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Visual Biofeedback and Game Adaptation in Relaxation Skill Transfer

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Abstract—This paper compares the effectiveness of two biofeedback mechanisms to promote acquisition and transfer of deep-breathing skills using a casual videogame. The first biofeedback mechanism, game adaptation, delivers respiratory information by altering an internal parameter of the game; the second, visual biofeedback, displays respiratory information explicitly without altering the game. We conduct a user study that examines visual biofeedback and game adaptation as independent variables with electrodermal activity, heart rate variability, and respiration as dependent variables. In particular, we evaluate these forms of biofeedback by their ability to facilitate acquisition of relaxation skills and promote skill transfer to subsequent stressful tasks. Our results indicate that game adaptation promotes skill acquisition and transfer more effectively than visual biofeedback, but that a combination of the two outperforms either in isolation. Combining visual and game biofeedback also results in faster learning of deep-breathing skills than either channel alone. Our study suggests that the two forms of biofeedback play different roles, with game adaptation being more effective in encouraging deep breathing, and visual channels helping players maintain the target breathing rate.

Index Terms— Biofeedback, deep breathing, games for health, relaxation, skill transfer, stress, video games, wearable sensors

1 INTRODUCTION

LEARNING to self-regulate in the presence of stressors is an invaluable skill in today's high-paced, stressful world. Self-regulation skills help us cope with demanding situations, reduce negative health outcomes, and increase overall quality of life. A number of methods exist to teach stress self-regulation, including cognitive behavior therapy (CBT), biofeedback, yoga, and meditation. While these methods can be effective in helping manage stress, they suffer from some drawbacks. For example, CBT is performed under the supervision of a therapist, which can be cost prohibitive. Biofeedback allows users to visualize their physiology to better regulate their stress response, but these visualizations (especially those based on electrodermal activity and electroencephalography) are non-intuitive to many users [1]. Self-guided interventions, including meditation and yoga, suffer from high dropout rates [2] due to the unengaging nature of the exercises and lack of motivation [3]. Furthermore, these techniques teach self-regulation in quiet, controlled settings, which may not generalize to real world stressors [4].

Videogames are well suited to address the shortcomings of existing methods for stress management. They are engaging and widely popular, so they can help improve motivation and adherence to regular practice. More importantly, certain types of videogames can be very effective at eliciting emotions [5-7], including stress and arousal [8, 9]. Thus, such videogames may be used to design interventions that allow patients to practice relaxation skills while performing demanding or stressful task. For example, several studies [10-12] have shown that delivering biofeedback during gameplay increases skill retention. Several design choices can affect the effectiveness of such interventions: the characteristics of game (e.g., immersive vs. casual, action vs. puzzles), the physiological signal used to monitor the patient's state (e.g., cardiovascular, central nervous system), the type of channel used to deliver biofeedback (e.g., auditory, visual, haptic), and the way in which the biofeedback and the game are integrated.

In a previous study [12], we examined one such design choice: the type of physiological variable used as input to the game. Our study compared three physiological modalities that have different degrees of voluntary control and selectivity to arousal: respiration (high control, low selectivity), electrodermal activity (low control, high selectivity), and heart rate variability (moderate control, moderate selectivity). In our design, the user received two types of biofeedback simultaneously: directly, through a peripheral visual display, and indirectly, through changes in the game mechanics. These modalities facilitate skill acquisition in distinct ways (i.e., top-down and bottom-up learning) and influence retention of skills. As such, our prior study was unable to determine whether one or the other form of biofeedback is more effective. Answering this question is the objective of our present study.

The rest of this manuscript is organized as follows. Section 2 reviews prior work on game-based interventions for health and wellness, playing particular attention to games and biofeedback games for stress management. Section 3 describes our biofeedback game and the three

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types of biofeedback used in this study. The first method, *visual biofeedback* (*VBF*), presents physiological information directly to the user (e.g., via a visual display), but otherwise does not affect gameplay. The second method, *game biofeedback* (*GBF*), presents the physiological information indirectly through subtle changes in gameplay, e.g., by changing game difficulty in proportion to the player's stress levels. The third method, *combined biofeedback* (*XBF*), delivers visual biofeedback and game biofeedback simultaneously, as in our previous study [12]. Section 4 describes the experimental protocol as well as the physiological and subjective measures we used to compare the three forms of biofeedback. We evaluate the three methods based on their ability to: 1) reduce arousal during game play; and 2) improve relaxation skill transfer to subsequent cognitively demanding tasks, when biofeedback is not present. Section 5 analyses experimental results from the study; we perform statistical analysis to identify the contribution of individual biofeedback channels in promoting relaxation, and also examine the learning curve for each form of biofeedback. The article concludes with a thorough discussion of these results and directions for future work.

