Physiological Modalities for Relaxation Skill Transfer in Biofeedback Games

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***Abstract*—We present an adaptive biofeedback game for teaching self-regulation of stress. Our approach consists of monitoring the user's physiology during gameplay and adapting the game using a positive feedback loop that rewards relaxing behaviors and penalizes states of high arousal. We evaluate the approach using a casual game under three biofeedback modalities: electrodermal activity, heart rate variability, and breathing rate. The three biosignals can be measured noninvasively with wearable sensors, and represent different degrees of voluntary control and selectivity toward arousal. We conducted an experiment trial with 25 participants to compare the three modalities against a standard treatment (deep breathing) and a control condition (the game without biofeedback). Our results indicate that breathing-based game biofeedback is more effective in inducing relaxation during treatment than the other four groups. Participants in this group also showed greater retention of the relaxation skills (without biofeedback) during a subsequent stressor.**

***Index Terms*—Biofeedback, breathing rate (BR), electrodermal activity (EDA), heart rate variability (HRV), skill transfer, stress, video games, wearable sensors.**

I. Introduction

MENTAL stress is a global epidemic that can have serious health consequences [1]. It contributes to obesity and is a risk factor for a number of chronic diseases, such as high blood pressure, diabetes, and cardiovascular diseases—the leading cause of death in the developed world [1], [2]. A number of techniques are available to teach relaxation skills, including cognitive behavioral therapy, mindfulness, meditation, deep breathing (DB), and biofeedback techniques [3]. Among these, biofeedback has been shown to be particularly effective in assisting individuals increase awareness of the underlying physiological processes and gain voluntary control over them [4]. In a typical biofeedback session, electrodes are attached to the patient's body to monitor key physiological variables, and the resulting signals are displayed on a computer monitor, while the patient performs relaxation exercises under the supervision of a therapist. As with other stress management interventions, biofeedback requires substantial commitment of time and other resources from both workers and employers [5], which may result in high dropout rates [6], [7]. More importantly, biofeedback and other stress-reduction techniques teach patients to regulate their stress response in a quiet relaxed environment, a skill that may not transfer to stressful high-stakes scenarios, where it is really needed [8].

To address these issues, we propose an intervention that combines the appeal of video games [9] and the availability of wearable sensors to allow individuals to practice biofeedback-based stress reduction anywhere, anytime [10]. Our approach consists of monitoring the patient's physiological signals during gameplay, and adapting the game in a way that rewards relaxing behaviors. Unlike conventional biofeedback training, where feedback is explicit (e.g., a visual display of the patient's physiology), our approach provides an implicit form of feedback through subtle changes in gameplay. This approach offers two key advantages. First, it allows patients to focus on the gameplay experience rather than on monitoring their physiological signals, which makes the training far more engaging (i.e., stealth learning). More importantly, it teaches patients to self-regulate their stress response, while performing a task that is known to increase arousal (i.e., a video game) [11], a form of contextualized learning that promotes skill transfer to real-world scenarios.

In this paper we describe a general framework for rewarding relaxation behaviors via *game biofeedback (GBF)*, and discuss various physiological indices of stress that can be measured noninvasively with commercial wearable sensors. We present a prototype implementation of our approach and three biofeedback modalities with different degrees of selectivity and voluntary control: electrodermal activity (EDA), heart rate variability (HRV), and breathing rate (BR). At the one end, EDA can be considered to be highly selective of stress—eccrine (sweat) glands are exclusively innervated by the sympathetic branch of the autonomic nervous system, but under poor voluntary control. At the other end, BR rate is not directly indicative of stress—though states of high stress are known to cause hyperventilation, but can be under complete voluntary control. Halfway across, HRV is partially selective—as it is under the influence of both autonomic branches: sympathetic and parasympathetic, and is also under partial voluntary control—through respiratory sinus arrhythmia (RSA). As such, these three modalities allow us to examine tradeoffs in the selectivity versus voluntary-control space. We evaluate the effectiveness of the three GBF modalities to teach stress self-regulation skills during gameplay and promote skill transfer.

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II. Related Work

A. Video Games and Biofeedback

Video games have been used to facilitate treatment for a variety of medical conditions [12] and to promote physical fitness in the general population [13]. The appeal of video games stems from their ability to increase the user's motivation and engagement, which is particularly beneficial when the treatment involves painful procedures (e.g., chemotherapy) or is intrinsically boring and repetitive (e.g., physical therapy) [12]. At one extreme, video games can be incorporated in a way that requires only minor modifications to the treatment. In a study Russoniello *et al.* [14] found that playing casual video games alone could decrease stress levels; a follow-up study on using video games to reduce anxiety reported compliance rates unusually large for other interventions [15]. At the other extreme, video games can be fully integrated into the treatment; as an example, racing games have been used in combination with exercise equipment to keep patients with various motor impairments motivated during physical therapy [16]. Video games have also been combined with biofeedback techniques to treat specific conditions. Vilozni *et al.* [17] developed a video game that taught breathing skills to children; in the game, the player controlled an animated critter with their breathing, measured with a spirometer. Herndon *et al.* [18] developed a biofeedback game to help children with voiding dysfunction learn to control their pelvic floor muscles.

A few authors have also explored biofeedback games to help patients regulate the impact of stress. Leahy *et al.* [19] developed a game to teach deep relaxation to patients with irritable bowel syndrome, a condition to which stress is a major contributor. Their results show that most patients learned to reach a relaxed state after four 30-min biofeedback sessions and reported a reduction in bowel symptom scores. Note, however, that the game was equivalent to biofeedback techniques because stress levels were only used for visualization purposes. Several commercial systems employ similar strategies to make biofeedback more intuitive by transforming biosignals into visually pleasing graphics and animations. While such elaborate biofeedback displays may be more appealing than visualizing raw signals, much more could be gained if biofeedback was fully integrated into a dynamic game [20]. As an example, Sharry *et al.* [21] developed *Relax to Win*, a biofeedback game to treat children with anxiety disorders. In the game, two players enter a race in which the speed of each player's avatar (a dragon) increases with the player's ability to relax, as measured with EDA; however, only anecdotal evidence was provided to support the effectiveness of the game.

