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BioNES: A plug-and-play MATLAB-based tool to use NES games for multimodal biofeedback

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A B S T R A C T

In the traditional biofeedback system, videogames are effectively used to increase engagement as a feedback delivery mechanism via changing in-game mechanics. The original 8-bit Nintendo Entertainment System (NES) games make them an excellent choice for biofeedback for their popularity and simple gameplay mechanics. For this, we present BioNES, which is a MATLAB-based GUI tool to leverage the NES games for multimodal biofeedback. The RR beats can be received from any Arduino compatible board to compute the heart rate variability (HRV). The deviation of HRV from baseline corresponds to the mental stress of the player and is used to compute feedback which is then delivered via NES game running in FCEUX emulator. The player can then use any relaxation protocol, like paced breathing to learn stress management during gameplay. The system performance and efficacy via randomized controlled trials have been proved in the separate open data research. The BioNES is meant to be a simple plug-and-play and affordable biofeedback solution for researchers without programming experience and casual users to use video games for health.

Code metadata

Current code version	v1.0.0
Permanent link to code/repository used of this code version	https://github.com/ElsevierSoftwareX/SOFTX-D-21-00100
Code Ocean compute capsule	NA
Legal Code License	GPL-3.0
Code versioning system used	git
Software code languages, tools, and services used	Microsoft Windows, MATLAB, LUA, C++
Compilation requirements, operating environments & dependencies	MATLAB v9.3 or later; Instrument Control Toolbox v3.12; FCEUX v2.3.0
If available Link to developer documentation/manual	https://kulbhushanchand.github.io/BioNES/
Support email for questions	kulbhushan.chand@gmail.com

Software metadata

Current software version	v1.0.0
Permanent link to executables of this version	https://github.com/kulbhushanchand/BioNES
Legal Software License	GPL-3.0
Computing platforms/Operating Systems	Microsoft Windows, MATLAB
Installation requirements & dependencies	MATLAB v9.3 or later; Instrument Control Toolbox v3.12; FCEUX v2.3.0
If available, link to user manual-if formally published include a reference to the publication in the reference list	https://kulbhushanchand.github.io/BioNES/
Support email for questions	kulbhushan.chand@gmail.com

1. Motivation and significance

Biofeedback is a popular form of alternative medicine and is effectively used in controlling anxiety, stress, achieving a state

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of mental relaxation, and a greater awareness of physiological/mental state [1–3]. In a traditional biofeedback session for stress management, the individual's physiological parameters (like heart rate) are measured and shown in real-time. One can follow some relaxation protocol (like deep/paced breathing) and see the real-time change in their physiological parameter to achieve some threshold value (like heart rate less than the baseline value). After several sessions, one can learn to better manage stress in their daily lives without the need for a biofeedback system [4].

Researchers have used video games as the delivery mechanism for biofeedback to increase engagement in the long and monotonous biofeedback sessions [5–9]. However, there are some notable issues with the biofeedback systems used in the literature. Firstly, the biofeedback hardware and software can be expensive due to the use of proprietary tools. The development and maintenance of video games will further escalate the cost of the system. Secondly, some of the video games used in the literature are not available/usable due to proprietary code, expired links, and non-maintenance of public code. Further, the games used are non-standardized and belong to different genres, which makes it difficult to compare results across studies.

The 8-bit games developed for the Nintendo Entertainment System (NES[1]) system can address the issues of using cost-effective standardized video games for biofeedback. These have the advantages of immense popularity, simple gameplay, and meticulous level design with keeping in mind the Zone of Proximal Development (ZPD) of the player. In literature, the clones of some NES games like Pong [10–12], Tetris [12,13], and Pac-Man [9,14], have been used for biofeedback. There are some custom-made Nintendo games used in healthcare research. *Packy and Marlon* [15] aim at diabetes self-management, and *Bronkie the Bronchiasaurus* [16] for self-management of asthma, among children. Also, the popular Nintendo Gameboy handheld console was effectively used to reduce pediatric preoperative anxiety [17] and management of compulsive habits [18]. The latest in series, the Nintendo Wii platform was also used in literature for biofeedback applications like balance training [19–21] and gait improvement [22]. From the literature, it is evident that 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 proprietary code of the NES games and the lack of an available tool to leverage these games for biofeedback.

Therefore, Biofeedback Nintendo Entertainment System (BioNES) is developed as a tool to leverage the NES games for multimodal biofeedback without modifying the source code of the games. It is to be noted that, the multimodal in BioNES is in the context of feedback delivery, where feedback is presented via more than one mode (visual, auditory, and game-mechanics). Another meaning of multimodal in biofeedback literature is regarding the use of more than one input signal/feature (HR, HRV, and EDA). So, BioNES is a multimodal system regarding the feedback modality and unimodal regarding the input signals. The system acquires the heartbeat pulses from Arduino compatible hardware, processes the data, and uses the FCEUX [23] emulator to deliver feedback via NES games. To deliver the feedback the real-time, the in-game variables are modified via the emulator, which circumvents the need to know and modify the source code of the game. BioNES can work without any modification with the Super Mario Bros. (SMB) [24] game and other games can be used with some slight changes.

[1] All products, company names, brand names, trademarks, and sprites are properties of their respective owners.

