study report. *Disability and Rehabilitation. Assistive Technology*, *11*(3), 251–262. https://doi.org/10.3109/17483107.2015.1080767

Lieberman, D. A. (2001). Management of Chronic Pediatric Diseases with Interactive Health Games: Theory and Research Findings. *The Journal of Ambulatory Care Management*, *24*(1), 26–38.

Lobel, A., Gotsis, M., Reynolds, E., Annetta, M., Engels, R. C. M. E., & Granic, I. (2016). Designing and Utilizing Biofeedback Games for Emotion Regulation: The Case of Nevermind. *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, 1945–1951. 10.1145/2851581.2892521

Loudon, G., Zampelis, D., & Deininger, G. (2017). Using Real-time Biofeedback of Heart Rate Variability Measures to Track and Help Improve Levels of Attention and Relaxation. *Proceedings of the 2017 ACM SIGCHI Conference on Creativity and Cognition*, 348–355. 10.1145/3059454.3059466

Lua Scripting. (n.d.). Retrieved March 21, 2021, from https://fceux.com/web/help/LuaScripting.html

Luo, H.-J., Lin, S.-X., Wu, S.-K., Tsai, M.-W., & Lee, S.-J. (2017). Comparison of segmental spinal movement control in adolescents with and without idiopathic scoliosis using modified pressure biofeedback unit. *PLoS One*, *12*(7), e0181915. https://doi.org/10.1371/journal.pone.0181915

Lupien, S. J., McEwen, B. S., Gunnar, M. R., & Heim, C. (2009). Effects of stress throughout the lifespan on the brain, behaviour and cognition. *Nature Reviews. Neuroscience*, *10*(6), 434–445. https://doi.org/10.1038/nrn2639

Maarsingh, B. M., Bos, J., Van Tuijn, C. F. J., & Renard, S. B. (2019). Changing Stress Mindset Through Stressjam: A Virtual Reality Game Using Biofeedback. *Games for Health Journal*, *8*(5), 326–331. https://doi.org/10.1089/g4h.2018.0145

Malik, M., Bigger, J. T., Camm, A. J., Kleiger, R. E., Malliani, A., Moss, A. J., & Schwartz, P. J. (1996). Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. *European Heart Journal*, *17*(3), 354–381. https://doi.org/10.1093/oxfordjournals.eurheartj.a014868

Malik, M., & Camm, A. J. (Eds.). (2004). *Dynamic Electrocardiography*. Blackwell Publishing. 10.1002/9780470987483

Mandryk, R. L., Dielschneider, S., Kalyn, M. R., Bertram, C. P., Gaetz, M., Doucette, A., Taylor, B. A., Orr, A. P., & Keiver, K. (2013). Games as neurofeedback training for children with FASD. *Proceedings of the 12th International Conference on Interaction Design and Children*, 165–172. 10.1145/2485760.2485762

Miller, A. B. P. K. J. (2009). Determining What Individual SUS Scores Mean: Adding an Adjective Rating Scale. *Journal of Usability Studies*, *4*(3), 114–123.

Moeyersons, B., Fuss, F. K., Tan, A. M., & Weizman, Y. (2016). Biofeedback System for Novice Snowboarding. *Procedia Engineering*, *147*, 781–786. https://doi.org/10.1016/j.proeng.2016.06.318

Moraveji, N., Olson, B., Nguyen, T., Saadat, M., Khalighi, Y., Pea, R., & Heer, J. (2011). Peripheral paced respiration: Influencing user physiology during information work. *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology*, 423–428. 10.1145/2047196.2047250

Murthy, R. S. (2017). National mental health survey of India 2015–2016. *Indian Journal of Psychiatry*, *59*(1), 21. https://doi.org/10.4103/psychiatry.IndianJPsychiatry_102_17

Nacke, L. E. (2011). Directions in Physiological Game Evaluation and Interaction. *CHI 2011 BBI Workshop Proceedings*.

Nacke, L. E., Kalyn, M., Lough, C., & Mandryk, R. L. (2011). Biofeedback game design: Using direct and indirect physiological control to enhance game interaction. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 103–112. 10.1145/1978942.1978958

Narducci, E., Mouttet, K., Shahbazi, A., Pool, D., & Tan, T. (2020). A Study of the Safety and Functionality of Gamified Electromyographic Biofeedback for Children with Cerebral Palsy. *2020 42nd Annual International Conference of the IEEE Engineering in Medicine Biology Society (EMBC)*, 5180–5183. 10.1109/EMBC44109.2020.9175654

Nogueira, P. A., Torres, V., Rodrigues, R., Oliveira, E., & Nacke, L. E. (2016). Vanishing scares: Biofeedback modulation of affective player experiences in a procedural horror game. *Journal on Multimodal User Interfaces*, *10*(1), 31–62. https://doi.org/10.1007/s12193-015-0208-1

