BioPad: Leveraging off-the-Shelf Video Games for Stress Self-Regulation

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***Abstract*—This paper presents an approach to use commercial videogames for biofeedback training. It consists of intercepting signals from the game controller and adapting them in real-time based on physiological measurements from the player. We present three sample implementations and a case study for teaching stress self-regulation via an immersive car racing game. We use a crossover gaming device to manipulate controller signals, and a respiratory sensor to monitor the players' breathing rate. We then alter the speed of the car to encourage slow deep breathing, in this way, allowing players to reduce their arousal while playing the game. We evaluate the approach against an alternative form of biofeedback that uses a graphic overlay to convey physiological information, and a control condition (playing the game without biofeedback). Experimental results show that our approach can promote deep breathing during gameplay, and also during a subsequent task, once biofeedback is removed. Our results also indicate that delivering biofeedback through subtle changes in gameplay can be as effective as delivering them directly through a visual display. These results open the possibility to develop low-cost and engaging biofeedback interventions using a variety of commercial videogames to promote adherence.**

***Index Terms*—Biofeedback, respiration, stress, video games.**

I. Introduction

STRESS has deleterious effects on the mind and the body [1]. It plays a major role in the development of mental disorders and neurodegenerative diseases [2], is associated with a greater risk of developing chronic disease (e.g., cardiovascular disease, diabetes [3], [4]), and contributes to the obesity epidemic [5]. Not surprisingly, stress is considered a major public health problem, as serious as infectious diseases, and one that invades our homes and workplaces [6]. Several traditional interventions exist for stress reduction (e.g., cognitive-behavioral therapy, mindfulness), but they require significant time and resources [7]. Technological interventions have also been developed. For example, biofeedback may be used to help patients increase awareness of involuntary autonomic responses to stress. However, biofeedback can be non-intuitive and monotonous.

To improve the appeal of biofeedback, several studies have examined the possibility of combining biofeedback with video games [8]–[13]. Biofeedback games measure the players' physiology (e.g., cardiovascular variables) and then adapt the game (e.g., difficulty, mechanics) to encourage players to maintain a desirable physiological state. However, developing custom biofeedback games is costly, and cannot provide many choices over game genres to maintain the patients' interest.

To address this issue, we present *Biofeedback Gamepad* (BioPad), an approach to leverage off-the-shelf video games for biofeedback training purposes, in this way avoiding the costly process of custom game development. BioPad can work with different games and gaming platforms, providing patients with abundant choices. It monitors the players' physiology during gameplay, and manipulates signals from the game controller accordingly. With minimal effort, researchers can develop new interventions that use different physiological signals, game genres, and adaptation functions for the game controller.

This paper describes an implementation of BioPad using a crossover gaming device to intercept signals from the game controller. We present three sample applications of BioPad for biofeedback training. We also present a case study in which BioPad is integrated with an immersive car racing game and a respiratory feedback loop that encourages the player to control their breathing rate (BR). By using an immersive racing game, we create a contextualized learning environment in which the training process is coupled with stress to facilitate the acquisition of stress management skills [9]. Using respiration rate as feedback modality allows players to practice deep breathing, a skill known to reduce the impact of stress [14]. We evaluate the effectiveness of BioPad in reducing BR during treatment and during a subsequent, more difficult task, as compared to the standard game without biofeedback. BioPad provides biofeedback indirectly, through subtle changes in game mechanics. As such, it has the potential to increase arousal levels–rather than reduce them, since it requires players to perform two tasks in addition to playing the game: inferring their BR, and maintaining it. Thus, we also evaluate BioPad against respiratory biofeedback provided in a more direct fashion through a graphic overlay [11].

The paper is organized as follows. Section II reviews the literature on biofeedback games. Section III describes the system design, sample applications, and its implementation to encourage self-regulation of BR with an immersive racing game.

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Sections IV and V describe our experimental setup and results from a user study. We conclude with a discussion of results and directions for future work.

II. Background

A. Biofeedback and Stress Self-Regulation

Biofeedback is an evidence-based technique that helps individuals control body functions by displaying physiological variables in real time. Through biofeedback, patients learn to trigger relaxation responses and control involuntary stress responses. Stress is associated with imbalances in autonomic regulation [15]. A standard measure of autonomic balance is heart rate variability (HRV); lowered HRV is associated with increased sympathetic activity and decreased parasympathetic activity, both being indicators of stress. Interventions that augment HRV have been shown to reduce stress, and may also protect against cardiac mortality [16]. Deep breathing, in particular, is an effective method to increase HRV and reduce stress; one can modulate HRV voluntarily with their breathing: heart rate increases with inhalation and decreases with exhalation. When breathing at a frequency around 6 breath cycles per minute, the cardiovascular system is rhythmically stimulated and HRV is maximized [17]. Biofeedback can help patients acquire breathing skills through self-correction, aiming to increase HRV and reduce both perceived stress and physiological responses to stress [18]–[20].

B. Biofeedback Games for Relaxation Training

Video games have been used with biofeedback to facilitate treatment for a variety of medical conditions and adherence to treatment regimens. Several studies have proposed creating biofeedback games for relaxation training. Vilozni *et al*. [21] designed a game to improve children's performance in spirometry. In the game, children controlled an animated critter with their breathing, and learned breathing skills while playing. Leahy *et al.* [22] developed a game to teach relaxation for patients with irritable bowel syndrome–a stress related disorder. Changes in stress were displayed as computer animations. Their approach was shown to be rapid and effective in teaching deep relaxation. Gromala *et al*. [23] developed a virtual reality (VR) biofeedback system to teach patients to manage stress and pain via meditation. Patients walked on foggy VR trails; when they approached an inferred meditative state, the fog began to dissipate and the sound became more audible and spatial. Essentially, biofeedback in this kind of games amounts to displaying physiological signals using visually-pleasing graphics and animations. Other studies have used physiological signals to change game mechanics or controls. For example, Sharry *et al*. [24] developed a two-player racing game to treat anxiety in children. In the game, each player controls a dragon whose speed is decided by the player's relaxation level; the player who is more relaxed wins the game. More recently, Parnandi and Gutierrez-Osuna [13] developed Chill-Out, an adaptive game for mobile platforms that promotes deep breathing by monitoring the player's BR. Chill-Out penalizes fast breathing by making the game harder, thus encouraging player to maintain a low BR. Also recently, Sonne *et al*. [25] presented ChillFish, a biofeedback game for breath training. ChillFish uses a game controller made from LEGO pieces, with a thermistor built inside to monitor breathing activities. Players control the position of a fish avatar in a video game by inhaling and exhaling through the LEGO controller. Schnädelbach *et al*. [26] developed ExoBuilding, a tent-like structure whose size and lighting changed in response to the user's physiology. Their experiments showed that spending time in ExoBuilding led to relaxing experiences. Biofeedback games have also been used in military applications. For example, Bouchard *et al*. [9] tested the efficacy of biofeedback games for stress management training among soldiers. Soldiers were asked to practice tactical breathing while immersed in a stressful first-person shooter game that provided both visual and audio feedback of their arousal levels. The approach was effective in reducing stress during the live and stressful simulation, suggesting that the stress-training process should be coupled with stressors. Unfortunately, these prior efforts require development of specialized games, which can be costly.