2 Literature Review

2.1 Games for health and wellness

Videogames (both commercial and custom-made) have application beyond entertainment, and can positively affect health-related outcomes [13]. For example, videogames have been used to reduce anxiety and provide cognitive distraction for children prior to surgery [14] and during painful medical procedures, e.g., chemotherapy for cancer and treatment for sickle cell disease [15, 16]. Studies have also reported that patients playing videogames during treatment have less nausea and lower blood pressure than control groups who were simply asked to relax [15, 17].

The repetitive nature of gameplay makes it well-suited to promote skill learning and practice [18]. As an example, Brown et al. [19] developed an instructional game for children with diabetes. To win the game, players had to manage their insulin levels and food intake to keep the glucose levels of their game character under control. Similar instructional games have been developed for asthma [20] and bowel dysfunction [21]. Researchers have also explored using videogames with children with impulsive and attention deficit disorders [22].

A large and growing set of console and PC-based videogames are designed to increase physical activity and help reduce obesity [23]. Videogames have been used for physiotherapy for patients with arm injuries and for improving hand strength [24]. Therapeutic benefits for videogames have also been reported for wheelchair users with spinal cord injuries [25], and patients with muscular dystrophy [26]. Commercial game consoles such as the Nintendo Wii and Microsoft Kinect, along with games such as *Dance Dance Revolution*, have been shown to significantly increase energy expenditure [27] and provide physical activities for users with sedentary lifestyles.

2.2 Games for stress self-regulation

Videogames have also been used to improve mood and stress recovery, and reduce the effects of stress [9, 28-30]. Russoniello et al. [28] studied the effects of casual videogames (CVG) on mood and stress. The authors tested whether playing popular casual games (Bejeweled, Bookworm Adventures, and Peggle) could drive/change the autonomic nervous system in a direction consistent with decreased stress and improved mood. They found that playing videogames led to improvements in positive mood (as measured by electroencephalogram) and reduction in stress (measured by heart rate variability). Reincke [9] showed that videogames have a significant potential for stress recovery. The author conducted an online survey with 1614 participant to study the relationship between mental fatigue, recovery, and video game usage. Based on the analysis, the author found that participants who play games showed improvements in all four facets of recovery: psychological detachment, relaxation, mastery, and control.

Holmgard et al. [31] presented a computer game (StartleMart) to detect mental conditions such as post-traumatic stress disorder (PTSD). The game uses concepts of exposure therapy and stress inoculation training (SIT) and simulates various scenarios from everyday life that are known to be stressful to PTSD patients while a stress detection mechanism profiles the severity and type of PTSD (with electrodermal activity). An experimental trial with veterans suffering from PTSD showed a high correlation between standardized measures of PTSD and the skin conductance responses. While the correlation results in detecting stress levels during gameplay seem encouraging, the treatment efficacy of this game as an SIT method remains open for investigation. Videogames have also been used to assist individuals coping with traumatic stress. A study with 1,000 active-duty soldiers in Afghanistan found that playing videogames 3 to 4 hours a day showed a significant increase in mental resilience [29]. Studies have shown that soldiers deployed in war zones who play first person shooter or combat games are less likely to develop post-traumatic stress disorder [29, 30].

In recent years, researchers have explored VR as a tool for delivering stress training [32-34]. VR based games allow individuals to become active participants within an artificially-generated scene. VR provides a way to immerse users in realistic simulations of the traumatic experiences and can be used for prolonged exposure therapy, treatment for combat-related stress and PTSD [32-34]. Rizzo et al. [34] used a VR treatment (depicting combat scenarios) over a 10-week period with active-duty soldiers. Survey results indicated significant reduction in PTSD levels. The authors also noted that the ability to customize the VR scenes and content can help better address the needs of clinical users with different levels of PTSD.

Researchers have explored the possibility of using biofeedback games to help patients regulate the impact of anxiety and stress. Sonne and Jensen [35] presented

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ChillFish, a breath-controlled biofeedback game to help children with ADHD relax in situations of acute stress. During gameplay, children control the size of a pufferfish with their respiration; slower breathing increased the size of the fish, which allowed them to collect more rewards. The authors reported significant increases in average HRV values of the ChillFish group compared to other activities (talking and playing Pacman). More recently, Dillon et al. [36] studied the effectiveness of mobile games ("The Loom" and "Relax and race") combined with a commercially available biofeedback device (Personal Input Pod, Galvanic Ltd., Ireland) to reduce stress. The authors measure the player's electrodermal activity during gameplay and use it to determine progress: the more relaxed the player, the greater the progress in the game. Thirty minutes of training with the biofeedback game led to a significant reduction in heart rate and self-rated stress measures, compared to a control group.