Since MATLAB is already an extensively used software in universities for experiment designs and FCEUX is open-source software, the cost, issue of availability, and maintenance of the BioNES is relatively low. The software is designed to completely integrate the data acquisition, signal conditioning, feature extraction, visualization, analysis, and data logging within the MATLAB environment which minimizes the dependencies. The efficacy, intrinsic motivation of use, and system usability of the BioNES has been validated by the randomized controlled trials [25] and the system performance via benchmarking a similar real-time data acquisition system in another study [26]. The trials were pre-registered[2] with Open Science Framework (OSF) registries prior to the creation of data and the trial data and analysis scripts are publicly available in the OSF project repository[3]. To date, the BioNES is used for the preliminary data acquisition needs and the biofeedback experiments in our lab. Now it is released in the public domain to assist the researchers in their simple data acquisition needs and biofeedback experiments.

2. Software description

BioNES is the software part of a complete biofeedback system. The overall block diagram of the biofeedback system is shown in Fig. 1(a). In a typical biofeedback session, a researcher is in control of the overall session. The user, to whom biofeedback is delivered, interacts only with the game and also tries to actively control some of the game elements by following some biofeedback protocol. As shown in Fig. 1(a), the user interacts with the game via a gamepad and receives feedback in the terms of visual (game screen), audio (game audio), and change in the game mechanics. The physiological parameter, Photoplethsomograph (PPG), is recorded via an external ear-clip sensor. The Arduino board captures the raw signal, pre-processes the data to remove any artifacts, and sends data to BioNES in a master–slave configuration. The BioNES acts as a data acquisition software and biofeedback controller. It acquires data from the Arduino, pre-processes the data, extracts features, displays real-time results, and drives feedback by communicating with the FCEUX.

2.1. Software architecture

The BioNES is developed with MATLAB ver.9.3 (R2017b) and requires Instrument Control Toolbox ver.3.12. It was also tested with MATLAB R2015b and R2018b for backward and forward compatibility respectively. The GUIDE tool in MATLAB is used to develop the GUI, which offers quick prototyping with drag-and-drop features and programmatically generating the call-back functions. Fig. 1(b) and Fig. 3, show the front-end of BioNES which is operated by the researcher. The BioNES GUI is modular in design with various sub-components arranged into different panels as per their functionality. The main components of the GUI are Settings, Control, Plot, and Information. Fig. 1(c) shows the emulator GUI where the player interacts with the game. Here, the feedback bar is overlaid on the main game screen at the top center position.

The structure of the BioNES encompasses three different software environments. Firstly, in the Arduino, the sketch file "BioNES.ino" contains the necessary firmware to prepare the Arduino board for data acquisition. The Arduino board intends to work as a slave to MATLAB, with custom commands (see Tables 1 and 2) for fetching data. Fig. 2(a) shows the flowchart of an

[2] Pre-registration of the trials is publicly available at https://doi.org/10.17605/OSF.IO/2UZCQ

[3] The trials data and analysis scripts are publicly available at https://doi.org/10.17605/OSF.IO/Q5EZ3