B. Physiological Interfaces

Biofeedback-based games have strong connections with the area of physiological interfaces [22]–[24]. Research in this area is aimed at developing human–computer interfaces that adapt in response to the user's psychophysiological state to improve either task performance or user experience. Within the broad area of physiological interfaces, the subfield of adaptive automation is particularly relevant to our research. Adaptive automation [25], [26] is concerned with maintaining an optimal level of vigilance in tasks that combine human and automatic monitoring (e.g., flying an airplane). In these scenarios, a high degree of automation can reduce the operator's vigilance and engagement with the task, whereas low levels of automation can result in excessive workloads. To address this problem, adaptive automation operates as a negative feedback loop, where task allocation to the operator is increased if she/he becomes hypovigilant and is decreased whenever the operator's workload becomes too high.

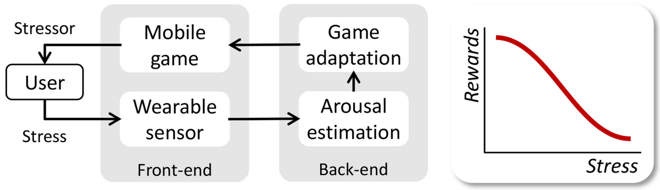
Finally, interest in physiological interfaces has exploded over the last decade, as demonstrated by the increased availability of low-cost commercial sensors for consumers [27], [28]. As an example, brain–computer interfaces have been incorporated into commercial games [29], and a variety of wearable sensors exist, from heart rate (HR) monitors [30] to skin conductance sensors [31] for fitness enthusiasts and the like. Research with physiological sensors has expanded to include topics such as fitness games [32], human activity recognition [33], as well as health monitoring [34].

C. Biofeedback and Skill Transfer

A handful of studies have explored whether relaxation skills learned with biofeedback transfer to new scenarios, where biofeedback is not present [35]–[37]. In an early study, Larkin *et al.* [36] examined the role of HR feedback and contingent reinforcement in reducing cardiovascular responses to stress; in contingency reinforcement, the game score was jointly determined by the participants' game performance and their ability to keep a low HR. As a second objective, the study also sought to determine whether reduced HR reactivity learned during training would generalize to a second task not employed during training. For this purpose, the authors divided participants into four groups depending on whether or not they received biofeedback, while playing the game (groups 1–2) and based on combined reinforcement score contingency (group 3) or solely by performance (group 4). They found that participants who received combined score and HR feedback showed a significant reduction in HR reactions in postassessment tasks (game without feedback and a novel mental arithmetic challenge). These results lead the authors to conclude that HR feedback during training facilitates the simultaneous learning of two tasks: improved game performance and reduced HR reactivity.

In a later study, Goodie *et al.* [35] trained participants to lower their HR, while performing three tasks (video game, mental arithmetic, handgrip) with HR feedback, then asked participants to repeat the three tasks and a new task (spontaneous speech) without HR feedback. Results from the study, however, show that HR reductions obtained with biofeedback training transfer when the same tasks are performed without biofeedback immediately after training, but do not transfer to a new task or when the three tasks are conducted after a short delay (1–2 days). The authors concluded that limitations in skill transfer may be due to topographic differences between the training task and the novel task, and suggested that successful skill transfer may require training using a variety of stressors that mimic real-world scenarios.

In a more recent study, Bouchard *et al.* [37] assessed the effectiveness of auditory and visual biofeedback in an immersive video game that aimed to teach tactical breathing (a stress



(a) (b)

Fig. 1. (a) System overview with its four main building blocks: mobile game, wearable sensor, stress estimation, and game adaptation. (b) Rewarding states of relaxation through gameplay.

management skill) to soldiers. In particular, the authors sought to determine whether relaxation practice in the presence of a stressor is more effective than conventional classroom training (i.e., formal description of techniques followed by brief practice). Study participants were soldiers with prior basic stress management training; they were divided into two groups: a treatment group and a control group. The treatment group participated in three sessions (one 30-min session per day) of immersive first-person shooter game followed by a stressful medical simulation for testing. Audio-visual biofeedback was provided during gameplay but not during testing. In turn, the control group received a 15-min briefing on stress management training on the first day, followed by testing on the 15th day. The authors found the biofeedback gaming method to be more effective in reducing stress during testing than the control group, as measured through salivary cortisol and HR. They also reported that the treatment group had significantly better task performance (identifying the appropriate treatment to a severe chest wound) than the control group during testing.

III. System Description

Our proposed system for GBF comprises of four basic components: a mobile video game and a wearable sensor at the front-end, and game adaptation and arousal estimation algorithms at the back-end [see Fig. 1(a)]. During an intervention, patients play the video game, while their physiological state is measured with a wearable sensor. At the back end, raw sensor signals are converted in real time into an estimate of the patient's stress level, which is then used by a game-adaptation engine to modify certain properties of the game (e.g., difficulty, randomness).

As illustrated in Fig. 1(b), the key element in the intervention is for the game to adapt in a way that rewards states of relaxation and penalizes stress. This is an unconventional strategy since it can lead to system instability (i.e., if the player's stress increases the game becomes more difficult, which in turn creates additional stress for the player); it also runs counter to techniques for dynamic difficulty adjustment [38], where one seeks to keep the player engaged regardless of their skill levels (i.e., by adjusting game difficulty based on the player's performance). Note, however, that the main objective of the intervention is not to entertain but to help patients learn to self-regulate their stress response were the game to be adapted in the opposite direction (i.e., by reducing difficulty with increased stress as done in [39]) it would not challenge patients to maintain control of their stress response.

TABLE I
Characteristics of the Three Physiological Signals

	EDA	HRV	BR
Arousal selectivity	High	Medium	Low
Voluntary control	Low	Medium	High

A. Arousal Estimation

A number of physiological correlates of stress have been identified, including EDA [40], electroencephalography (EEG) [41], HRV [42], pupillary fluctuations [43], BR [44], and biomarkers, such as cortisol and alpha amylase [45]. Among these, EDA, HRV, and BR appear ideally suited for our purpose as they can be measured inconspicuously with wearable sensors—critical in ambulatory settings, can produce a continuous measure of stress—also critical for gameplay adaptation, and are relatively robust to environmental disturbances.[1] As discussed in Section I, these three measures also allow us to examine tradeoffs in their selectivity toward stress and degree of voluntary control; see Table I.