C. Biofeedback With off-the-Shelf Video Games

A handful of studies have examined using commercial video games for biofeedback. Using commercial games is appealing, since it avoids the costly process of developing customized games. Pope *et al.* [27] first proposed the idea of blending biofeedback with off-the-shelf video games. The authors presented a hardware solution to modulate a PlayStation controller using electroencephalography (EEG). The game controller became more responsive when players produced faster beta waves, and more sluggish with slower delta waves. The system had a substantial therapeutic effect on ADHD symptoms, and was also rated to be more enjoyable than standard neurofeedback training. However, their approach was limited to the PlayStation console and EEG signals. More recently, Walther-Franks *et al*. [28] designed Exercise My Game (XMG), a framework to turn off-the-shelf videogames into exercise games. They used a virtual joystick device driver (vJoy) to emulate a joystick and integrated it with a Kinect. XMG detects the user's full-body motion patterns based on the skeletal recognition provided by the Kinect SDK; these patterns are then mapped onto traditional joystick input patterns, thus motivating players to carry out physical exercises while playing games. Also recently, Mandryk *et al.* [11] proposed a technique that uses a textured graphic overlay to display physiological signals. When participants are not in the desired physiological state, the textures obscure the game scene, making it harder and less enjoyable to play. The authors conducted a 12-week user study with children suffering from fetal alcohol spectrum disorder (FASD), using EEG as the biofeedback modality. Though the effectiveness of the approach as a treatment for FASD remains to be established, results from the study indicate that it can hold the child's attention over a long treatment.

In summary, prior work has shown that biofeedback games can be used as an alternative to traditional biofeedback training.

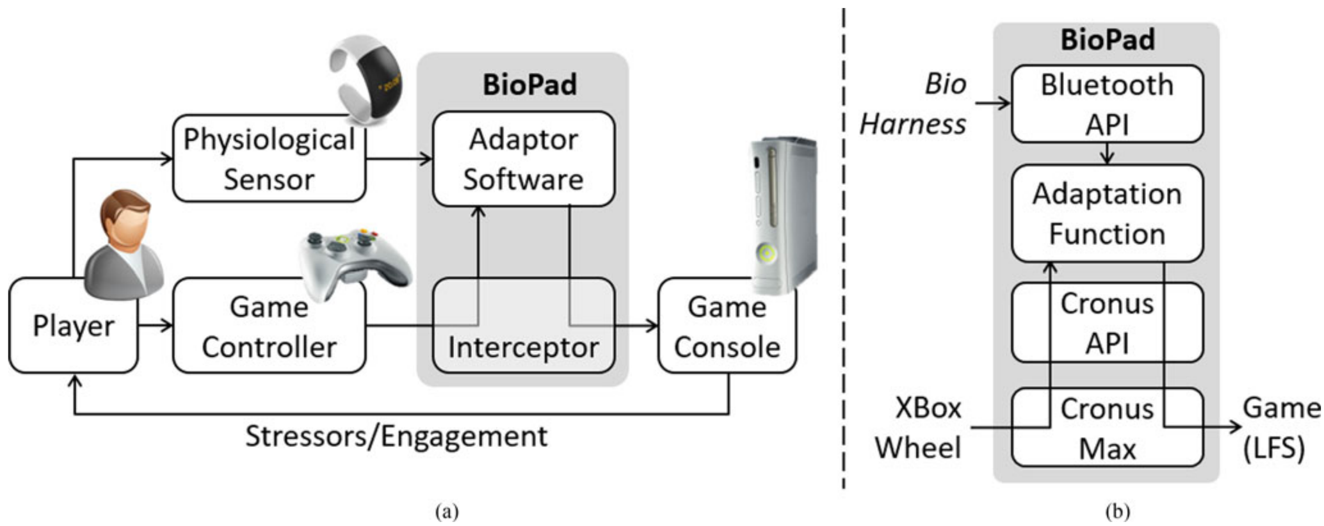

Fig. 1. (a) Hardware setup: signals from the game controller are intercepted and adapted based on the player's physiology. (b) Control software and APIs.

Several attempts have been made towards leveraging existing video games, but we are not aware of prior studies that use crossover gaming devices a generic solution to turn existing games into biofeedback games.

III. System Design and Applications[1]

A. System Framework

Fig. 1(a) illustrates our overall approach. At its core is BioPad, a hardware/software solution consisting of two key modules: the Interceptor and the Adaptor.

The Interceptor is a hardware device that captures signals from the gamepad controller before they reach the game console. The interceptor provides full access to controller signals, allowing us to modify the game mechanics. Commercial interceptors are designed for cross-over gaming (i.e., playing with a game controller that does not match a game console); thus, these devices are designed to be compatible with multiple game consoles and controllers. This feature enables BioPad to adapt to most existing games. As an example, our system uses a crossover device, the CronusMax[2], which is compatible with Sony PlayStation, Microsoft Xbox, Nintendo Wii, as well as PCs with standard keyboard and mouse input.