Chester [37] integrated heart rate variability (HRV) biofeedback in the game Half Life 2. During an experimental trial the treatment group played the biofeedback game for 5 hours (1 hr/day) while the control group played a non-biofeedback version of the game for 5 hours. HRV increased following the biofeedback game based treatment, compared to the control group. The authors also reported reduction in somatic complaints, sleep complaints, negative affect, disruptions in emotion regulation, state anxiety, trait anxiety, and perceived levels of stress (as noted in subjective questionnaire) following the HRV biofeedback game training. In a related study, Lobel et al. [38] present Nevermind, a horror-themed biofeedback game for emotion regulation. In Nevermind, the player's HRV is used to adapt the game such that negative affective arousal (i.e. high stress and low HRV) causes the horror-themed settings in the game to become more disturbing. The aim of this game is to challenge the players to self-regulate their affective state towards more healthy levels (i.e. high HRV) while facing a stressful situation. The authors conducted an observational study with 47 participants to assess the potential connections between players' in-game and real world behaviors. The author presented anecdotal results for three participants, however, a comprehensive quantitative analysis on the effects of the game on user physiology behavior during or after the gameplay was not presented.

2.3 Biofeedback games for relaxation skill transfer

A handful of studies have examined whether relaxation skills transfer beyond the immediate biofeedback training period. Larkin et al. [39] combined heart rate (HR) biofeedback with score contingency (SC) in a game that aimed to reduce cardiac reactivity. HR feedback was presented during gameplay in the form of a peripheral display that indicated to the players whether their HR was increasing or decreasing. In SC reinforcement, the player's score depended on their game performance and their ability to maintain a low HR. The authors sought to determine whether the skills learned during gameplay would be retained to novel tasks (mental arithmetic challenge). They conducted an experimental trial with a 2×2 design with visual biofeedback and SC as independent variables. Participants receiving SC feedback showed a significant reduction in HR reactivity[1] during gameplay and mental arithmetic, whereas visual biofeedback had no effect on HR. In a later study, Goodie and Larkin [10] investigated whether transfer of HR feedback training to novel tasks can be improved by using multiple tasks during the biofeedback training phase. Participants received HR biofeedback training with various combinations of three tasks that had varying stimulus-response characteristics: videogame, mental arithmetic, and handgrip. Following training, participants were tested by their ability to maintain a reduced HR while performing the three tasks and a novel speech task, this time without biofeedback. Transfer of training was assessed during an immediate post-training period, after a short delay (1-2 days), and after a long delay (1-2 weeks). Participants were able to reduce their HR during biofeedback training and retained these skills when the training task was repeated immediately after. However, participants did not show skill transfer to the novel speech task or after the delay (short and long). The authors concluded that transfer of HR reduction skills to new tasks was limited, and did not improve by training across multiple stressors.

Bouchard et al. [11] assessed the effectiveness of using audio-visual biofeedback in an immersive 3D videogame to teach tactical breathing skills to soldiers. The aim of the study was to evaluate whether practicing stress management during a stressful and demanding task would be more effective than "training as usual" (i.e. formal descriptions of techniques followed by brief practice). Soldiers in the treatment group performed three 30 min sessions of a first-person shooter game. The authors provided audio-visual biofeedback to the players to indicate their stress levels. In contrast, soldiers in the control group received a briefing on stress management and were asked to practice the skills on their own. After training, both groups performed an assessment comprising of a stressful medical simulation. Participants in the treatment group had significantly lower arousal during assessment than those in the control group, as measured by salivary cortisol and heart rate. They also had higher performance in applying the medical protocol during the simulation.

More recently, Wang, et al. [40] presented an approach to use commercial videogames for biofeedback games for stress self-regulation. The approach consisted of capturing physiological signals and modifying the game controls accordingly so as to drive the user towards relaxation. The authors used a car racing game and compared two different biofeedback mechanisms in the game, namely car speed and visual overlay. Experimental results showed that compared to a control group, both the biofeedback groups were able to promote deep breathing in participants during treatment and also facilitate skill transfer during subsequent driving simulations.

[1] HR reactivity refers to the mean increase in HR observed in response to a task or stressor.