1) Electrodermal Activity: EDA reflects changes in conductance at the skin surface due to activation of the sweat glands. Unlike most other organs, sweat glands are innervated exclusively by the sympathetic nervous system. As such, EDA is a relatively selective measure of arousal [47]. EDA is affected by a number of brain centers[2] [48] and is considered to be independent of voluntary/cognitive control. Though individuals are generally unable to voluntarily influence EDA [49], classical and instrumental conditioning techniques can be used to gain some degree of control over the EDA response; (see [40, Sec. 3.1.2]).

The EDA response consists of two components: 1) a slowly changing offset known as the skin conductance level which is highly subject dependent, and 2) a tonic response in the form of transient peaks known as skin conductance responses (SCR) that occur in reaction to startle events, cognitive activity, emotion arousal, and also spontaneously, in which case they are referred to as nonspecific [see Fig. 2(a)]. Our system uses the tonic response as a measure of stress, computed as the number of SCRs over a 30-s window. Namely, an increase in EDA is considered an SCR if the signal slope is greater than $0.01\ \mu\text{S/s}$ and its amplitude larger than $0.05\ \mu\text{S}$; see Table II for pseudocode. We used this algorithm (as opposed to more elaborate EDA analysis tools, such as LedaLab [50]) since SCRs have to be detected in real time on a mobile phone during gameplay. We monitor EDA with a Shimmer sensor[3] and disposable AgCl electrodes

[1] In contrast, cortisol and alpha amylase must be measured analytically and the measures are discrete in time, whereas pupillary measures are invasive and susceptible to ambient illumination. Though EEG devices have garnered recent attention as an input modality for gaming [46], they are still fairly cumbersome for everyday use as they require head-mounted electrodes.

[2] EDA response is mediated by hypothalamus for thermoregulatory sweating, amygdala for affective processing, prefrontal cortex for attention, and premotor cortex during motor control [48]. It is also known to be affected by skeletal responses, such as breathing and muscular movement.

[3] http://www.shimmersensing.com.

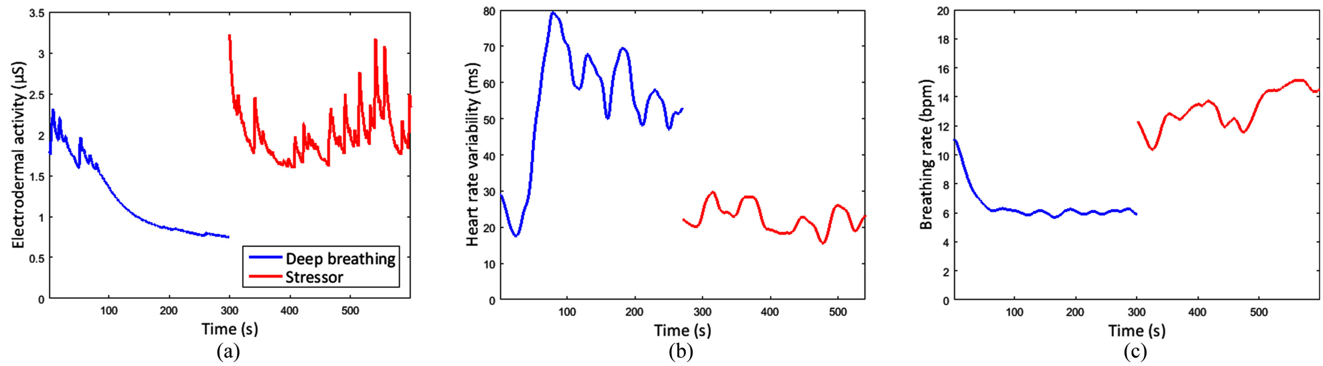


Fig. 2. Physiological signals while a participant performs relaxation exercise (DB) and a cognitively demanding task (CWT). (a) EDA. (b) HRV. (c) BR.

TABLE II
PSEUDOCODE OF THE SCR DETECTION ALGORITHM

```
procedure f SCR (SC, δmin, Ampmin)
Initialization:
    1) Rise ← false
    2) scrCount ← 0
for i = 1 to Length(SC)
    δ ← SC(i) − SC(i − 1)
    if (Rise = false AND δ > δmin)
        Rise ← true
        StartEDA ← SC(i)
    elseif (Rise = true AND δ < 0)
            Rise ← False
            if (SC(i) − StartEDA ≥ Ampmin)
                scrCount ← scrCount + 1
            endif
    endif
endfor
Return scrCount
```

placed at the palmar and hypothenar eminences of the player's nondominant hand. We chose this recording site because it has high density of eccrine sweat glands (200–600 per cm^2), and, therefore, is well suited to recording EDA [50].

2) Heart Rate Variability: In contrast with sweat glands, the heart is innervated by both autonomic branches (parasympathetic and sympathetic), which generally act antagonistically to regulate the period between consecutive heart beats; increased sympathetic activity leads to higher HR, whereas increase parasympathetic activity slows down the heart. The end result, HRV, can be used as a measure of stress; albeit a less selective one than EDA given that it results from the continuous interplay between both branches. Moreover, fluctuations in beat-to-beat period are driven by the respiratory cycle; HR increases during inhalation and decreases during exhalation—a phenomenon known as RSA, and these fluctuations have been shown to reach a maximum at a BR of approximately 6 breaths/min (br/min) or 0.1 Hz [51]. Thus, given that respiration can influence HRV, the latter can be viewed as being under partial voluntary control.

We chose HRV as a measure of arousal (instead of HR) since it is an indicator of autonomic imbalance [42]; activation of the sympathetic branch leads to reduction in HRV (fight/flight response—high arousal), while activation of the parasympathetic branch is associated with increases in HRV (relaxed state); see Fig. 2(b). In contrast HR, which is modulated by the ANS, is also affected by activity, posture, and other somatic variables including respiration and circadian rhythm [52] making it an unreliable indicator of arousal.