The Adaptor is a desktop software module we developed (in C++). It captures game controller signals and player physiological signals as inputs, modifies the controller signals according to an adaptation function, and sends them back to the interceptor, which then relays them to the game console. The adaptor uses APIs to communicate with the physiological sensors (via Bluetooth) and with the controller–see Section III-C for details. The adaptation function changes the controller signals in response to the player's physiological signals, which in turn changes the game mechanics. The *Adaptor* also logs time stamps, controller data, physiological data, and visualizes them on a GUI. The GUI allows the experimenter to select among various predefined adaptation functions based on their needs. Adaptation mechanisms include introducing random button presses, linearly changing button values, reversing control axes, changing the control sensitivity, and adding jitter to directional controls. The GUI also allows the experimenter to change the parameters of the adaptation functions. Various sensors can be integrated with Biopad to target different health concerns, as long as the physiological signals can be processed in real time; e.g., accelerometers to estimate physical activity in exercise games, EEG to estimate attention in interventions for ADHD, or HRV in interventions for stress.

Our design is robust to signal transmission and data processing delays. First, BioPad runs two asynchronous parallel threads: one to process sensor data and another to intercept game controller inputs. If data packets are lost, BioPad maintains the controller at the previous state until a new data packet is received; timestamps from the different devices are synchronized relative to the same PC clock prior to each experiment. Second, Biopad uses an aggregated physiological response, computed over several seconds, to modulate the game mechanics[3]. While rapidly changing biosignals (e.g., EEG, EDA) allow faster adaptation rates[4], changing game mechanics too often would disrupt the player. Thus, even when a fast physiological sensor is used, an aggregate response over several seconds is recommended.

B. Sample Applications

Here we describe three sample applications to illustrate the ability of BioPad to leverage existing games for biofeedback.

1) Biofeedback Tetris Game: The first application is a clone of the Tetris game that is played on a PC using the arrow

[1]Source code is available on https://github.com/wzlxjtu/BioPad.

[2]CronusMax is a crossover device that allows players to use their preferred game controller across multiple consoles. It can also be used to apply various "mods" to commercial games, and remap buttons to any custom configuration.

[3]BioPad requests data from physiological sensors at a fixed sampling rate of 1 Hz. We chose this sampling rate since Bluetooth devices typically have transmission delays significantly below 1 sec (around 150 ms).

[4]In these situations, it would be essential to calibrate the transmission delays of each sensor, so that the sensor data streams could be time aligned.

keys. We use BioPad to intercept keyboard inputs and introduce random arrow-key presses when the player's physiology deviates from the target state. This adds random movements to the game pieces, thus increasing the game difficulty. This is a form of stress training, and has been shown to be effective in reducing arousal and lead to a relaxed state [12], [13]. BioPad could also be extended to a multitude of PC games that are played using the keyboard, e.g., Minecraft, FIFA. In these games, BioPad could be used to change the movements of the avatar and other game characteristics based on player's physiology.

2) Biofeedback Typing: Like the previous example, this application uses the PC keyboard as the input. It is designed to allow the player to practice biofeedback while typing. Namely, the adaptation function introduces random presses to letter keys when the user deviates from the desired physiological states. Such exercises can be used to practice biofeedback while playing competitive touch-typing games (e.g., TypeRacer), and also during routine computer tasks.

3) Biofeedback Racing Game: The third sample application is based on racing games that use Xbox controllers. We use BioPad to intercept the controller signal, and apply several adaptations, e.g., adding steering jitter, changing car speed. The remainder of this manuscript describe this application in greater detail as an intervention for stress self-regulation.

C. Case Study: Stress Self-Regulation With a Car Racing Game

1) Choice of Game: Based on our prior work [29], we decided to use an immersive car racing game for stress training. Car racing games are also intuitive and simulate a stressor (e.g., driving) that most individuals experience in real life. We used the game *Live for Speed*[5], which provides a first-person view and a driving experience that has been praised as highly realistic. We set up a gaming environment with a driving cockpit (Playseat Evolution) and an Xbox steering wheel.

2) Choice of Physiological Signal: A number of physiological signals can be used for biofeedback, including breathing rate (BR), heart rate variability (HRV), electrodermal activity (EDA), or a combination of these, e.g., a multimodal stress index. Based on our prior work [13], we chose BR since it outperforms HRV and EDA for game based stress management interventions that require a limited training period. In fact, breathing exercises (e.g. deep breathing, pranayama) are intuitive evidenced-based methods for reducing stress [30]. Deep breathing activates the parasympathetic branch of the autonomic nervous system (ANS), which lowers heart rate and creates a feeling of relaxation. Prior work [17] has shown that breathing at 6 breaths/min maximizes HRV. Finally, in contrast with EDA and HRV, which are primarily controlled by the ANS and are not directly under user's control, respiration can be controlled voluntarily. This makes the intervention easier to learn and practice. We monitor respiration with a BioHarness 3 (Zephyr Tech), connected to the Adaptor module via Bluetooth.

[5]Live for Speed: https://www.lfs.net/.

3) Adaptation Function: We designed the adaptation function to reward slow BRs during gameplay. The function modifies the controller signals based on an intensity value I derived from the player's respiration rate R (in cycles per minute; cpm):

$$I = \begin{cases} 0 & R < 8 \\ (R-8)/12 & 8 \le R \le 20 \\ 1 & R > 20 \end{cases} \quad (1)$$

Below 8 cpm, BioPad does not apply any modification[6]. Between 8-20 cpm, the intensity of the modification increases linearly; beyond 20 cpm, BioPad applies the highest modification ($I = 1$) to the controller signal.

The Cronus API provides access to all the Xbox controller signals, each allowing us to alter the game mechanics in a unique way. We evaluated changing several game mechanics for biofeedback, including steering jitter, steering sensitivity, and car speed. Early on, we found that adding steering jitter could lead to motion sickness, while increasing the control sensitivity and car speed made the game hard to play as it led to frequent car collisions. In contrast, we found that reducing the car's speed increased the game's playability and also had a calming effect. Therefore, we used an adaptation function that would slow the car whenever the players' breathing was high.