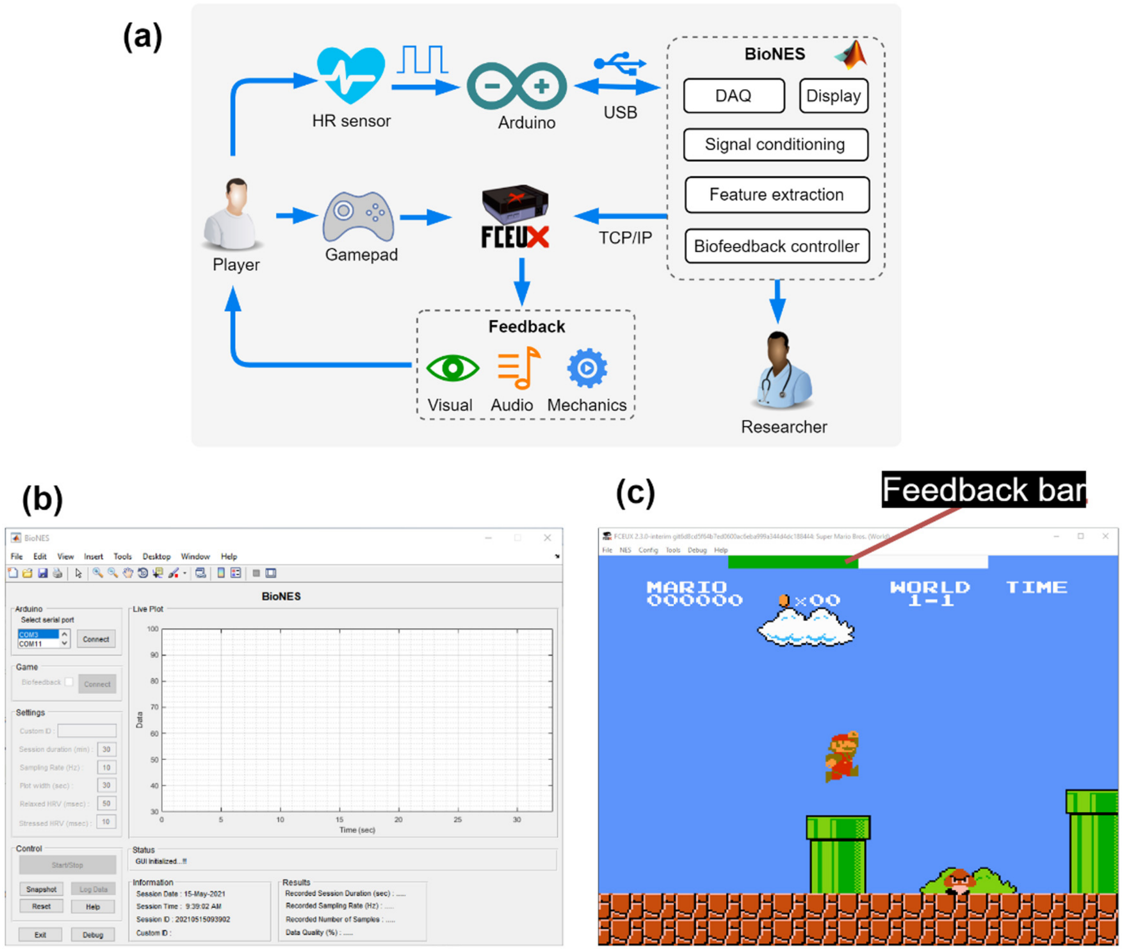

Fig. 1. (a) Block diagram of overall biofeedback system. BioNES forms the software part for the system, (b) Graphical user interface of BioNES, (c) Screenshot of NES game running in FCEUX. The biofeedback bar (current position is at bar = 4) is shown at the top of the in-game screen.

implementation of the "BioNES.ino" firmware on the Arduino. A hardware interrupt is used to capture the precise time intervals of the occurrence of the heartbeats. The interrupt service routine (ISR) is kept terse to faithfully catch all the interrupts while simultaneously rejecting the spurious interrupts due to high-frequency artifacts from the heart rate sensor. The previous data is stored until the fetch command is received from MATLAB over the COM port at a 10 Hz sampling rate.

Secondly, for the FCEUX, the "BioNES.lua" file contains the necessary functions that allow to take over the control of the emulator. It also makes the emulator as a TCP/IP client to MATLAB and periodically checks for commands (see Table 2) for displaying feedback or sending data to MATLAB. The flowchart in Fig. 2(b) details the implementation of the "BioNES.lua" file that runs within the emulator. In this process, the normal execution control of FCEUX is taken over by the Lua script, and commands from MATLAB are received over the TCP/IP port at a 60 Hz or 50 Hz sampling rate depending upon the NTSC or PAL video settings respectively within the emulator. The feedback is displayed by creating a bar within the game via directly manipulating the contents of the PPU (Picture Processing Unit) memory and using in-game sprites.

Thirdly, for MATLAB, the "BioNES.m" file creates the necessary GUI to interact with the biofeedback system. It initializes GUI as the master to Arduino and FCEUX. The researchers have to only interact with the BioNES GUI, and the rest of the system is programmatically controlled within MATLAB. Fig. 2(c) details the implementation of the main "BioNES.m" file in MATLAB. This process is semi-automatic requiring the user's intervention. MATLAB is designed for offline-data processing and is not optimized for designing real-time constrained applications. In our prior study [26], with designing a real-time biofeedback system with MATLAB, we have analyzed timing jitters with serial communication between MATLAB and Arduino and proposed a simple timing jitter correction mechanism to reliably acquire data from Arduino at precise intervals. The data and results are publicly available in the OSF repository[4]. The same timing jitter correction mechanism is employed in BioNES for acquiring the data from Arduino at set precise intervals. During acquisition, the initialization stage is responsible for displaying and initializing the GUI, connecting to Arduino and FCEUX. The recording stage is responsible for data acquisition, pre-processing of data, feature extraction, computing biofeedback parameters, and data visualization. The system sampling rate is recommended to be set below 20 Hz (default to 10 Hz) and can be adjusted via the settings panel of the GUI. The storage is accompanied by the post-processing of acquired data and the computation of various results.

2.2. Software functionalities

As per the researcher's preferences, the BioNES can run under three different modes namely: physiological data acquisition only, non-biofeedback gameplay and biofeedback enabled gameplay. Only one type of mode can run in a single session.