A number of HRV indices have been proposed [42] which can be grouped into time- and frequency-domain measures. Our current implementation uses a time-domain measure known as the square root of the mean-squared differences of successive R–R intervals (RMSSD); see Eq. (1) [42]. We chose this measure since it has low computational complexity: $O(n)$ which is important as it must run in real time on a smartphone. In contrast, frequency domain measures are more expensive, primarily due to the interpolation[4] required to resample the irregularly sampled R–R interval series to obtain a uniformly sampled signal before spectral analysis: $O(n^2)$ for polynomial interpolation followed by FFT: $O(n \operatorname{Log} n)$. We extract HRV from a Bioharness BT chest strap sensor[5] which also provides the respiratory signal. The sensor is worn across the player's sternum—immediately below the pectoral muscles

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

3) Breathing Rate: In contrast with EDA and HRV, respiration is under both autonomic and behavioral (voluntary) control. Autonomic control occurs in the respiratory center in the brain (located in the medulla oblongata) and is involuntary. The control center modulates the depth and frequency of breathing to maintain homeostatic levels of O_2 and CO_2 in arterial blood [53]. In contrast, behavioral control is voluntary and requires a certain amount of focus. Voluntary control of breathing happens to accommodate changes resulting from, e.g., stress, emotional stimuli, or physical activity, and is provided by the cerebral cortex. Due to this voluntary aspect, controlled breathing—specifically DB, is regularly recommended as a technique for

[4]Irregular sampling is not an issue in the time domain but has to be taken into account in the frequency domain, otherwise the spectrum will contain additional harmonics that affect the HRV estimates.

[5]www.zephyr-technology.com.

relaxation. DB addresses the autonomic imbalance that arises from exposure to a stressor by recruiting the parasympathetic branch and inhibiting the sympathetic action leading to a calmer state [44]. In Fig. 2(c), we show BR plot for a participant performing DB at 6 br/m followed by a cognitively demanding task which results in a higher BR.

Studies on the effect of stress on respiration patterns have shown that hyperventilation occurs during periods of intense mental effort and stress [54]. However, BR alone is an insufficient measure of stress response to psychological stimuli, and additional variables, such as tidal volume, end-tidal CO_2 should be used[6]. Thus, BR is not a particularly selective measure of stress/arousal.

4) Sensor Calibration: Raw physiological measures, particularly those from EDA and HRV, fluctuate quite significantly not only across participants (e.g., due to age, health, and fitness levels) but also within participant across sessions (e.g., time of day, rest, and diet). Thus, these measures must be normalized before they can be used for game adaptation. We follow a two-step calibration procedure to reduce inter- and intraparticipant variability. In a first step (offline), we ask participants to perform a 2-min relaxation exercise that consists of following an audiovisual pacing signal of 6 br/min, a respiration rate that has been shown to maximize HRV [51] and lead to a calm relaxed state [44].

Average EDA and HRV values over the last minute of the relaxation period are treated as a baseline (r_0) for the user.[7] In a second step (online), we then [0–1] normalize relative to the minimum $(r_{\min})$ and maximum $(r_{\max})$ values observed during gameplay—initial $(r_{\min},\ r_{\max})$ are obtained from the relaxation phase. This normalized value is updated every second, and serves as the current arousal level (r) for game adaptation as described next.

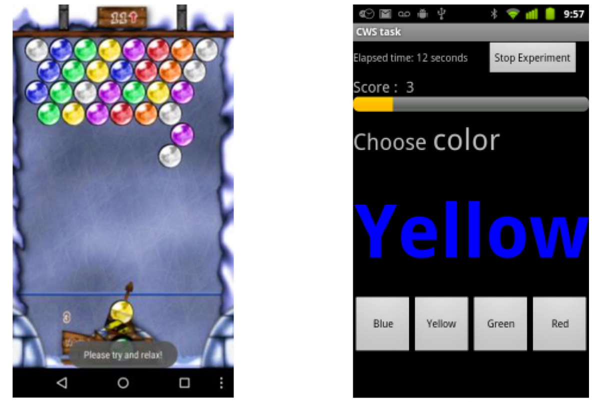
B. Biofeedback Game

To establish proof-of-concept for our approach, we adapted the casual game Frozen Bubble [55], which is available through an open-source license. Fig. 3(a) shows a screenshot of the game; the player controls the aim and firing of a small cannon that shoots bubbles of different colors into a playing area. The objective of the game is to eliminate all the hanging bubbles by grouping three or more bubbles of the same color, which causes them to burst. The game also has an element of time pressure whereby the ceiling drops over time; thus, reducing the size of the playing area until it eventually collapses.

1) Game Adaptation: A few elements in the game are amenable to adaptation, including the arrangement of bubbles (e.g., randomly versus clustered by colors), the ceiling (e.g., the speed at which it drops), and the cannon (e.g., whether its aim oscillates in a pendulum-like fashion, whether or not it shoots balls randomly). We chose the latter (autoshooting) as the adaptation mechanism, namely by modifying the interval at which the cannon fires automatically without explicit user input.

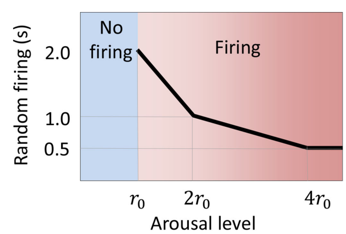
[6]However, measuring tidal volume and end-tidal CO_2 requires face masks or capnography, which are obtrusive and restrict the primary activity (gameplay).

[7]For respiration, a value of 6 br/min is taken as baseline.



(a) (b)

Fig. 3. (a) Screenshots of the Frozen Bubble game showing the prompt at the bottom. (b) Screenshot of the Stroop CWT.



(a)

	$r \le r_0$	$r > r_0$
$\frac{dr}{dt} < 0$	No penalty	No penalty
$\frac{dr}{dt} \ge 0$	No penalty	Penalty

(b)

Fig. 4. (a) Relationship between user's arousal and automatic shooting frequency in the game when conditions for penalty ($r > r_0$ *and* $\frac{dr}{dt} \ge 0$) are satisfied; r_0 = baseline. (b) Mapping arousal level (r) and its rate of change (Δr) to penalty (random firing) during the game.

The relationship between autoshooting and arousal follows the piecewise linear function in Fig. 4(a). Starting at baseline (r_0), the interval between two random bubble shots decreases as the player's arousal (r). increases; at twice the baseline arousal, bubbles are shot every second, whereas at four times above baseline bubbles are shot every half second, making the game increasingly harder to play.