We manipulate the car's speed by linearly changing the values of the Gas (G) and Brake (B) pedals according to (2). When $I = 0$, no modification is applied, and players can drive naturally. As $I > 0$, we reduce G and increase B; both pedals are in the range of $[0,\ 100]$. Thus, the higher the value of I, the lower the acceleration and the higher the braking, which slows down the car. When $I = 1$, players are unable to accelerate at all ($G = 0$), and the car stops quickly because of the brake ($B = 100$). We derived (2) through experimentation; model parameters can be adjusted flexibly from the software GUI.

$$\begin{aligned} G &= \max\ (G - 150 \times I,\ 0) \\ B &= \min\ (B + 30,\ 100) \quad if\ I > 0 \end{aligned} \quad (2)$$

The software includes two additional components: BioHarness communication and CronusMax interfacing; see Fig. 1(b). We communicate with the BioHarness using a Bluetooth protocol provided by the manufacturer. It opens a communication channel following a request/response format; when the BioHarness receives a specified request message, it responds with actions (e.g., set date, get battery status) or returns periodic data packets, including BR, heart rate and body temperature. In our implementation, we set the Bluetooth channel to transfer summary data packets at 1 Hz. We communicate with CronusMax using an API developed by the manufacturer. The Cronus API provides a programming interface for applications to receive input data from supported game controllers and send commands to game consoles in real time. The Cronus API reads the Xbox controller data as a data array, which we then modify before sending it to the game.

[6]While the optimal BR is around 6 cpm–see Section II. A, we used a more conservative target of 8 cpm since playing the game can be challenging. Based on prior studies [18], 8 cpm is also a more feasible goal for a single training session, particularly when players are not familiar with deep breathing.

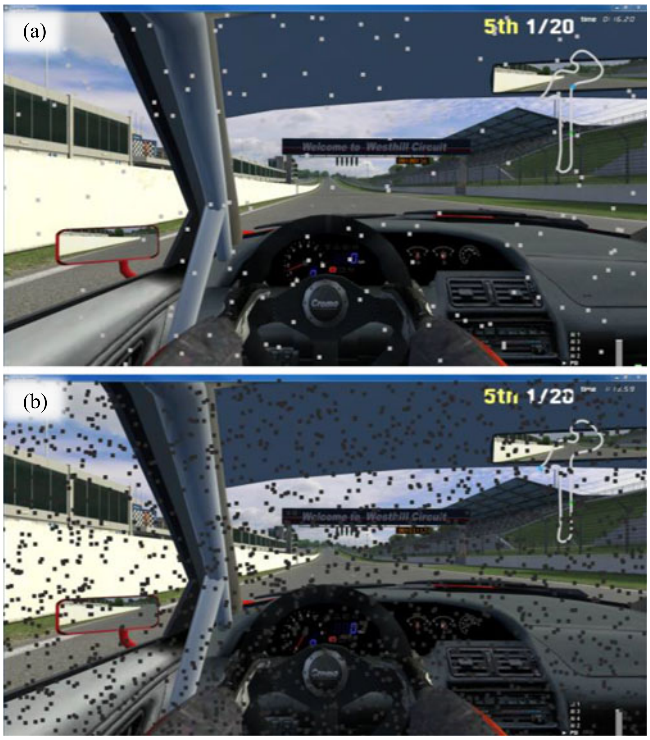

Fig. 2. Texture overlay for intensity values of (a) $I = 0.1$ and (b) $I = 1$. In (b), 1800 particles are rendered, which cover only a small portion on the screen.

D. Experimental Control

BioPad provides biofeedback indirectly through subtle changes in game mechanics. This requires the player to perform two tasks in addition to the game: inferring their BR from changes in the speed of the car, and then maintaining their BR below threshold. As such, there is the potential for our intervention to increase arousal levels – rather than reduce them. To guard against this possibility, we decided to compare BioPad against an alternative form of biofeedback [11], in which respiratory biofeedback is provided in a more direct fashion through a graphic overlay. Our implementation uses the Microsoft DirectX graphics libraries. It places a transparent window on top of the game window, and renders salt-and-pepper noise at random positions. As the intensity level I increases, the number of particles rendered on the screen changes linearly from 0 to 1800, and also the RGB value (8 bits) of each particle from [200,200,200] to [40,40,40]; see Fig. 2. The overlay is updated once per second, and was designed to introduce a nuisance without blocking the field of the view.

IV. User Study

We conducted a user study to validate our implementation of the adaptive car-racing game. Participants were randomly assigned to one of three experimental groups: BioPad, Overlay, or Control. The BioPad group received the speed biofeedback intervention (see Section III-C), whereas the Overlay group received the graphic overlay biofeedback intervention (see Section III-D); the Control group played the game without biofeedback. The experiment lasted 1 hour and consisted of four phases:

- ***Deep breathing (DB).*** Participants were fitted with physiological sensors, then were asked to practice DB for 5 min with an audiovisual pacing signal. The pacing signal was set to 6 cpm (4s inhalation, 6s exhalation), in accordance to prior studies [31] showing that short inspiration followed by long expiration leads to higher HRV than the opposite. This phase allowed us to collect physiological signals at baseline and instruct participants on how to perform DB.
- ***Pre-test.*** Participants played the game using a relatively easy racing track[7] (Westhill National) for 5 min, *without* biofeedback. This phase allowed participants to familiarize themselves with the game, and allowed us to measure their stress responses prior to treatment.
- ***Treatment.*** Participants received instructions specific to their group (see Section IV-A below), then were asked to play the game on the easy track for 20 min. The BioPad group received the speed intervention as biofeedback, the Overlay group received graphic overlay as biofeedback, and the Control group received no biofeedback.
- ***Post-test.*** Participants played the game on a relatively harder racing track (Blackwood GP) for 5 min, with four AI cars as competitors to increase the challenge level. No biofeedback was applied to any group in this phase. This was designed to test whether training effects extended beyond the training conditions, when tasks were executed without biofeedback.

Participants (N = 33) were students from Texas A&M Univ., recruited via email and flyers. No participant reported major health issues. One participant reported motion sickness while playing, so her experiment was terminated. Data from two participants were corrupted due to sensor issues. We discarded these data, and used the remaining 30 participants (10 in each group), aged 19-28 years (mean: 23.1; SD: 2.3; 29 males). We received approval from the Institutional Review Board prior to the study and informed consent from each participant.