4 The performance benchmark data and results are publicly available at https://doi.org/10.17605/OSF.IO/VCTJM

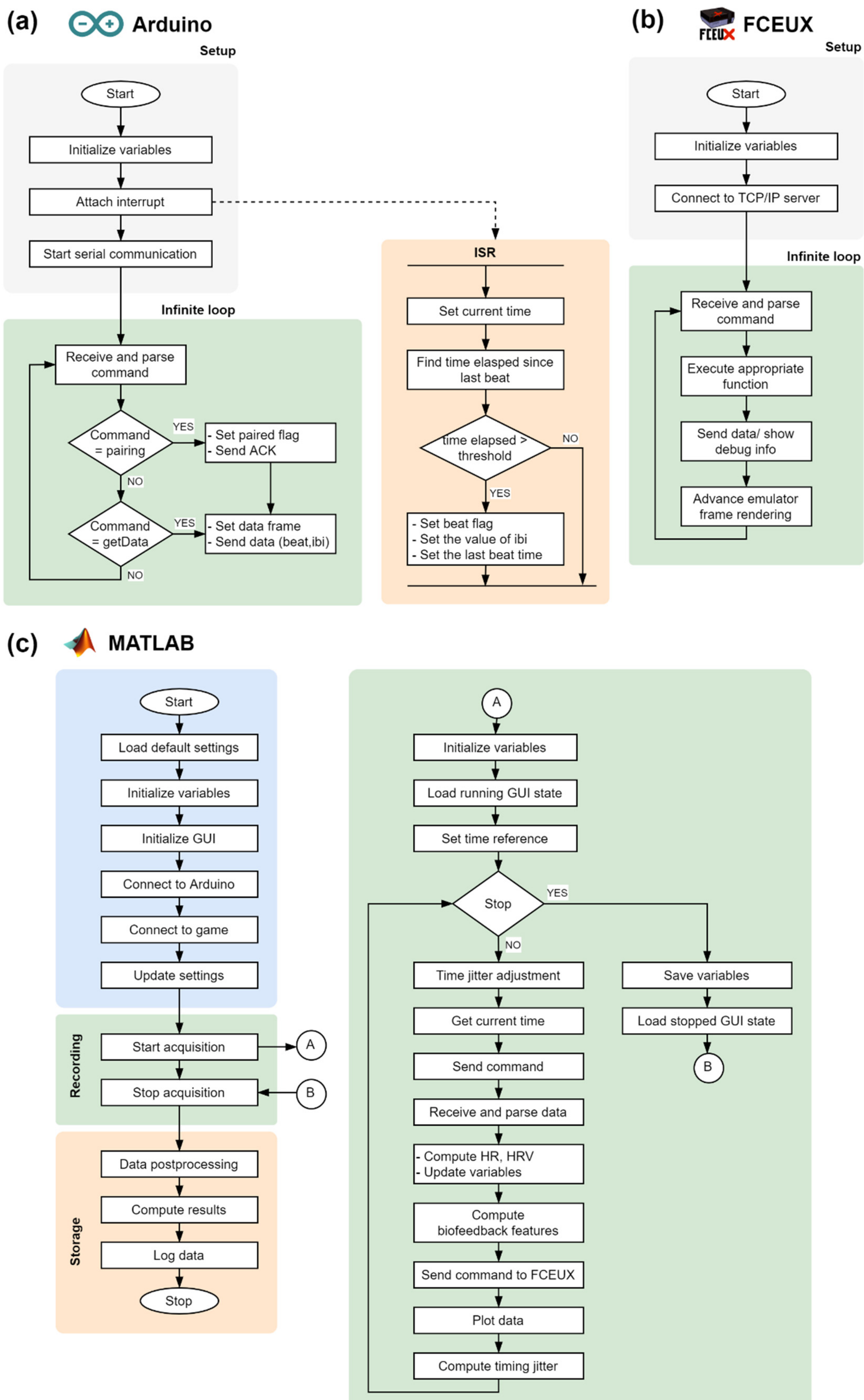

Fig. 2. Flowchart describing the implementation of the real-time processes at (a) Arduino, (b) FCEUX, and (c) MATLAB.

Table 1
Available custom functions in BioNES. The programmatically created GUI callback functions in BioNES.m are not listed but are documented in the file itself.

Function name	Description
In BioNES.ino file	
ReceiveParseCommand	Receive and parse commands from the serial port
Pairing	Handshake with MATLAB during pairing
GetData()	Create data packet and send over COM port
sensorPinHR_ISR()	ISR to run in the event of interrupt
In BioNES.lua file	
StartClient	Start TCP/IP connection and handshake with the server (MATLAB)
PassiveUpdate	Receive and parse commands from the TCP/IP port
memory.writebyteppu	Write a byte to the specific PPU memory location of the emulator
memory.writebyterangeppu	Write a range of bytes from the given starting location of the PPU memory
SetBar0 ∼ SetBar8	Set of 9 functions to set the level of output feedback bar
GetData	Create data packet and send over TCP/IP port
SetTimerZero	Set the game timer to zero (Result is in-game player dies)
SoundEffect	Auditory warning to the player
In BioNES.m file	
BioNES	Main function.
Help	Holds the callback functions of the help GUI.
CalculateResults	Calculates the final results like recorded session duration, sampling frequency, number of samples, and data quality.
connectArduino	Defines the logic to connect with the 'Arduino' board.
connectGame	Connect with the FCEUX and start the game.
GuiStates	Initialize the GUI sub-components as per various states.
InitializeVariables	Function file that initializes variables to their default state.
logSys	Log system state for debugging.
SetParam	Set color and text parameters for various GUI components.

Table 2
Custom commands for communication between MATLAB & Arduino and MATLAB & FCEUX.

HEX Command	Function	Description
MATLAB to Arduino		
0×20	Pairing	Send pairing request to Arduino
0xA0	GetData	Returns heartbeat status and latest IBI value
MATLAB to FCEUX		
0×00	Bar0	Show blinking full red bar
0×01	Bar1	Show red bar at level 1
0×02	Bar2	Show red bar at level 2
0×03	Bar3	Show red bar at level 3
0×04	Bar4	Show green bar at level 4
0×05	Bar5	Show green bar at level 5
0×06	Bar6	Show green bar at level 6
0×07	Bar7	Show green bar at level 7
0×08	Bar8	Show green bar at level 8
0×0B	GetData	Get data payload
0×0C	SetTimerZero	Set timer to zero
0×0D	SoundEffect	Show auditory warning
0×0E	Debug	For debugging purpose

2.2.1. Physiological data acquisition only

In this mode, the BioNES can record real-time HR and HRV. The biofeedback and game functions are not used and the rest of the functionality (data visualization and logging) remains the same. From Fig. 3, the steps (in chronological order) to use the BioNES for this mode are 1,2, and 5. The acquired RR intervals can contain high-frequency artifacts that arise due to a significant player's movement. The HRV is highly susceptible to these artifacts [27, 28] and thus the raw data is processed using a custom algorithm adapted from the literature [29]. Further, HRV is calculated as the root mean square of successive differences (RMSSD) (ms) values of last N (=2) beats from successive RR intervals (Eq. (1)). The median of RMSSD values taken over a sliding window of length M (=30) is used as the current averaged HRV value [30]. The M = 30 was an optimum balance between the lag (deep breathing and corresponding increase in HRV feedback) and artifact rejection (because of any spurious RR point). Similarly, the average (mean) HR is also calculated from the last M (=30) values of RR intervals taken over a sliding window [30].