To help the player return to a relaxed state once autoshooting starts, the game adaptation engine also monitors the rate of change in arousal and disables autoshooting if arousal begins to decrease. In other words, autoshooting only occurs if arousal is above baseline *and* increasing [see Fig. 4(b)]. The game also provides a few visual cues to help the player lower their arousal; BR is displayed on top of the screen along with a colored arrow to indicate whether arousal is increasing (red) or decreasing (green), and a text message ("Please try and relax") is displayed unobtrusively whenever the player's arousal level is above baseline and increasing.

We developed the biofeedback game on a Google Nexus 5 running Android 4.4. The system architecture has three layers: game, sensor libraries, and Android OS. The first layer comprises of the game, game adaptation, and arousal estimation routines. It uses sensor-specific libraries in the subsequent layer to connect with the wearable sensors via Bluetooth and query for physiological data. This data is then used to compute arousal and adapt the game.

IV. Experimental Details

We conducted a user study to evaluate the effectiveness of GBF in inducing relaxation and promoting skill transfer. Along with the three biofeedback groups (EDA, HRV, and BR), we used a nonbiofeedback version of the game as a control group and DB (a traditional relaxation method) as the standard treatment. Experimental trials were conducted as part of an independent study with each participant being randomly assigned to one of the three biofeedback groups, the control group, or the standard treatment. We adopted a between-subjects design to avoid ordering effects due to learning or fatigue. Twenty five participants (15 male, ten female; 19–33 years) participated in the study, five participants per group. BR, EDA, and HRV readings from all participants were collected during the entire experiment session for monitoring purposes (and game adaptation in the respective biofeedback groups). We received approval from the Institutional Review Board prior to the study and consent from each participant before the session. The experimental protocol consisted of four phases (I–IV).

Phase I (baseline): Participants were asked to follow an audio pacing signal that guided them to breathe at a rate of 6 br/min for 2 min.[8] Data from this phase provided a baseline for the three physiological signals.

Phase II (pretest): Participants performed a modified Stroop color word test (CWT) [57] for 4 min [see Fig. 3(b)], which served as a pretest condition to assess their physiological response to stress prior to treatment. Instructions on how to perform the CWT were provided prior to the beginning of the task. The CWT is widely used in psychology studies to induce mental workload and arousal. In the conventional CWT, participants are shown one of four words (red, blue, green, and yellow) displayed in different ink colors, and are asked to choose either the displayed word or the ink color of the displayed word. To reduce learning effects, our implementation switches between two modes (congruent and incongruent) every 30 s. In the congruent mode, the word and the ink color match, whereas in incongruent mode they do not. Furthermore, the location of the answer buttons at the bottom of the screen is also randomized with each presentation. Every correct answer increases the score by one, while a wrong answer adds a penalty of negative one; selecting the wrong answer also causes a distracting sound to be played. During the assessment, the stimulus was flashed for 1 s, and the participant had 3 s to respond.

Phase III (treatment): Participants were assigned to one of five groups: breathing rate game biofeedback (BR-GBF), heart rate variability game biofeedback (HRV-GBF), electrodermal activity game biofeedback (EDA-GBF), DB, and game only (GO). The duration of the treatment was 8 min for all groups, with the following procedure during the treatment session.

1) *GBF (Experimental Treatment):* Participants played one of the three biofeedback games. They were instructed to 1) do the best they could in the game and score maximum points, and 2) stay calm during the gameplay and try and breathe slowly, i.e., in the same way they had practiced during the baseline phase. All participants were given the same instructions regardless of treatment type.
2) *GO (Control):* Participants played the nonbiofeedback game. They were given the same instructions as those in the GBF conditions.
3) *DB (Standard Treatment):* Participants in this group did not play a game. Instead, they were instructed to stay calm and try and breathe slowly by following an audio pacing signal that guided them to breathe at a rate of 6 br/min (inhale for 4 s and exhale for 6 s).

Phase IV (posttest): participants repeated the CWT for 4 min as a posttest to study the transfer of relaxation skills. In this phase, participants were asked to stay calm by using the skills they had learned during the treatment phase.

V. Results

A. Average Physiological Response Per Treatment

To compare the efficacy of the five methods in teaching relaxation skills, we analyzed the participants' BR, EDA, and HRV during the pretest, treatment, and posttest. Fig. 5(a) and (b) shows the average BR and changes in BR relative to pretest. During treatment, the BR-GBF and DB groups had lower BRs than during pretest, whereas the other two biofeedback groups (EDA-GBF and HRV-GBF) only had a moderate reduction in BR and the GO group had a moderate increase. During posttest, participants in the BR-GBF and DB groups continued to have lower BRs than during pretest, a result that indicates the deep-breathing skill was transferred; note, however, that the reduction in BR at posttest is more pronounced in the BR-GBF group than in the DB group. The remaining groups did not have a reduction BR during the posttest, which suggests the deep-breathing skill did not transfer.

To assess the statistical significance of these results, we performed one-way ANOVA on the difference between pre- and posttest BRs. This analysis showed a marginally significant difference between the five groups: $F\,(4, 20) = 2.83, p = 0.052$. We also performed pairwise post hoc tests to analyze differences between pairs of groups; results are presented in Table III.

We observed statistically significant differences in BR-GBF versus HRV-GBF and in BR-GBF versus EDA-GBF groups, and marginally significant differences in BR-GBF versus DB and BR-GBF versus GO groups, which indicates the effectiveness of BR-GBF in promoting skill transfer. No statistically significant differences were found in any other pairs.

In turn, Fig. 5(c) and (d) shows the average HRV during treatment, pre- and posttests, and the relative changes. During treatment, HRV increased noticeably for participants in the BR-GBF and DB groups, compared to only modest increases for the HRV-GBF and EDA-GBF groups and a reduction for the

[8] More specifically, the pacing signal instructed participants to inspire for 4 s and exhale for 6 s, an experimental choice motivated by prior work showing that a respiratory cycle with a short inspiration followed by a long expiration period leads to higher RSA than a respiratory cycle with a long inspiration and a short expiration [56].