A. Instructions

Upon arrival, we told each participant that the purpose of the experiment was to evaluate the effects of video games on stress. At the start of deep breathing, we asked participants to focus on the pacing signal, which was presented on a tablet using a free app (Paced Breathing; Trex LLC). At the start of pre-test, we showed participants how to play the game, then allowed them to practice freely. At the start of treatment, we announced to the participants that their game performance would be evaluated, and that their game score would be based on their *fastest* lap time. These instructions encouraged participants to improve their lap times while being forgiving of crashes or a few slow laps. BioPad and Overlay participants were told to breathe at 6 cpm, and were informed of the effect that BR had on their respective biofeedback intervention; Control participants received

[7]Throughout the experiment, we used a car model (FXO GTR) that is easy to control but fast and fun to drive. To improve immersiveness, we delivered audio from the game (e.g., engine sounds) using headphones.

no breathing instructions. At the start of post-test, BioPad and Overlay participants were told to breathe slowly and remain calm, but were not informed that the biofeedback was cancelled; for consistency, control participants did not receive additional instructions other than to play the game.

B. Measurements

As noted earlier, we measured respiration and R-R series with a BioHarness 3 chest strap. As an independent measure of stress, we also used EDA, recorded with a FlexComp Infiniti (Thought Technology Ltd.). Since the participants' hands were occupied with the steering wheel and the right foot with the accelerator/brake pedal, we attached disposable electrodes to the arch of the left foot[8]. We used HRV and EDA features as indicators of stress. We measured HRV as the root mean square of successive R-R differences (RMSSD)[9], as recommended in [16]. Likewise, we extracted EDA features using the discrete deconvolution algorithm in Ledalab [34] on raw EDA data, and then computed the sum of skin conductance response amplitude ($\mathrm{SCR_{amp}}$) over a 1-min window (units: μS/min) [35]. $\mathrm{SCR_{amp}}$ quantifies autonomic arousal level and correlates with the area under the curve of the skin conductance signal. Lower $\mathrm{SCR_{amp}}$ is indicative of relaxation.

V. Results

We compared the three groups based on their BR, HRV and $\mathrm{SCR_{amp}}$ using one-way Analysis of Variance (ANOVA). Post-hoc t-tests were performed for pairwise comparisons. Repeated one-way ANOVA and paired-samples t-tests were performed within each group to test significant time effects (difference between time/phases within group). Data from the initial 50 sec in each phase were excluded to avoid transients. To remove outliers, we conducted Grubb's test for different physiological modalities separately before each statistical test. The criterion for statistical significance was set to $p \leq 0.05$. For multiple comparisons (post-hoc t-tests), we use Bonferroni correction, which alters the criterion to $p \leq 0.05/3 \approx 0.017$.

A. Breathing Rate

Fig. 3(a) shows the time course of the BR for all participants, averaged by group. During DB, the three groups were able to maintain a BR of 6 cpm; see Fig. 3(d) for averages per phase. One-way ANOVA shows that the BRs across the three groups were not statistically different during DB ($F(2, 24) = 0.77$, $p = 0.47$), indicating that all participants were able to follow the pacing signals correctly. During pre-test, the average BR increases for the three groups, but differences across groups are not significant ($F(2, 24) = 0.41$, $p = 0.67$), as one would expect. During treatment, however, we observe large statistical differences across the three groups ($F(2, 24) = 44.9$, $p<0.01$). Post-hoc t-tests (with Bonferroni correction) show that the BR of the two treatment groups (BioPad, Overlay) is significantly lower than that of the Control group: ($t(17) = 7.61$, $p<0.01$), and ($t(15) = 6.52$, $p<0.01$), respectively. BRs for both treatment groups fluctuate around 8 cpm, but are not statistically different ($t(16) = -0.33$, $p = 0.74$). During post-test, BRs for the three groups are still statistically different ($F(2, 24) = 11.98$, $p<0.01$). As in the treatment phase, BRs for the two treatment groups are significantly lower than those of the Control group: ($t(17) = 3.83$, $p<0.01$), and ($t(15) = 4.17$, $p<0.01$), respectively. BRs for the two treatment groups are higher during post-test than during treatment, and show an increasing trend over time. This suggests that, though the effect carries over a more difficult task, it is also short lived. Differences between the two treatment groups at post-test are not statistically significant: ($t(16) = -0.04$, $p = 0.74$). In summary, these results indicate that the two forms of biofeedback (BioPad, Overlay) can elicit a significant reduction in BR during treatment, and that the effects carry over temporarily to a follow-on task.

B. Heart Rate Variability

Fig. 3(b) shows the time course of the normalized HRV for all participants; HRV values were log transformed since they were not normally distributed. To remove individual differences, we applied min-max normalization within subject so that each value is a proportion of the individualized range. During deep breathing, HRV across the three groups is similar ($F(2, 24) = 0.01$, $p = 0.99$). During pre-test, the average HRV decreased for the three groups; see Fig. 3(e). This is to be expected since the racing game is a challenging task that reverts the participants' BR to their normal values, if not elevates it due to the challenge. HRV across the three groups are not statistically different during pre-test ($F(2, 24) = 0.56$, $p = 0.58$). During treatment, HRV of the control group remains low, while HRV of the two treatment groups increase as a consequence of the lower BR elicited by the two biofeedback loops; one-way ANOVA: ($F(2, 24) = 4.79$, $p<0.02$). Post-hoc t-tests show that HRV of the BioPad group is marginally statistically higher than the control group ($t(17) = -2.20$, $0.017<p<0.05$), HRV of the Overlay group is statistically higher than the control group ($t(15) = -3.94$, $p<0.01$), but HRV of the Overlay group is not statistically different from the BioPad group ($t(16) = -0.51$, $p = 0.61$). During post-test, HRV is not significantly different across the three groups: ($F(2, 24) = 1.12$, $p = 0.34$). In summary, the analysis shows that our biofeedback method increases HRV during the treatment, but the statistical effect is marginal.

C. Skin Conductance Response

Fig. 3(c) shows the time course of normalized EDA for all participants, whereas Fig. 3(f) shows the $\mathrm{SCR_{amp}}$. As with HRV, we removed individual differences in $\mathrm{SCR_{amp}}$ by applying min-max normalization. One-way ANOVA across groups shows no statistical differences in any phase;

[8] Dooren and Janssen in [32] has shown that the foot is well-suited for recording EDA data. Notice also that multiple arousal theory [33] suggests that EDA responses from the left and the right side of the body may not be interchangeable, thus we used the left foot consistently.