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In a recent study [12], we evaluated the effectiveness of three physiological indices (breathing rate, heart rate variability, and electrodermal activity) when used in a game biofeedback intervention that aimed to promote relaxation skills and skill transfer. The game biofeedback intervention consisted of playing a casual game (see section 3) whose difficulty increased in proportion to the player's arousal, measured with one of the three indices. Skill transfer was measured during a subsequent stressor (Stroop color word test). We found that adapting the game in proportion to breathing rate was more effective (i.e. improved relaxation during training and improved skill transfer) than adapting the game in proportion to heart rate variability or electrodermal activity. This suggests that having voluntary control over the physiological variable is critical at least for short-term interventions. The breathing-rate intervention was also more effective than a standard treatment (deep breathing) and a control condition (playing the game without biofeedback).

The current work differs from the prior study in several ways. First, we examine three types of biofeedback outputs in games (game adaptation, visual, and combined) and their influence on skill acquisition and transfer. Second, we evaluate the contribution of individual biofeedback channels in promoting relaxation and analyze the learning curve for each form of biofeedback over the course of a longer treatment session. Finally, in addition to physiological measures of arousal, we also consider qualitative feedback from user questionnaires.

3 Methods

3.1 Game

To evaluate the three forms of biofeedback, we adapted an open-source casual game known as Frozen Bubble [41]. In this game –see Fig 1(a), the player is presented with an arena containing a spatial arrangement of colored bubbles, and the goal is to clear the arena. For this purpose, the player controls the orientation and firing of a small cannon that shoots bubbles of random colors. Placing a new bubble next to two or more of the same color makes them disappear; otherwise they pile up until the arena fills up, at which point the game ends. The ceiling of the arena drops one notch every eight moves, which reduces the play area over time and adds an element of time pressure. Different initial arrangements of bubbles can be used to make the game arbitrarily easy or hard, allowing us to increase the challenge level as the player progresses from one screen to the next. We built the game on a Google Nexus 5 running Android 5.0.

The central mechanism in teaching relaxation skills with game biofeedback is instrumental conditioning[2]. The GBF approach has been developed using the concept of negative reinforcement instrumental conditioning (NR-IC). Under a NR-IC setup, the target behavior eliminates the occurrence of an aversive stimulus. This leads to a reinforcement of the behavior. In the context of (NR-IC), GBF forces the users to lower their arousal level (i.e. the instrumental response) to reduce game penalty (the aversive outcome) and progress in the game. In other words, there is a negative contingency between the instrumental response and aversive outcome. This is a form of stress training that has been used in prior work for teaching stress self-regulation skills in military and other settings [44]. Therefore, by adapting the game in a way that encourages relaxing behavior, the user is prompted to modify their response to stressors and learn to self-regulate. Furthermore, NR-IC increases the likelihood that the instrumental behavior will be repeated in the future [45] indicating skill transfer.

3.2 Biofeedback in the game

Based on our prior study [12], we chose breathing rate (BR) as the physiological variable to be used for biofeedback in the game. Compared to other physiological variables (e.g., heart rate, electrodermal activity), which are primarily under autonomic control, breathing is unique because it can be manipulated voluntarily by the player. Reducing one's breathing rate shifts the autonomic balance [46] and can provide relief from stress [47]. In fact, prior studies [48] have shown that the cardiovascular system has a resonant frequency of 0.1 Hz (6 breaths per minute): breathing at that rate maximizes heart rate variability, an indicator of relaxation. Thus, breathing parameters (breathing rate in particular) are not only intuitive to the player, but also an effective way to influence their physiology [49, 50].

As discussed in the introduction, the purpose of our study was to evaluate three types of biofeedback: based on peripheral visual cues, based on game adaptation, and based on combined visual/game adaptation. We implemented these three forms as follows.

3.1.1 *Biofeedback through peripheral visual display*

We presented visual biofeedback (*VBF*) by means of two visual cues: a numeric indicator of the player's BR at the top of the game screen, and an icon indicating whether their BR is increasing (red up-arrow) or decreasing (green down-arrow). Both cues were displayed continuously throughout the game. In addition, we displayed the text prompt *'Please try and relax!'* at the bottom of the screen whenever the player's BR was increasing. Both types of displays are illustrated in Fig 1(b).

3.1.2 *Biofeedback through game adaptation*

We implemented game biofeedback (*GBF*) by manipulating the game based on the player's BR. Specifically, we allowed the cannon to fire bubbles automatically without user

[2] Instrumental conditioning is the process of presenting rewards or penalties to the user based on their response. This is also known as the reinforcement, and can be used to modify a behavior [42, 43].