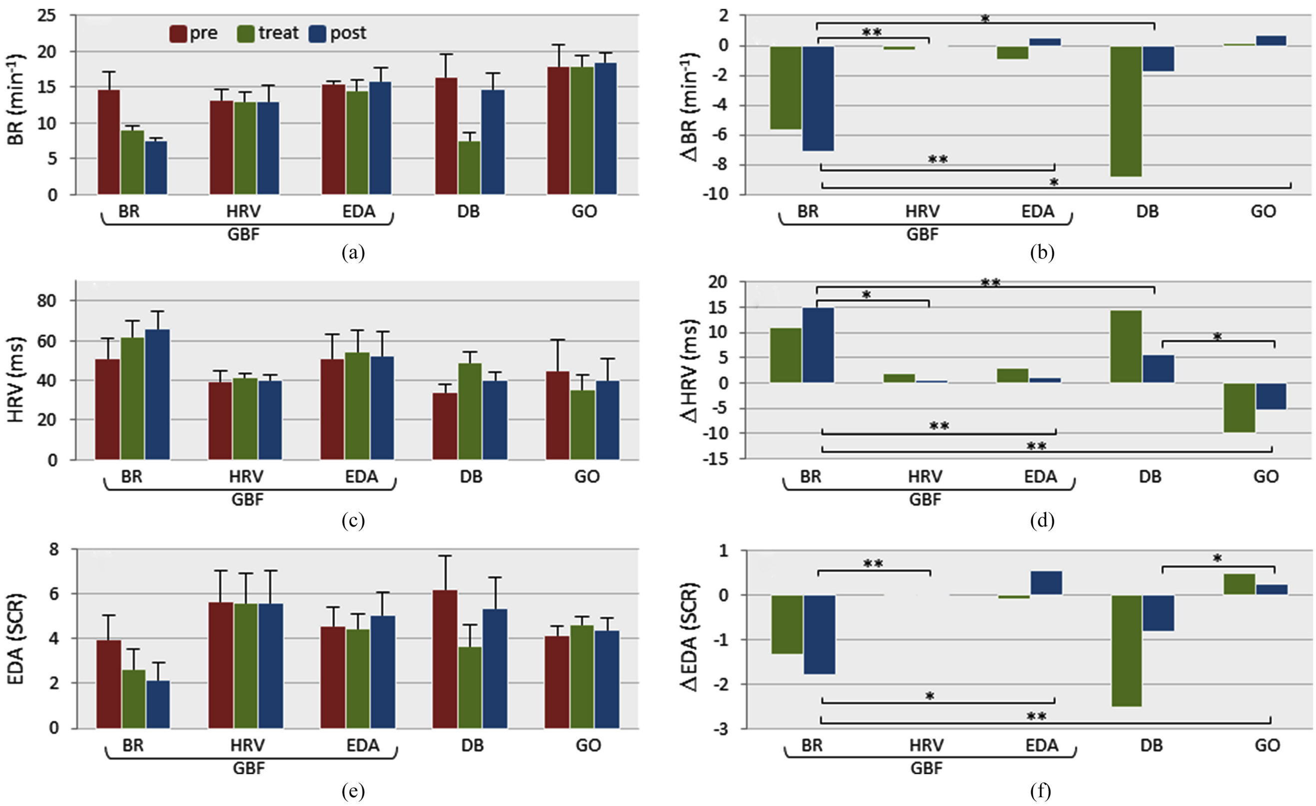


Fig. 5. Left column: (a), (c), (e) Physiological response (BR, HRV, EDA) during pretest, treatment, and posttest for the five experimental groups. Right column: (b), (d), (e) Change in physiological response during treatment and posttest with respect to pretest. Statistical significance results (pairwise one-way ANOVA) on the difference between pre- and posttest physiological readings are also presented ($^{**}p < 0.05$ and $^{*}p < 0.1$); see Tables III–V for more details.

GO group. During posttest, the BR-GBF group had a further increase in HRV (relative to treatment), compared to a reduction for the DB, HRV-GBF, and EDA-GBF groups (also relative to treatment). In summary, these results indicate that EDA-GBF and HRV-GBF were less effective than BR-GBF (or DB) in reducing arousal levels during the treatment and led to negligible transfer of relaxation skills during posttest.

One-way ANOVA on the delta values shows a statistically significant difference between the five groups: $F(4, 20) = 2.9, p < 0.05$. Pairwise post hoc analysis show a statistically significant difference in BR-GBF versus EDA-GBF groups, in BR-GBF versus DB groups, and in BR-GBF versus GO groups, and marginally significant differences in BR-GBF versus HRV-GBF groups, and in DB versus GO groups; see Table IV. No statistically significant differences were found in any other pairs.

Finally, Fig. 5(e) and (f) summarizes EDA results in terms of the number of SCRs per 30 s ($SCR_{\#}$). Participants in the BR-GBF group had a monotonic decrease in EDA from pretest to treatment to posttest, indicating that the treatment led to reduction in arousal. Likewise, participants in the DB group had lower EDA during treatment and posttest (relative to pretest), though EDA increased at posttest relative to during treatment. No particular trend was seen in the HRV-GBF group during treatment or posttest, while the EDA-GBF group had a minor decrease in EDA during treatment followed by an increase during posttest. Finally, there was an increase in EDA during the treatment and

TABLE III
STATISTICAL DIFFERENCE (F-RATIO) BETWEEN THE FIVE GROUPS IN TERMS OF BR CHANGE (POST–PRE)

	BR-GBF	HRV-GBF	EDA-GBF	DB	GO
BR-GBF	–	6.23^{**}	6.43^{**}	3.34^{*}	4.37^{*}
HRV-GBF		–	0.13	0.82	0.01
EDA-GBF			–	1.18	0.02
DB				–	0.49
GO					–

($^{**}p < 0.05$; $^{*}p < 0.1$). Degree of freedom: df_1 (between groups) = 1 and df_2 (within groups) = 8.

posttest for the GO group. One-way ANOVA of the five groups did not find a significant difference: $F(4, 20) = 1.98, p = 0.13$. However, pairwise post hoc analysis revealed a statistically significant difference in BR-GBF versus GO groups, and a marginally significant differences in BR-GBF versus HRV-GBF groups, in BR-GBF versus EDA-GBF groups, and in GO versus DB groups; see Table V. In summary, the preceding analyses reveal a significant difference between subjects who underwent treatment in the BR-GBF group (lower BR, lower EDA, and higher HRV, all indicative of reduced arousal) during posttraining compared to the other four groups. While the DB group showed a lowering of arousal during treatment, this was followed by an increase during posttest, which indicates minimal

TABLE IV
STATISTICAL DIFFERENCE (F-RATIO) BETWEEN THE FIVE GROUPS IN TERMS OF HRV CHANGE (POST–PRE)

	BR-GBF	HRV-GBF	EDA-GBF	DB	GO
BR-GBF	–	4.54*	5.39**	6.5**	14.3**
HRV-GBF		–	0.01	0.62	0.59
EDA-GBF			–	0.64	0.87
DB				–	4.76*
GO					–

($^{**}p < 0.05$; $^{*}p < 0.1$). $\mathrm{df}_1 = 1$ and $\mathrm{df}_2 = 8$.