[9] Frequency based analysis like the LF/HF ratio may not be applicable because participants are asked to breathe at 6 cpm (0.1Hz), which falls inside the LF range (0.04Hz - 0.15Hz). Thus, in our case, the LF/HF ratio is likely to increase rather than decrease with parasympathetic activation.

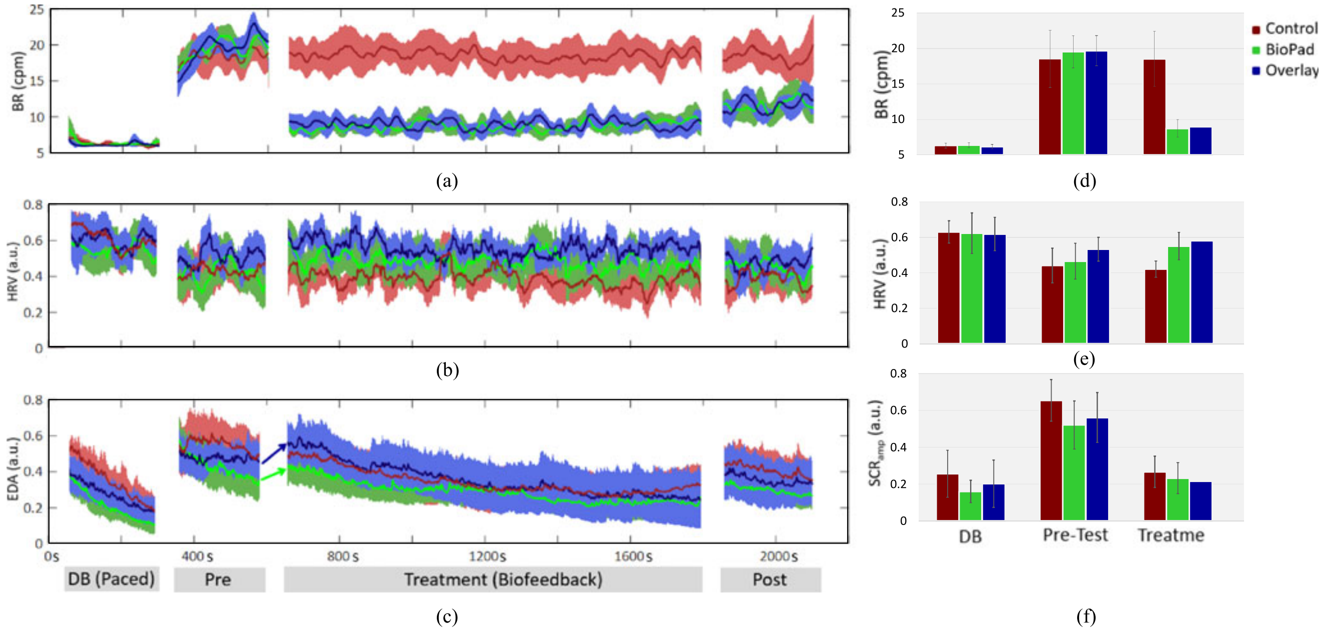

Fig. 3. Left column: Realigned time course of (a) BR, (b) normalized HRV and (c) normalized EDA, averaged across participants. The center line represents the average, whereas the width of the shaded region represents one standard deviation. Right column: (d) average BR, (e) average HRV after min-max normalization, (f) average $\mathrm{SCR}_{\mathrm{amp}}$ after min-max normalization, for each phase. Error bars represent one standard deviation. Min-max normalization was applied per subject.

DB: $F(2,24) = 0.50$, $p = 0.61$; Pre-test: $F(2,24) = 0.74$, $p = 0.49$; Treatment: $F(2,24) = 0.18$, $p = 0.84$; Post-Test: $F(2,24) = 0.95$, $p = 0.40$. Within group, however, we observe that $\mathrm{SCR}_{\mathrm{amp}}$ vary across phases; see Fig. 3(f). We confirm this variation by conducting one-way ANOVA with repeated measures on $\mathrm{SCR}_{\mathrm{amp}}$ for each group separately. The results show statistically significant effects of time for the three groups; Control: $F(3,27) = 5.77$, $p<0.01$; BioPad: $F(3,27) = 8.21$, $p<0.01$; Overlay: $F(3,18) = 3.60$, $p = 0.03$. $\mathrm{SCR}_{\mathrm{amp}}$ follow a similar pattern for the three groups: an initially low level during deep breathing, followed by an increase during pre-test, a steady decrease during treatment, and a modest increase at post-test. The transition from pre-test to treatment shows a sudden increase in $\mathrm{SCR}_{\mathrm{amp}}$ for the two biofeedback groups, but not for the control group; see arrows in Fig. 3(c). This result is consistent with the fact that both biofeedback groups have to perform an additional task during treatment (i.e., controlling their BR), and that sudden voluntary changes in breathing can significantly increase $\mathrm{SCR}_{\mathrm{amp}}$ [36]. It is therefore a positive result that the three groups show a similar, steady decline in $\mathrm{SCR}_{\mathrm{amp}}$ over the course of the 20 min treatment. Two conclusions can be extracted from this result. First, adding a secondary task to the car racing game (i.e., controlling one's respiration) does not increase $\mathrm{SCR}_{\mathrm{amp}}$, which otherwise would be an indication of added arousal. Second, the additional effort of having to infer one's respiration rate through the game (as BioPad requires the player to do) does not appear to have detrimental effects, as compared to the easier task of inferring one's respiration from the graphic overlay. Altogether, these results indicate that the two treatment conditions do not induce additional stress compared to the standard game (Control).

VI. Discussion

We have presented BioPad, a tool to leverage off-the-shelf video games for biofeedback training. BioPad is compatible with virtually all existing games due to the generic interface of the interceptor. With minimum effort, developers can add new adaptation functions to change game mechanics in different ways and integrate BioPad with other physiological sensors to target different health issues. Players can use BioPad in a plug-and-play manner for various games and switch between different modes via the software GUI.

We compared BioPad against an alternative approach that uses a graphic overlay to display physiological information to the player. The main advantage of BioPad is that it provides a wider range of options for adaptation (potentially as many as control inputs in the game), whereas overlays only provide one form of feedback (visual). Taking the example of our racing game, manipulating the acceleration yields a very different game experience than manipulating the steering. This allows the user to practice biofeedback under a variety of gameplay conditions. Moreover, being able to use different control inputs allows researchers to design the biofeedback in a way that blends more naturally with the genre of the game. An additional advantage is that BioPad can be used with any game console (e.g., Xbox, PlayStation) since it only requires access to the controller signals, whereas graphic overlays manipulate video output, and are therefore unusable on most game consoles.