Othmer, S., & Kaiser, D. (2000). Implementation of Virtual Reality in EEG Biofeedback. *Cyberpsychology & Behavior*, *3*(3), 415–420. https://doi.org/10.1089/10949310050078878

Parnandi, A., & Gutierrez-Osuna, R. (2017). Physiological Modalities for Relaxation Skill Transfer in Biofeedback Games. *IEEE Journal of Biomedical and Health Informatics*, *21*(2), 361–371. https://doi.org/10.1109/JBHI.2015.2511665

Parnandi, A., & Gutierrez-Osuna, R. (2019). Visual Biofeedback and Game Adaptation in Relaxation Skill Transfer. *IEEE Transactions on Affective Computing*, *10*(2), 276–289. https://doi.org/10.1109/TAFFC.2017.2705088

Patel, A., Schieble, T., Davidson, M., Tran, M. C. J., Schoenberg, C., Delphin, E., & Bennett, H. (2006). Distraction with a hand-held video game reduces pediatric preoperative anxiety. *Pediatric Anesthesia, 16*(10), 1019–1027. 10.1111/j.1460-9592.2006.01914.x

Phillips, W. R. (1991). Video-game therapy. *The New England Journal of Medicine*, *325*(17), 1256–1257. https://doi.org/10.1056/NEJM199110243251718

Polo, A., Narvaez, P., & Robles Algarín, C. (2018). Implementation of a Cost-Effective Didactic Prototype for the Acquisition of Biomedical Signals. *Electronics (Basel)*, *7*(5), 77. https://doi.org/10.3390/electronics7050077

Pope, A. T., & Palsson, O. S. (2001). *Helping Video Games Rewire "Our Minds"*. https://ntrs.nasa.gov/citations/20040086464

Porges, S. W., & Byrne, E. A. (1992). Research methods for measurement of heart rate and respiration. *Biological Psychology*, *34*(2), 93–130. https://doi.org/10.1016/0301-0511(92)90012-J

Rand, J., Hoover, A., Fishel, S., Moss, J., Pappas, J., & Muth, E. (2007). Real-Time Correction of Heart Interbeat Intervals. *IEEE Transactions on Biomedical Engineering*, *54*(5), 946–950. https://doi.org/10.1109/TBME.2007.893491

RStudio Team. (2021). *RStudio: Integrated Development Environment for R* (1.4.1103) [Computer software]. RStudio, PBC. https://www.rstudio.com/

Ryan, R. M. (1982). Control and information in the intrapersonal sphere: An extension of cognitive evaluation theory. *Journal of Personality and Social Psychology*, *43*(3), 450–461. https://doi.org/10.1037/0022-3514.43.3.450

Schwartz, M. S. (2010). 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*, *38*(3), 88–90. https://doi.org/10.5298/1081-5937-38.3.88

Sherlin, L., Gevirtz, R., Wyckoff, S., & Muench, F. (2009). Effects of respiratory sinus arrhythmia biofeedback versus passive biofeedback control. *International Journal of Stress Management*, *16*(3), 233–248. https://doi.org/10.1037/a0016047

Sonne, T., & Jensen, M. M. (2016). ChillFish: A Respiration Game for Children with ADHD. *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*, 271–278. 10.1145/2839462.2839480

Stoet, G. (2010). PsyToolkit: A software package for programming psychological experiments using Linux. *Behavior Research Methods*, *42*(4), 1096–1104. https://doi.org/10.3758/BRM.42.4.1096

Stoet, G. (2017). PsyToolkit: A Novel Web-Based Method for Running Online Questionnaires and Reaction-Time Experiments. *Teaching of Psychology*, *44*(1), 24–31. https://doi.org/10.1177/0098628316677643

Strauss-Blasche, G., Moser, M., Voica, M., McLeod, D., Klammer, N., & Marktl, W. (2000). Relative Timing Of Inspiration And Expiration Affects Respiratory Sinus Arrhythmia. *Clinical and Experimental Pharmacology & Physiology*, *27*(8), 601–606. https://doi.org/10.1046/j.1440-1681.2000.03306.x

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*(6), 643–662. https://doi.org/10.1037/h0054651

Super Mario Bros.: RAM map—Data Crystal. (n.d.). Retrieved March 21, 2021, from https://datacrystal.romhacking.net/wiki/Super_Mario_Bros.:RAM_map

Super Mario Bros. - Super Mario Wiki, the Mario encyclopedia. (n.d.). Retrieved April 12, 2021, from https://www.mariowiki.com/Super_Mario_Bros