TABLE V
STATISTICAL DIFFERENCE (F-RATIO) BETWEEN THE FIVE GROUPS IN TERMS OF EDA CHANGE (POST–PRE)

	BR-GBF	HRV-GBF	EDA-GBF	DB	GO
BR-GBF	–	5.07**	3.49*	3.17	9.24**
HRV-GBF		–	0.18	1.37	0.1
EDA-GBF			–	1.31	0.06
DB				–	3.81*
GO					–

($^{**}p < 0.05$; $^{*}p < 0.1$). $\mathrm{df}_1 = 1$ and $\mathrm{df}_2 = 8$.

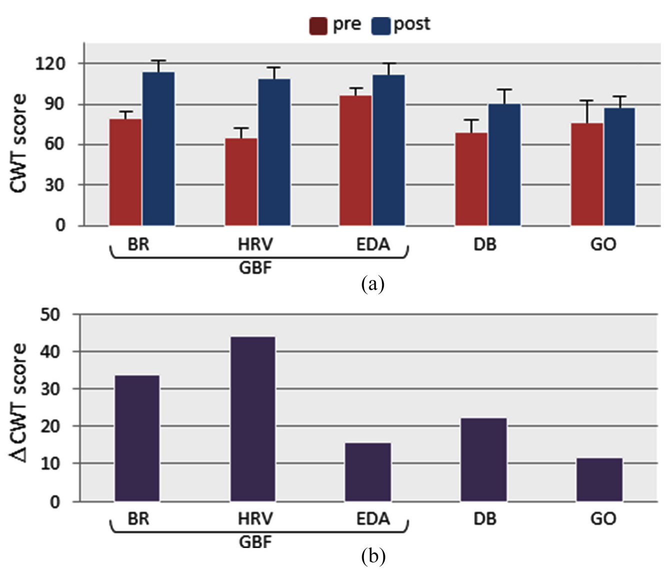


Fig. 6. Pre- and posttest task performance (CWT score) for the five groups.

transfer of relaxation skills. In addition, participants in the HRV-GBF and EDA-GBF groups did not show much difference between the three sessions, whereas participants in the GO group had higher arousal during both treatment and posttest—an expected result since games are known to increase arousal.

B. Performance Results

We also analyzed whether the different treatments had an effect on task performance, measured as differences in CWT scores at pre- and at posttest. Results are presented in Fig. 6. Task performance improved for all groups, which suggests some

TABLE VI
PEARSON CORRELATION COEFFICIENT ρ (p-VALUE) BETWEEN CHANGES (POST–PRE) IN CWT SCORES AND CHANGES IN PHYSIOLOGICAL RESPONSE FOR ALL PARTICIPANTS

	BR	HRV	EDA
CWT	0.06 (0.77)	0.07 (0.72)	−0.06 (0.76)

learning effects took place. One-way ANOVA on the delta values showed a marginally significant difference $(F(4, 20) = 2.41,$ $p < 0.08)$ across groups. Post hoc assessment also showed marginally significant differences in BR-GBF versus EDA-GBF $(F(1, 8) = 5.12; p < 0.06)$, in BR-GBF versus GO $(F(1, 8) = 4.04; p < 0.07)$, in EDA-GBF versus HRV-GBF $(F(1, 8) = 3.78; p < 0.09)$, and in HRV-GBF versus GO $(F(1, 8) = 3.89;$ $p < 0.08)$. No significant group differences were observed between other pairs.

In a final step, we analyzed the effect of arousal on performance for participants in the five groups; results are presented in Table VI. Differences in CWT scores (post–pre) show no correlation with changes in each of the three physiological signals (BR, HRV, EDA); see Fig. 6(b). The improvement in performance seen in all the groups may, therefore, be attributed to learning effects in the CWT.

VI. DISCUSSION

We have presented an approach that leverages the appeal of video games to encourage the acquisition of relaxation skills. The approach consists of monitoring physiological signals during gameplay and adapting the game to encourage relaxing behaviors. To test the feasibility of the approach, we have developed a casual mobile game that increases in difficulty with increases in arousal, as measured with non-invasive wearable sensors. Specifically, we compared three biofeedback modalities for game adaptation (EDA, HRV, and BR) against a control group (GO) and a standard treatment (DB) by their ability to teach relaxation skills. Our results show that breathing-based game biofeedback (BR-GBF) is more effective than the other groups in terms of lowering arousal during the treatment and transferring relaxation skills to a subsequent acute stressor.

The advantage of BR-GBF over GO and DB in lowering arousal during treatment and the subsequent acute stressor may be the result of *contextualized learning*. BR-GBF combines virtual objects (e.g., video game) and real-world tasks (e.g., DB), in this way allowing players to internalize and reinforce the relaxation process, while performing a task that is designed to increase arousal. This may lead to a better transfer of skills to other real world tasks. The superior performance of BR-GBF may also be attributed to *instrumental conditioning*, i.e., rewarding relaxing behaviors and penalizing others.

A plausible explanation for differences among the three GBF groups is the degree to which the individual has voluntary control of the physiological signal modulating the game (e.g., BR, EDA, or HRV). Breathing is normally controlled by the autonomic nervous system, but can be overridden voluntarily, and, therefore, can be considered to be under full voluntary control. In contrast, HRV is not under direct voluntary control but is the result of autonomic processes that regulate blood pressure and respiratory efficiency [58]. However, HRV can be altered with proper breathing technique, so it can be viewed as being under partial voluntary control. Finally, controlling EDA (reducing it, in particular) is more difficult than HRV or respiration, so EDA can be considered to be under low voluntary control. According to this argument, having a higher degree of control of the physiological signal, participants in the BR-GBF group could self-initiate the lowering of BR during gameplay, which in turn led to a lowering of their arousal. This is an interesting finding, because though EDA is the most specific indicator of arousal among the three modalities, EDA-GBF did not assist participants in lowering their arousal. This indicates that, for biofeedback gameplay, physiological variables that can be directly manipulated by the participants may facilitate learning of stress self-regulation skills.