Both biofeedback groups (BioPad, Overlay) maintained a low BR during treatment, though not as regular as during the initial DB session. This result is to be expected since the DB session provided an audiovisual pacing signal that participants could follow, whereas no pacing signal was provided during treatment so participants would internalize the target BR. Evidence of this internalization is that the two biofeedback groups have lower BRs at post-test, even after 5 min of difficult racing with competing cars and without biofeedback. However, BRs for the two biofeedback groups increases steadily during post-test, so one would expect that they eventually return to their normal values. This tendency may be countered with sustained practice.

The two biofeedback tasks introduce additional challenges to the players, who not only play the game but also have to keep their BRs under control. Thus, at the onset of the study we were concerned that the added complexity would make the game hard to play. In particular, we wondered if the BioPad treatment would prove too challenging, since the player has to infer their BR from subtle changes in the speed of the car, which is not only harder but also introduces a time lag. An additional reason for caution was that the two forms of biofeedback could lead to frustration, visual noise in Overlay, and reduced speed in BioPad. Would these two issues (added task complexity, and potential frustration) prevent players from learning to control their BRs in a single session? While this is possible, and indeed several participants reported that it was challenging to control breathing while playing, our results show that players in the two biofeedback groups do manage to keep their BRs at target. Our results also show no difference in EDA among the two biofeedback groups, for whom EDA decline steadily during treatment. This decrease is not attributable to the biofeedback, however, since a similar decrease also occurs in the control group. Instead, the decrease is likely due to habituation[10].

A potential criticism is our approach may affect the effectiveness of breathing exercises, which reduce stress partially by inducing an increased focus on internal sensations and a relative neglect of external stimuli. Hence, combining breathing exercises with video games forces the player to multi-task, which may prevent an inward focus. Note, however, that our goal is not to teach to relax in isolation but *while* performing a task. As such, coupling relaxation exercises with a stressor is a form of contextualized learning.

Our study focused on BR as the single parameter that players had to control. Our choice was based on prior studies showing that slow, deep breathing can lead to relaxation. One limitation of our study is that it assumed that the optimal BR was identical for all subjects. While our subjects were all young adults (college students), the optimum BR is subject dependent; breathing at one's resonant frequency can maximize the relaxation effects [17]. Thus, an interesting future direction is to customize the BR to match each subject's resonant frequency, possibly coupled with behavioral shaping techniques to help subjects reach that goal. Future experiments may also go beyond a single session and use various games, so subjects may learn to automatically slow their breathing when exposed to stressors. Future studies may also explore effects of the controller type, which is shown to influence game experience [38]. Several other respiratory parameters may also be explored, such as inhalation/exhalation (I/E) ratios and depth of breathing. For example, a recent study [39] has shown that participants breathing at a low I/E ratio reported increased relaxation, stress reduction and positive energy compared to participants breathing at a high I/E ratio. Other physiological parameters may also be explored, depending on their suitability for the health concern and target population. Our study used a sample of convenience but future studies may target specific health concerns (e.g., stress disorders). Future studies may also elucidate dosage and persistence effects of the intervention, and the role that multiple games play in promoting adherence.

[10]An alternative explanation, that EDA decline reflected epidermal mechanisms not associated with emotional deactivation [37], is less likely since EDA increase again at post-test.

VII. Conclusion

Motivated by the demand for affordable and enjoyable biofeedback methods, we have developed BioPad, a hardware/software solution for both developers and players to integrate biofeedback training with off-the-shelf video games. We have described the framework design and illustrated three sample applications. We evaluated BioPad for teaching stress self-regulation through an immersive car racing game. The biofeedback intervention consists of measuring the player's BR during gameplay and modifying the car's speed to reward slow, deep breathing. Our study shows that BioPad successfully reduced participants' BRs and physiological stress during the game. In summary, BioPad provides a generic solution to leverage off-the-shelf video games for biofeedback training and offers new possibilities to change existing games. BioPad can be an effective alternative to traditional forms of biofeedback or custom biofeedback games.

References

[1] L. Sonia *et al.*, "Effects of stress throughout the lifespan on the brain, behaviour and cognition," *Nature Rev. Neurosci.*, vol. 10, pp. 434–445, 2009.

[2] T. Esch *et al.*, "The role of stress in neurodegenerative diseases and mental disorders," *Neuro Endocrinol. Lett.*, vol. 23, pp. 199–208, 2002.

[3] C. Sheldon *et al.*, "*Chronic stress, glucocorticoid receptor resistance, inflammation, and disease risk*," *Nat. Acad. Sci.*, vol. 109, pp. 5995–5999, 2012.

[4] K. T. Larkin, *Stress and Hypertension: Examining the Relation Between Psychological Stress and High Blood Pressure*. New Haven, CT, USA: Yale Univ. Press, 2005.

[5] M. Dallman, "Stress-induced obesity and the emotional nervous system," *Trends Endocrinol. Metabolism*, vol. 21, pp. 159–165, 2010.

[6] M. DeVries and B. Wilkerson, "Stress, work and mental health: A global perspective," *Acta Neuropsychiatrica*, vol. 15, pp. 44–53, 2003.

[7] G. Henriques *et al.*, "Exploring the effectiveness of a computer-based heart rate variability biofeedback program in reducing anxiety in college students," *Appl. Psychophysiol. Biofeedback*, vol. 36, pp. 101–112, 2011.

[8] D. Bersak *et al.*, "Intelligent biofeedback using an immersive competitive environment," in *Proc. Des. Ubiquitous Comput. Games Workshop at UbiComp*, 2001. [Online]. Available: https://pdfs.semanticscholar.org/a614/57caf4c1a75db4276352f5b93eb0e046e807.pdf

[9] S. Bouchard *et al.*, "Using biofeedback while immersed in a stressful videogame increases the effectiveness of stress management skills in soldiers," *PloS One*, vol. 7, p. e36169, 2012.