Tarchanoff, J. R. (1885). Ueber die willkürliche Acceleration der Herzschläge beim Menschen [Voluntary acceleration of the heart beat in man]. *Archiv für die gesamte Physiologie des Menschen und der Tiere, 35*(1), 109–137. 10.1007/BF01612726

Tetris 64. (n.d.). *Nintendo*. Retrieved December 5, 2020, from https://nintendo.fandom.com/wiki/Tetris_64

The Atari Mindlink System. (n.d.). Retrieved December 2, 2020, from http://www.atarimuseum.com/videogames/consoles/2600/mindlink.html

Thurber, M. R., Bodenhamer-Davis, E., Johnson, M., Chesky, K., & Chandler, C. K. (2010). Effects of Heart Rate Variability Coherence Biofeedback Training and Emotional Management Techniques to Decrease Music Performance Anxiety. *Biofeedback*, *38*(1), 28–40. https://doi.org/10.5298/1081-5937-38.1.28

Travers, B. G., Mason, A. H., Mrotek, L. A., Ellertson, A., Dean, D. C., Engel, C., Gomez, A., Dadalko, O. I., & McLaughlin, K. (2018). Biofeedback-Based, Videogame Balance Training in Autism. *Journal of Autism and Developmental Disorders*, *48*(1), 163–175. https://doi.org/10.1007/s10803-017-3310-2

Vaschillo, E. G., Vaschillo, B., & Lehrer, P. M. (2006). Characteristics of Resonance in Heart Rate Variability Stimulated by Biofeedback. *Applied Psychophysiology and Biofeedback*, *31*(2), 129–142. https://doi.org/10.1007/s10484-006-9009-3

Walther-Franks, B., Wenig, D., Smeddinck, J., & Malaka, R. (2013). Exercise My Game: Turning Off-The-Shelf Games into Exergames. In J. C. Anacleto, E. W. G. Clua, F. S. C. da Silva, S. Fels, & H. S. Yang (Eds.), Entertainment Computing – ICEC 2013 (pp. 126–131). Springer. https://doi.org/10.1007/978-3-642-41106-9_15.

Wang, Z., Parnandi, A., & Gutierrez-Osuna, R. (2018). BioPad: Leveraging off-the-Shelf Video Games for Stress Self-Regulation. *IEEE Journal of Biomedical and Health Informatics*, *22*(1), 47–55. https://doi.org/10.1109/JBHI.2017.2671788

Wii Vitality Sensor. (n.d.). *Nintendo*. Retrieved December 2, 2020, from https://nintendo.fandom.com/wiki/Wii_Vitality_Sensor

Zafar, M. A., Ahmed, B., & Gutierrez-Osuna, R. (2017). Playing with and without Biofeedback. *2017 IEEE 5th International Conference on Serious Games and Applications for Health (SeGAH)*, 1–7. 10.1109/SeGAH.2017.7939272

Zafar, M. A., Ahmed, B., Rihawi, R. A., & Gutierrez-Osuna, R. (2020). Gaming Away Stress: Using Biofeedback Games to Learn Paced Breathing. *IEEE Transactions on Affective Computing*, *11*(3), 519–531. https://doi.org/10.1109/TAFFC.2018.2816945

Zhang, J. (2007). Effect of Age and Sex on Heart Rate Variability in Healthy Subjects. *Journal of Manipulative and Physiological Therapeutics*, *30*(5), 374–379. https://doi.org/10.1016/j.jmpt.2007.04.001

ENDNOTES

1 All products, company names, brand names, trademarks, and sprites are properties of their respective owners.
2 In the present study, multimodal refers to more than one mode (like visual, auditory, haptic etc.) of delivering the biofeedback.
3 BioNES translated to Biofeedback Nintendo Entertainment System.
4 G*Power is used to derive Cohen's f values from η^2 (eta-squared).
5 Publicly available at https://doi.org/10.17605/OSF.IO/2UZCQ
6 Publicly available at https://github.com/kulbhushanchand/BioNES

Kulbhushan Chand received the B.Tech. degree in Electronics and Communication Engineering from the Guru Nanak Dev University, India, in 2010, and the M.Tech. degree in Electronics and Communication Engineering from the Lovely Professional University, India, in 2013. He is currently working towards the Ph.D. degree in Electronics and Communication Engineering with Dr. Arun Khosla at the Dr. B R Ambedkar National Institute of Technology Jalandhar, India. His research interests include biofeedback, embedded systems, wearable physiological sensors, computing, healthcare, and gamification.

Arun Khosla is a Professor in the Department of Electronics and Communication Engineering at Dr B R Ambedkar National Institute of Technology, Jalandhar, Punjab. His research interests include soft computing, artificial intelligence, machine learning, assisted technologies, healthcare, and gamification.