A second factor underlying the observed results may be the instructions given to participants during the experiment. Prior to treatment, participants in the three GBF groups were asked to "*stay calm during the gameplay and try and breathe slowly, i.e., in the same way they practiced during the* baseline phase" (see Section IV). No specific instructions in reference to maintaining high HRV or low EDA levels were provided. Thus, even though slow breathing is shown to lower the arousal levels, the lack of specific instructions and/or training may have led to the poorer performance in the EDA-GBF and HRV-GBF groups. In an early study, Blanchard *et al.* [59] showed that subjects who were provided HR biofeedback and were told that they were being trained to change HR did better than those who were not; this group in turn did better than those told being trained to change skin conductance, indicating the importance of providing specific instructions during training. More recently, Raaijmakers *et al.* [60] studied the effect of EDA and HRV biofeedback-based games on affective state. In this study, participants were not informed about the biofeedback modality (i.e., EDA or HRV) controlling the game and were not given any instructions on how to control their EDA and HRV; instead, they were told to "*find out themselves how to achieve control*." Their results showed no effect of biofeedback on the user's affective state. Based on these results, it may be tempting to conclude that HRV- or EDA-driven GBF are not effective in reducing stress reactivity. However, past research has shown that instrumental conditioning can be used to train users to control visceral responses—including HRV and EDA [61]. Thus, a promising direction for future work is the development of effective instructions and training paradigms for HRV and EDA-based adaptation during GBF. This may include investigating the effect of treatment durations, since longer training periods may be needed to help improve the perception of certain visceral responses (e.g., states of high arousal) and to teach voluntary control of them.

For breathing-based GBF, special consideration must be given to the ratio of expiration time to inspiration time (E/I ratio). As an example, using controlled breathing trials Strauss-Blasche *et al.* [56] have shown that short inspiration followed by long expiration leads to higher RSA than long inspiration followed by short expiration. This is primarily because rapid inspiration inhibits vagal activity and increases the phasic HR, while exhaling activates the vagus nerve and therefore decreases HR. While participants in our study were guided to use a large E/I ratio during the paced breathing session (4-s inspiration, 6-s expiration), further training may be needed to teach effective breathing technique. The issue of hyperventilation is also pertinent to our intervention. Adults normal (i.e., spontaneous) BR is in the range of 12–20 br/min, and it is known that deliberate slow breathing can lead to disordered cardio-vascular regulation and even anxiety [51], which in turn inhibits parasympathetic activity and decreases HRV. Combined, issues of optimal E/I ratio and hyperventilation point to a need for further research on training protocols to teach proper deep-breathing technique. Additional research is also needed to determine long-term persistence effects of our intervention; this will likely require multiple training sessions and testing in real-world ambulatory settings.

Results presented in this paper and prior work [10], [35]–[37] show that biofeedback video games can be an effective technique to teach relaxation skills; due to the repetitive nature of video games, these skills are reinforced and can potentially be applied to subsequent tasks without biofeedback. This leads to an important question: how does learning and reinforcement of relaxation skills occur? A plausible mechanism proposed by Pope *et al.* [4] is that of a two-step process of instrumental learning and classic conditioning. The authors argue that, with player's inherent motivation to excel in the game and through repeated associations, the learned changes can be generalized to other scenarios. The underlying principle that explains the reinforcement process is known as Premack prepotent principle, according to which "*a high probability behavior will reinforce a low probability behavior*" [62]. In our context, a high-probability behavior is the activity that the user performs more frequently (i.e., playing a game in this case), whereas the low-probability behavior is the elicitation of desired physiological response, i.e., staying calm. A study by Koepp *et al.* [63] on the effect of video games on the brain showed that playing a video game led to substantial dopamine release compared to baseline. Dopamine release is an indicator of memory storage events, learning, reinforcement of behavior, and attention, and helps learn stimuli or actions that predict rewarding or aversive outcomes. In their study, players showed a steady increase in the level of dopamine during a gameplay session, which stayed at levels higher than baseline after the gaming session ended [63]. These results provide a link between behavioral manipulation and dopamine release, and suggest that biofeedback video games can chemically prepare the brain for learning and can be used to detect stress triggers, and learn/reinforce relaxation skills.

VII. Conclusion

The objective of this paper was to develop an engaging intervention to allow individuals practice stress management. In this context, the study presented here has two main contributions. First, we proposed a GBF approach which uses instrumental conditioning and a positive feedback loop for acquisition and retention of stress self-regulation skills. Second, we showed how various physiological signals (BR, EDA, and HRV) which differ in the degree of selectivity in measuring arousal and voluntary control may be used in GBF. Following our method other biomarkers (e.g., EEG, EMG) may also be used for biofeedback game adaptation. Finally, we analyzed the findings in the light of psychological theories of learning and reinforcement [4], [62] and neuroscience [63] and provided a theoretical basis for our work.

Our approach of game adaptation with a positive feedback loop is closely related to traditional biofeedback, but has two fundamental differences. First, in traditional biofeedback the user has explicit access to his physiological state (e.g., via visual display); in contrast, in biofeedback game the user engages in the game while the physiological signals are available *implicitly* (e.g., via game adaptation). Hence, the user must focus on the game rather than monitor his biosignals, which makes the training more engaging. Second, GBF teaches relaxation techniques, while performing a task (i.e., a game) that is designed to increase the user's arousal level. And herein lies the main difference with traditional relaxation methods, which encourage practice in quiet settings that do not reflect the environments encountered in daily life. As a result, and as demonstrated in our study, GBF may lead to better transfer of relaxation skills to other tasks. This hypothesis is also supported by prior research on stress exposure training in military settings, which shows that normal training procedures do not improve performance when the task is later performed under stress [37]. We believe that the system described here can enable new forms of gameplay and applications including entertainment, game-like health interventions, and affective interfaces.

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