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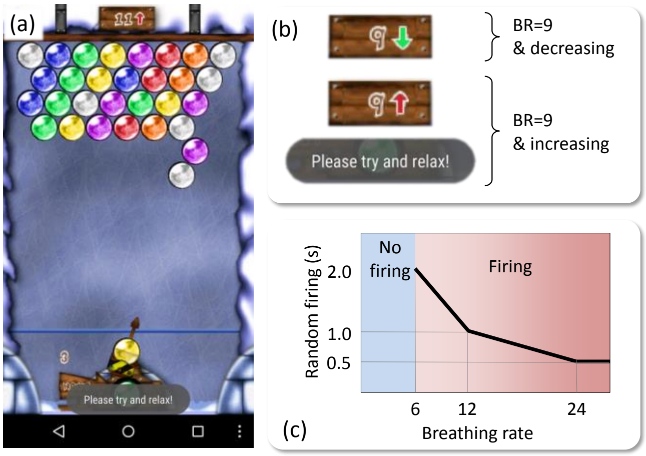

Fig 1 (a) Screenshots of the casual game. (b) Peripheral visual display of breathing rate. (c) Relationship between breathing rate and automatic shooting frequency.

input, the auto-shooting interval being defined as a piece-wise linear function of the player's BR –see Fig 1(c). As the user's BR increases, the interval between consecutive random bubble shot decreases: at BR = 12 bpm, bubbles are automatically shot every second, whereas at BR = 24 bpm, auto-shooting occurs every half second, making the game increasingly difficult. To facilitate recovery, the game adaptation algorithm also monitors the rate of change of BR and disables auto-shooting if the player's BR begins to decrease. In other words, auto-shooting only occurs if the BR is above a target value of 6 breaths per min (bpm)[3] *and* increasing.

3.1.3 *Combined game biofeedback*

We implemented combined game biofeedback (*XBF*) by integrating visual biofeedback and game adaptation. Thus, in this condition users are presented physiological information via both biofeedback mechanisms during gameplay. This group allows us to study interaction effects.

4 EXPERIMENTS

We conducted experimental trials as part of an independent study with each participant playing a single randomly assigned treatment (visual, game biofeedback, combined) or a control condition (game only). We adopted this between-subject design to minimize fatigue, carryover effects (where the first treatment interferes with the second treatment) and learning effects (resulting in a better performance and/or unexplained trends in arousal during the assessment tasks).

- Visual biofeedback (*VBF*): The player's BR is displayed numerically along with the up/down arrows and text prompts, but the game does not adapt based on BR.
- Game biofeedback (*GBF*): The game adapts based on the player's BR, but the numeric indicator, up/down arrows, and text prompts are not displayed.
- Visual and game biofeedback (*XBF*): The game adapts based on BR, <u>and</u> also displays the numeric indicator, up/down arrows, and text prompts.
- Game only (*Control*): Participants play a game without biofeedback or displays of physiological information. This serves as the control group.

Game difficulty for the *VBF* and *control* groups was set to the normal mode (medium difficulty), whereas participants in the *GBF* and *XBF* could only play at this level under slow and sustained breathing.

Participant recruitment was done by posting flyers across the university campus. 24 participants (6 participants per group) were recruited for this study: 9 females and 15 males, all university students or staff, all in the age range of 19-31 years. No particular inclusion/exclusion criterion was used during the recruitment process. All participants had experience playing mobile casual games but did not have any prior experience with biofeedback tools. We received approval from the Institutional Review Board prior to the study, and signed consent from each individual participant before the session. Participants played the game on a Google Nexus 5 phone placed on a smartphone cradle. The participants used a headphone to listen to game event related sounds (e.g. level clear, level fail, bubble match). To avoid motion artifacts in the EDA signal, participants were instructed to play the game using their dominant hand while the EDA electrodes were attached to the non-dominant hand; see Section 4.3.

4.1 Protocol

The experimental session is summarized in Fig 2. It consisted of five phases: baseline, pre-treatment assessment (pre-test), training, treatment, and post-treatment assessment (post-test).

- Baseline**:** Participants followed an auditory pacing signal, which guided them to breathe at 6 bpm: inhaling for 4 sec and exhaling for 6 sec. This choice was motivated by prior work [51] showing that a respiratory pattern with a short inspiration followed by long expiration leads to a higher respiratory sinus arrhythmia (RSA)[4]. The baseline phase lasted 5 min.
- Pre-test: Participants performed a modified Stroop Color Word Test for 3 min; see section 4.5 for details. This phase provided an initial measure of the player's arousal when presented with a mild stressor. No biofeedback is presented to the user during this phase.