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

2.2.2. Non-biofeedback gameplay

In this mode, the BioNES can be used to capture the real-time physiological signal while enabling the player to play the non-biofeedback version of the NES game. This mode is used to capture the effects of gameplay on the player's physiology (particularly stress arising due to gameplay) without biofeedback. From Fig. 3, the steps (in chronological order) to use the BioNES for this mode are 1, 2, 4, and 5.

2.2.3. Biofeedback enabled gameplay

In this mode, the BioNES is used to its full potential as a multimodal biofeedback system. The real-time physiological signals are captured and corresponding in-game feedback is shown to the player. From Fig. 3, the steps (in chronological order) to use the BioNES for this mode are 1, 2, 3, 4, and 5. The feedback is computed from the percentage deviation of the player's current HRV value from their baseline HRV value. The baseline HRV values strongly correlate with age [31], therefore feedback to each player is given based on their baseline HRV values only. The provision to adjust the upper and lower limit of the HRV threshold for computing feedback is provided in the BioNES GUI (see Fig. 3). The baseline values can be recorded by using BioNES in the data acquisition mode. The upper limit of the HRV baseline can be obtained by deep breathing, a protocol known to induce relaxation and increase HRV [32,33]. The lower limit of the HRV baseline can be obtained from any standardized stress test (like Stroop Color-Word Test [34]) that is known to induce mental stress and thus reduce the HRV [35].

From the baseline HRV (HRV_B) and stressed HRV (HRV_S), the percentage deviation (HRV_D) of current HRV (HRV_C) is computed (Eq. (2)) and translated to the in-game 9-level evenly-distributed horizontal top bar via linear adaptation functions (Eq. (3) and

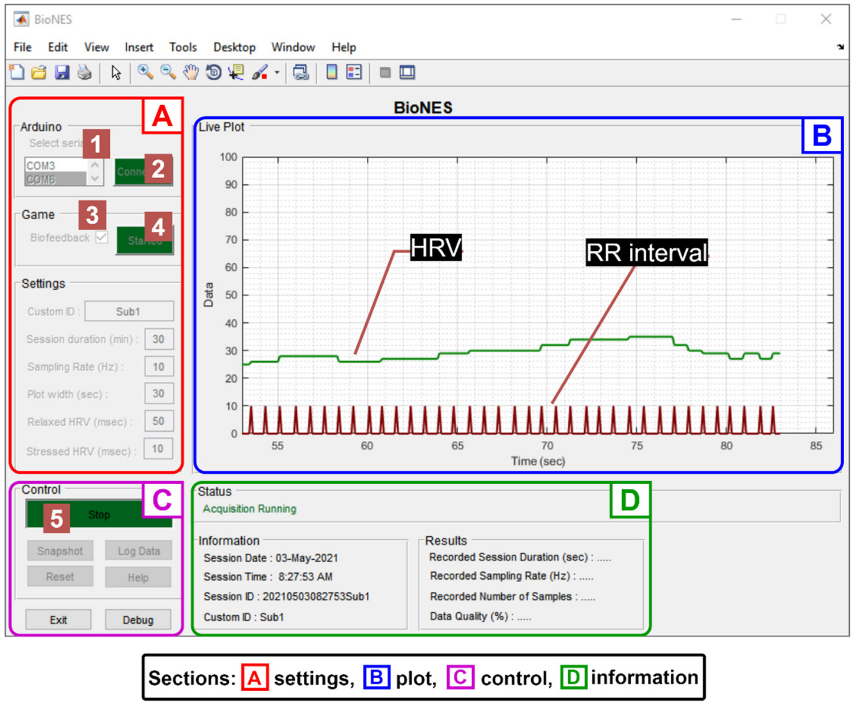

Fig. 3. GUI of BioNES. Sub-components are arranged into different panels (A, B, C, and D). Minimal steps to use BioNES in three different modes are also marked (1, 2, 3, 4, and 5)