[10] K. Kuikkaniemi *et al.*, "The influence of implicit and explicit biofeedback in first-person shooter games," in *Proc. Conf. Hum. Factors Comput. Syst.*, 2010, pp. 859–868.

[11] R. L. Mandryk *et al.*, "Games as neurofeedback training for children with FASD," in *Proc. Interact. Des. Children Conf.*, 2013, pp. 165–172.

[12] A. Parnandi *et al.*, "Chill-out: Relaxation training through respiratory biofeedback in a mobile casual game," in *Proc. 2014 Int. Conf. Mobile Comput., Appl. Serv.*, pp. 252–260.

[13] A. Parnandi and R. Gutierrez-Osuna, "Physiological modalities for relaxation skill transfer in biofeedback games," *IEEE J. Biomed. Health Informat.*, vol. PP, p. 1, 2015.
[14] R. Jerath *et al.*, "Physiology of long pranayamic breathing: Neural respiratory elements may provide a mechanism that explains how slow deep breathing shifts the autonomic nervous system," *Med. Hypotheses*, vol. 67, pp. 566–571, 2006.
[15] G. G. Berntson and J. T. Cacioppo, "Heart rate variability: Stress and psychiatric conditions," M. Malik and A. J. Camm, Eds., in *Dyn. Electrocardiogr.*, Futura, New York, pp. 57–64, 2004.
[16] Task Force of the European Society of Cardiology, "Heart rate variability: Standards of measurement, physiological interpretation and clinical use," *Eur. Heart J.*, vol. 17, pp. 354–381, 1996.
[17] E. G. Vaschillo *et al.*, "Characteristics of resonance in heart rate variability stimulated by biofeedback," *Appl. Psychophysiol. Biofeedback*, vol. 31, pp. 129–142, 2006.
[18] R. Bhandari *et al.*, "Music-based respiratory biofeedback in visually-demanding tasks," in *Proc. Int. Conf. New Interface Musical Expression*, 2015, pp. 78–82.
[19] R. Reiner, "Integrating a portable biofeedback device into clinical practice for patients with anxiety disorders: Results of a pilot study," *Appl. Psychophysiol. Biofeedback*, vol. 33, pp. 55–61, 2008.
[20] L. Sherlin *et al.*, "Effects of respiratory sinus arrhythmia biofeedback versus passive biofeedback control," *Int. J. Stress Manage.*, vol. 16, pp. 233–248, 2009.
[21] D. Vilozni *et al.*, "An interactive computer-animated system (SpiroGame) facilitates spirometry in preschool children," *Amer. J. Resp. Crit. Care Med.*, vol. 164, pp. 2200–2205, 2001.
[22] A. Leahy *et al.*, "Computerised biofeedback games: A new method for teaching stress management and its use in irritable bowel syndrome," *J. Roy. Coll. Phys. Lond.*, vol. 32, pp. 552–556, 1997.
[23] D. Gromala *et al.*, "The virtual meditative walk: Virtual reality therapy for chronic pain management," in *Proc. Conf. Hum. Factors Comput. Syst.*, 2015, pp. 521–524.
[24] J. Sharry *et al.*, "Relax to win: Treating children with anxiety problems with a biofeedback video game," *Eisteach*, vol. 2, pp. 22–26, 2003.
[25] T. Sonne and M. M. Jensen, "ChillFish: A respiration game for children with ADHD," in *Proc. 10th Int. Conf. Tangible, Embedded, Embodied Interact.*, 2016, pp. 271–278.
[26] H. Schnädelbach *et al.*, "ExoBuilding: Physiologically driven adaptive architecture," *ACM Trans. Comput.-Hum. Interact.*, vol. 19, 2012, Art. no. 25.
[27] A. Pope and O. Palsson, "Helping video games 'rewire our minds'," presented at the Playing by the Rules Conf., University of California, Santa Barbara, CA, USA, 2001.
[28] B. Walther-Franks *et al.*, "Exercise my game: Turning off-the-shelf games into exergames," in *Proc. Int. Conf. Entertainment Comput.*, 2013, pp. 126–131.
[29] A. Parnandi and R. Gutierrez-Osuna, "A comparative study of game mechanics and control laws for an adaptive physiological game," *J. Multimodal User Interfaces*, vol. 9, pp. 31–42, 2014.
[30] R. Jerath *et al.*, "Physiology of long pranayamic breathing: Neural respiratory elements may provide a mechanism that explains how slow deep breathing shifts the autonomic nervous system," *Med. Hypotheses*, vol. 67, pp. 566–571, 2006.
[31] G. Strauss-Blasche *et al.*, "Relative timing of inspiration and expiration affects respiratory sinus arrhythmia," *Clin. Exp. Pharmacol. Physiol.*, vol. 27, pp. 601–606, 2000.
[32] M. van Dooren and J. H. Janssen, "Emotional sweating across the body: Comparing 16 different skin conductance measurement locations," *Physiol. Behav.*, vol. 106, pp. 298–304, 2012.
[33] R. Picard *et al.*, "Multiple arousal theory and daily-life electrodermal activity asymmetry," *Emotion Rev.*, vol. 8, pp. 62–75, 2016.
[34] M. Benedek and C. Kaernbach, "A continuous measure of phasic electrodermal activity," *J. Neurosci. Methods*, vol. 190, pp. 80–91, 2010.
[35] D. R. Bach *et al.*, "Analytic measures for quantification of arousal from spontaneous skin conductance fluctuations," *Int. J. Psychophysiol.*, vol. 76, pp. 52–55, 2010.
[36] R. Schneider *et al.*, "Respiration-related artifacts in EDA recordings: Introducing a standardized method to overcome multiple interpretations," *Psycholog. Rep.*, vol. 93, pp. 907–920, 2003.
[37] D. C. Fowles and R. E. Schneider, "Effects of epidermal hydration on skin conductance responses and levels," *Biolog. Psychol.*, vol. 2, pp. 67–77, 1974.
[38] M. Birk and R. L. Mandryk, "Control your game-self: Effects of controller type on enjoyment, motivation, and personality in game," in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.*, 2013, pp. 685–694.
[39] I. Van Diest *et al.*, "Inhalation/exhalation ratio modulates the effect of slow breathing on heart rate variability and relaxation," *Appl. Psychophysiol. Biofeedback*, vol. 39, pp. 171–180, 2014.