[3] As discussed earlier, breathing rates near 6 bpm (0.1 Hz) maximize heart rate variability [48].

[4] RSA refers to the natural fluctuations in the HR caused by breathing patterns; HR increases during inhalation and decreases during exhalation.

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- Training: Participants played the game (without adaptation or biofeedback) for 3 min to familiarize themselves with the game prior to the treatment.
- Treatment: Participants are assigned to one of the four groups (*VBF, GBF, XBF*, or *control)*. They play the corresponding version of the game for 6 sessions, each session lasting 5 min (30 min total) with a 1 min break between sessions. During this break, participants are given their game score and relaxation score (see section 4.4), and are asked to improve both.
- Post-test: Following treatment, participants complete the Stroop color word test (CWT) a second time, and a previously-unseen mental arithmetic task (King of Math), each lasting 3 min; see section 4.5 for details. We counterbalance the order of the two tasks to remove any ordering effects.

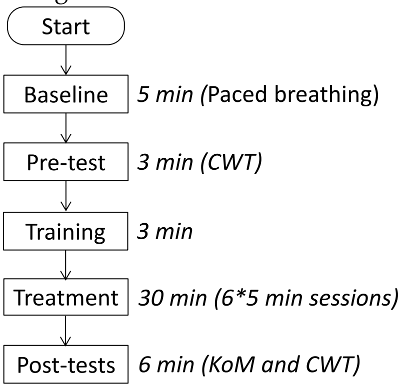

Fig 2 Experimental protocol. CWT: color word test, KOM: King of Math (mental arithmetic task)

4.2 Instructions

Participants were provided with specific instructions at different points during the experimental session, depending on the group to which they had been randomly assigned. These instructions were as follows:

- Common to the four groups:
  - Before treatment. "*Relax: Try and breathe slowly, maintaining your BR around 6 bpm. Try and do the best in the game to score maximum points*"
  - Before post-test. "*Stay calm by using the skills you learned during the treatment session. Try and do the best in both assessment tasks*"
- Common to the three biofeedback groups:
  - Scoring scheme. "*Your score will depend on both your game performance and how relaxed you are while playing the game. At the end of each game session, I will give you two scores: your game score and your relaxation score. Try to improve on both*"
- Specific to each group:
  - VBF: "*During gameplay you will be shown your BR and whether it is increasing or decreasing*"
  - GBF: "*The game will be affected by your BR; higher BR will make the game more difficult*"
  - XBF: "*The game will be affected by your BR; higher BR will make the game more difficult. In addition, during gameplay you will be shown your BR and whether it is increasing or decreasing*"
  - Control: No relaxation scores were provided; participants were only asked to stay calm and do well in the game.

4.3 Physiological measures

We measured stress reactivity and skill transfer by means of three physiological variables: breathing rate (BR)[5], heart rate variability (HRV), and electrodermal activity (EDA). We measured BR using a Bioharness BT (Zephyr Tech.) [52], worn across the player's sternum, immediately below the pectoral muscles. We computed HRV from the RR intervals provided by the Bioharness BT. Specifically, we used the time domain measure pNN50[6]. Finally, we measured EDA using a FlexComp Infinity encoder (Thought Technology Ltd.) [53] and disposable AgCl electrodes placed at the palmar and hypothenar eminences of the player's non-dominant hand. From the raw EDA signal, we extracted the number of skin conductance responses (SCRs) using Ledalab [54]. A change in the EDA signal is considered an SCR if the signal slope is increasing and its amplitude larger than a minimum amplitude criterion, which in our case was set to 0.05 μS [12, 54].

4.4 Computation of relaxation score

Following Larkin et al. [39], participants in the three biofeedback groups (VBF, GBF, XBF) were verbally informed about their relaxation score after each 5-min gameplay session. The relaxation score captured the participant's ability to maintain a slow breathing pace during treatment. It was computed by analyzing BR data in 30-second windows (sliding by 1 second) as follows:

1) If the BR remained in the range of 4-8 bpm during the 30s window, the score was increased by 5 points;
2) If the BR was outside that range consistently throughout the 30s window, the score was decreased by 5 points;
3) Otherwise, the score remained intact (0 points).

In addition to this relaxation score, players were also verbally informed of the change in relaxation score and the game score.