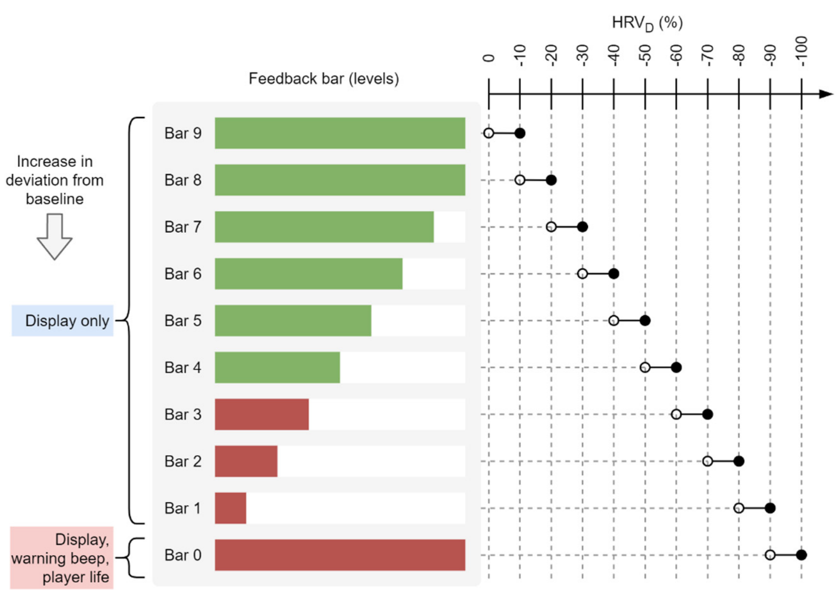

Fig. 4. Linear translation of HRV deviation (current HRV from baseline HRV) to different levels of in-game feedback bar. The increase in deviation of HRV from the baseline value corresponds to the descending order of bars. Bar 9 to bar 1, shows visual feedback only, whereas bar 0, shows visual feedback, audio feedback (after 10 s), and change in-game mechanics (loss of player life after 10 s)

Eq. (4)). Fig. 4 shows the feedback bar levels as per the HRV deviation and the associated game mechanics.

$$HRV_D = \frac{HRV_C - HRV_B}{HRV_B - HRV_S} * 100 \qquad (2)$$

$$HRV_D^{-} = \begin{cases} -100, & HRV_D < -100 \\ HRV_D, & -100 \leq HRV_D \geq 0 \\ 0, & HRV_D > 0 \end{cases} \qquad (3)$$

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

3. Illustrative examples

In this section, as an example, the walkthrough of the BioNES functioning in the biofeedback-enabled gameplay mode is presented. Fig. 5 shows the first author playing the SMB game with the BioNES. The PPG sensor, Data Acquisition Hardware (DAQ H/W), and in-game feedback are highlighted in the figure. The objective is to achieve the highest possible score in the game. Concurrently, the player has to keep the mental relaxation above a threshold level by deep breathing. The in-game feedback bar shows mental relaxation, where the higher deviation equals more stress and lower bar levels (see Fig. 4). First, as shown in Fig. 6,

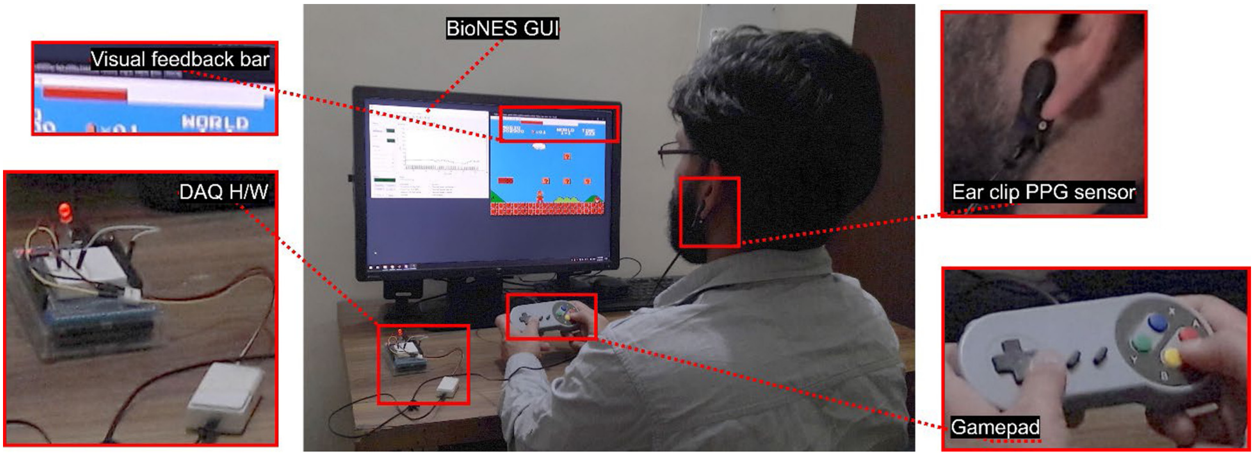

Fig. 5. The player interacts with the system during biofeedback intervention. The acquisition hardware is attached to the ear-lobe to acquire the PPG signal. The screen shows both the BioNES GUI and FCEUX window.

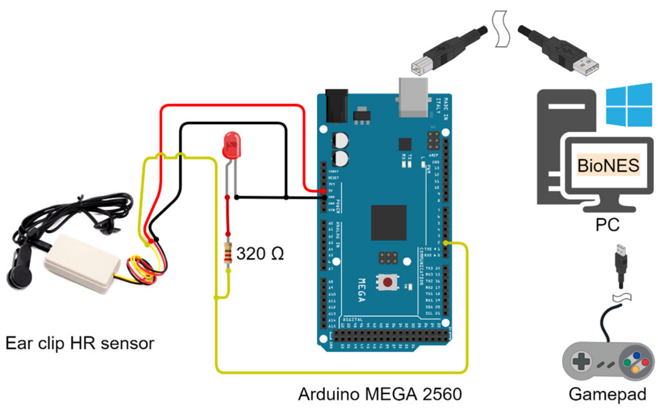

Fig. 6. Hardware setup for the data acquisition.

for the hardware setup, Grove - Ear-clip Heart Rate Sensor [36] is used which is a photoplethysmograph-based sensor and can be connected to the ear-lobe and has a digital output of HIGH and LOW indicating the presence and absence of the heartbeat. It is then connected to the digital pin D2 of Arduino MEGA. An LED with a current limiting resistor is used for visual indication to the researcher of the real-time heartbeat acquisition by the ear-clip sensor.

Next, BioNES is started from within the MATLAB by running "BioNES.m". The settings are automatically initialized to defaults. The SMB game file needs to be available in the ROMs folder of the FCEUX directory. Steps marked 1 to 5, as shown in Fig. 3 will start the biofeedback session. Fig. 7 presents the detailed sequence diagram for this example with the interaction between the user, Arduino, MATLAB, and FCEUX. A simple SNES-style USB gamepad is used to play the game. The PC used in the study was an HP workstation (HPZ440) with specifications of Intel Xeon E5-1607 v3 processor, 20 GB DDR5 RAM, NVIDIA Quadro K2200 4 GB graphics card running Windows 10 pro (64 bit) and MATLAB v2017. Finally, at the end of the session, the data can be logged locally to mat files for offline analysis. The MATLAB scripts available in the analysis folder can be used for the statistical analysis of acquired data. In the example, The BioNES is used four times for the four different conditions as briefly described below-

- Deep Breathing (DB) — Paced breathing is followed (6 breaths per minute) for 4 min to simulate a relaxed situation. The BioNES is used in the "Physiological data acquisition only" mode.
- Stress Test (CWT) — Stroop Color Word Test (CWT) [34] is followed for 4 min to simulate a stressful situation. The BioNES is used in the "Physiological data acquisition only" mode.
- NBF-Game (Control) — The participants played the SMB game with no biofeedback. The BioNES is used in the "Non-biofeedback gameplay" mode.
- BF-Game (Experiment) — The participants played a biofeedback version of the SMB game. The BioNES is used in the "Biofeedback enabled gameplay" mode.

Fig. 8 shows the modulation of Respiratory Sinus Arrhythmia (RSA) exhibited by the author across the four conditions for the first 50 samples in each. It is evident that the RSA is highly pronounced during the deep breathing and biofeedback enabled game and the RSA desynchronization occurs during the stress test and the original game. As RSA is an indicator of HRV and in turn the level of relaxation [32], the visual inspection of Fig. 8, confirms the relaxation effects of the biofeedback enabled SMB game in contrast to the original SMB game.

4. Impact

The main impact of BioNES is to give a boost to the biofeedback studies by making available an easy-to-deploy multimodal biofeedback software. Additionally, the use of the same NES games across different biofeedback studies can greatly improve the replicability of experiments and the comparison of results. Further use of popular NES games with simple gameplay mechanics can help to better understand the gamification of biofeedback sessions. Besides biofeedback, the understanding of physiological response (primarily stress) that arises due to game and game mechanics can be explored and results can be compared by using the same NES games across studies. Interestingly, on another side, the BioNES can be used to study the ZPD in the NES games. The availability of logging real-time game state variables can help to correlate the physiological response of the player to the instantaneous game-state/game-level and thus provides insights into the in-game stressors, player's position on the ZPD curve, and game-level design.

We have evaluated the efficacy of the BioNES as a multimodal biofeedback system for mental relaxation [25]. The study led to the understanding of stress response evoked by the original SMB game and how the game mechanics can be modified for biofeedback to help the player achieve relaxation and combat stress. In this study, a within-subjects crossover randomized design study with 16 participants was conducted. The biofeedback