4.5 Assessment tasks

We used two tasks to elicit stress during the experiments: a modified version of the Stroop Color Word Test (CWT) and a mental arithmetic task. The CWT is widely used in psychophysiology to increase arousal [55]. In the conventional CWT, participants are shown one of four words (red, blue, green, and yellow) displayed in differ-

[5] Breathing rate was used both assessment of arousal and for real-time game adaptation. For game adaptation, BR greater than 6 bpm and increasing was taken as a state of non-relaxation; see Fig 1(c).

[6] The parameter pNN50 is the number of successive RR intervals greater than 50 ms divided by the total number of RR intervals, i.e. the fraction of consecutive RR intervals greater than 50 ms.

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ent ink color, and are asked to choose the ink color of the displayed word; see Fig 3(a). To make the task more challenging, our implementation switched between asking for the ink color or the text of the word, and also switched between two modes (congruent and incongruent) every 30 seconds. In the congruent mode, the concept and the ink color were the same, e.g., the word "red" in red ink. In the incongruent mode, the concept and ink color were different, e.g., word "blue" in red ink. During pre-test, the stimulus was displayed for 1 second, and the participant had 3 seconds to respond; the response time was reduced to 2 seconds during post-test to ensure that the task remained challenging despite any learning effects from pre-test.

For the mental arithmetic task, we used King of Math (KOM) [56], a game-like app that allows the player to practice various math concepts, including basic arithmetic, geometry, and fractions. During a KOM session, the participant solves math problems by choosing the correct answer from four options; see Fig 3(b). We used the *mixed* section of the app, which presents the user with an assortment of questions from the various categories. Each level consists of 10 questions, which have to be completed in a limited amount of time (100 seconds). Each level starts with an initial score of 100,000, which is reduced by 1,000 every second spent at that level. Thus, the faster the participant answers, the higher score they attain. In addition, every mistake carries a 5,000-point penalty, and 3 mistakes within a single level prevent the participant from progressing to the next level.

(a) (b)

Fig 3 Screenshot of tasks used for assessment (a) Color word test (b) King of Math

5 Results

To assess the effectiveness of the different biofeedback mechanisms, we first examine the physiological variables (BR, HRV, and EDA). Next, we evaluate the pace of acquisition of deep-breathing skills during treatment and performance during the assessment tasks. Finally, we present the subjective evaluation from participants. We also analyze the results to assess their statistical significance. Prior to the statistical analyses, we performed one-sample Kolmogorov-Smirnov (KS) test on the BR, EDA, and HRV data to assess the null hypothesis that the data is drawn from normal distribution. The KS test for the three signals failed to reject the null hypothesis (at 5% significant level i.e. $P<0.05$), which indicates that the data for each signal was normally distributed.

To test the assumption of homogeneity of variance (HOV)[7] before ANOVA analysis, we performed two-sample and multiple-sample variance tests on the data. We tested the HOV assumption with Bartlett and Levene tests with a null hypothesis that the data in the different groups comes from normal distribution with the same variance. Both group-wise (comparing all four groups) and pair-wise (comparing pairs of two groups at one time) HOV tests failed to reject the null hypothesis.

5.1 Physiological variables

5.1.1 *Breathing rate (BR)*

Fig 4 shows the average BR for participants in the four groups during paced breathing, pre-test, treatment, and post-test.

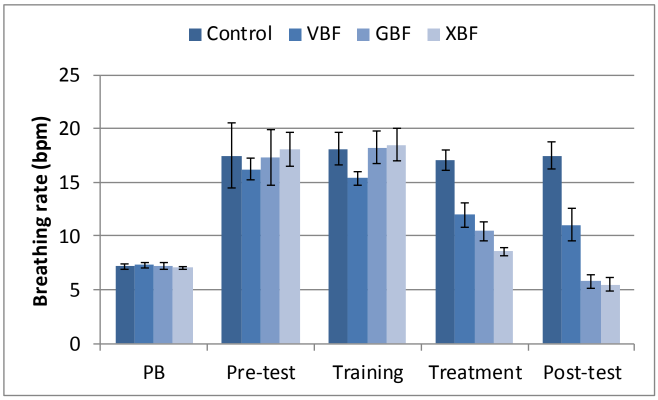

Fig 4 Average breathing rate per group during paced breathing (PB), pre-test (CWT 1), treatment, and post-test (CWT 2 and KOM) for all the groups.