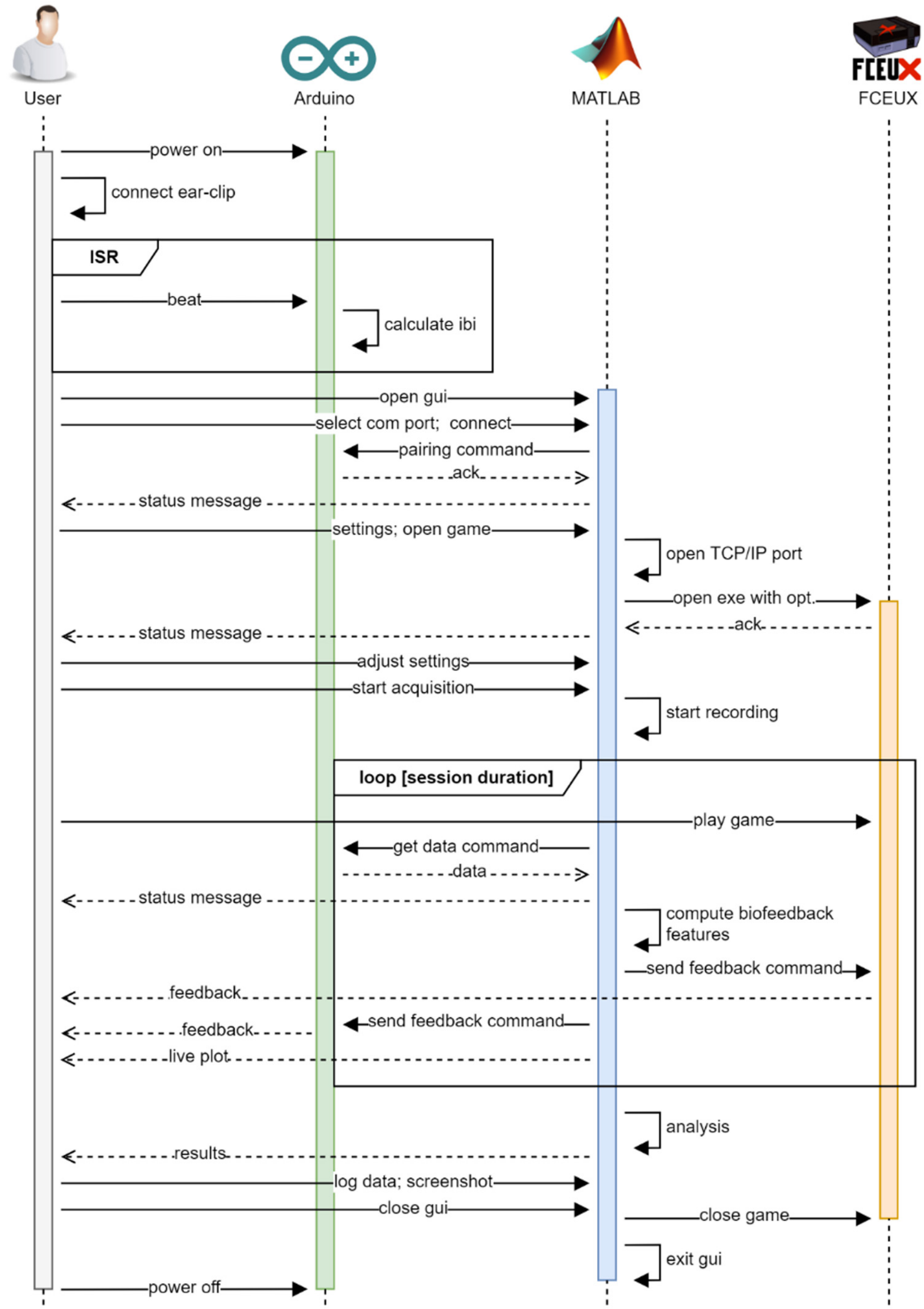

Fig. 7. Sequence diagram showing the interaction between the user, Arduino, MATLAB, and FCEUX for a biofeedback session.

version (experiment) of the SMB game was compared with the original/non-biofeedback version (control) of the SMB game. The average HRV of the participants during the intervention was used as the repeated measure to compare the level of relaxation among various groups. The participant reported significantly higher relaxation during the biofeedback version (experiment) of the SMB game than the original/non-biofeedback version (control) of the SMB game (Control) ($t(15) = 9.14$, $p < 0.0001$, 95% CI (3.84, 7.66), $d_z = 2.29$). The same study also evaluates the engagement of the SMB game using Octalysis analysis which showed a significant influence of the development and accomplishment core drive and avoidance core drive. For this reason, the corresponding game mechanics, "number of player's lives" and "keep the health bar above 0th level" falling under these core drives respectively were chosen to modify during the biofeedback process.

Besides biofeedback, we use BioNES for HR/HRV acquisition for our preliminary studies. Apart from in-lab use by researchers, the users can play biofeedback-enabled NES games to learn relaxation skills for better stress management in their daily lives.

5. Conclusions

The BioNES is developed for researchers in the biofeedback domain looking for a simple plug-and-play multimodal biofeedback system employing video games as a delivery mechanism. The capability of real-time heartbeat acquisition, HR and HRV calculation, real-time data display, and using any NES game for biofeedback delivery makes it an excellent tool for quickly testing different biofeedback protocols. Its efficacy, intrinsic motivation,

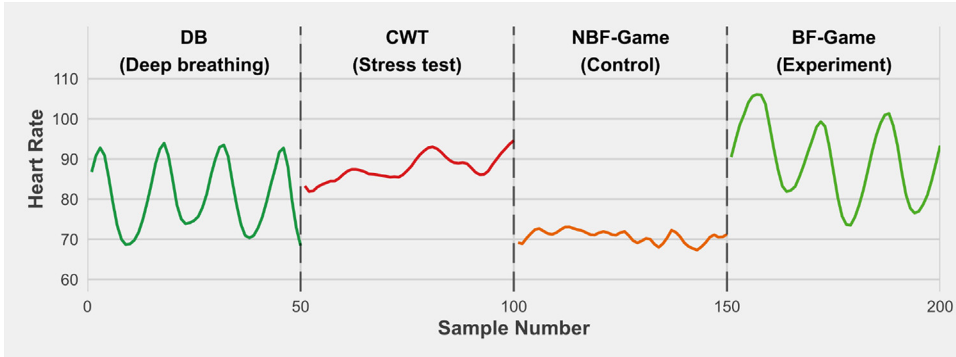

Fig. 8. Respiratory Sinus Arrhythmia (RSA) was exhibited by the author during the illustrative example. The RSA is pronounced in the DB and Experiment conditions, whereas desynchronization occurs in both CWT and control conditions.

and system usability as a multimodal biofeedback system for mental relaxation have been validated via randomized controlled trials. Besides biofeedback, it can be also be used as a simple data acquisition software, which further expands its area of use. With its simple GUI, researchers with no programming experience can easily execute biofeedback sessions without the need to write any code. Its modular design offers flexibility for advanced researchers to add enhancements to the BioNES as per their needs. We expect that BioNES with its lesser cost, availability as open-source, and use of standardized NES games can be a worthy tool in the biofeedback studies.

CRediT authorship contribution statement

Kulbhushan Chand: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Arun Khosla:** Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.softx.2022.101184.

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