BRs for the four groups are equivalent during the first two phases: a low of approximately 6 bpm during the initial paced breathing session, which shows that participants successfully followed the pacing signal, and a maximum of approximately 17 bpm during pre-test, an expected result since the color word test acts as a mild stressor. Differences between the four groups emerge during treatment: participants in the *control* group maintain the high BR at pre-test, whereas those in the three biofeedback groups show a marked reduction in BR. Among the latter, combined biofeedback elicits the lowest BR during treatment, followed by game biofeedback. Differences among the three biofeedback groups become stark at post-test: the two game-adaptation groups (*GBF* and *XBF*) lower their BRs beyond those achieved during

[7] The assumption of homogeneity of variance implies that the comparison groups have the same variance. It should be noted that moderate deviations from the assumptions of equal variances do not significantly affect the ANOVA statistics as long as the group sizes are equal i.e. ANOVA is robust to small deviations from the HOV assumption.

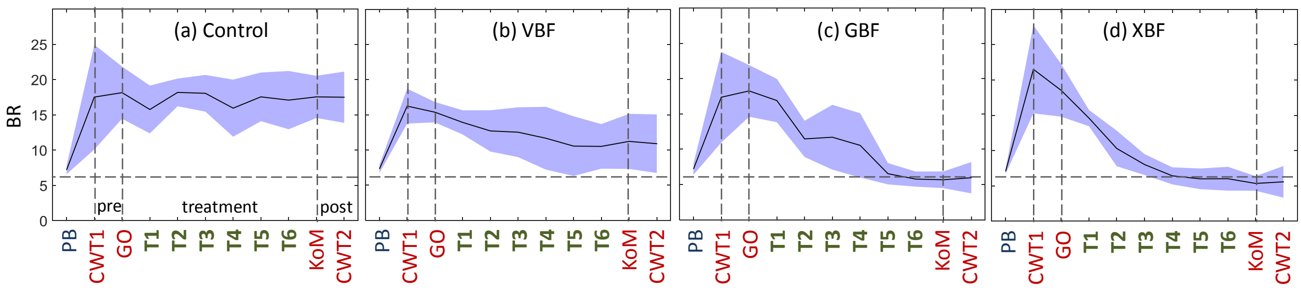

Fig 5 Average breathing rate during the course of the experiment (a) *control* (b) *visual (VBF)* (c) *game biofeedback (GBF)* (d) *combined (XBF)*. Shaded bands indicate one standard deviation. PB: paced breathing, CWT: color word test, control: game only, T1-T6: 6 treatment session, KOM: king of math. Vertical lines show onset of pre-test, treatment, and post-test; horizontal line shows 6 bpm (i.e. the target BR) for reference.

treatment, making them comparable to those attained during paced breathing, whereas those in the *VBF* group have the BRs attained during treatment, but not lower. Participants in the control group do not show any reduction in BR compared to pre-test. These results provide strong evidence of skill transfer for the three biofeedback groups, with a clear advantage for game adaptation.

To validate these results, we performed 1-way ANOVA on the difference in BR between pre- and post-test. This analysis showed a statistically significant difference between the four groups: $F(3,20) = 23.51, p < 0.05$. We also performed 2-way ANOVA with the two biofeedback mechanisms (visual and game adaptation) as independent factors and BR gains as the dependent variable. We observed a main effect for both factors (*GBF*: $F(1,20) = 56.04, p < 0.05$, *VBF*: $F(1,20) = 10.38, p < 0.05$), and a marginally significant interaction: $F(1,20) = 4.1, p < 0.06$. We also performed a 1-way ANOVA between the *VBF* and the *GBF* groups (i.e. removing the interaction term) and found a significant difference in their means: $F(1,10) = 10.35, p < 0.05$. This analysis suggests that both biofeedback mechanisms help users lower their BR. Based on the group means and F-scores, we posit that game adaptation triggers a relaxation response (since it affects gameplay) and is more effective in reducing BRs, while visual biofeedback helps maintain the target BR.

Finally, we examined the time course of BRs during the experiment, with particular attention to the six treatment sessions (T1-T6). Results are summarized in Fig 5. The two game adaptation groups (*GBF* and *XBF*) show a sharp decline in BRs as the treatment sessions progress and reach the target BR in the last two sessions (T5, T6). In contrast, the *VBF* group has a moderate decline as the treatment progresses, but the BR never reaches the target range. Also of note, BRs for participants who received only one form of biofeedback (*VBF* or *GBF*) show a larger variance during treatment compared to participants who receive the two forms of biofeedback combined (i.e., XBF). The high variance observed in the *GBF* group (especially during the initial part of the treatment) may be attributed to the time it takes participants to understand the biofeedback mechanism (i.e. game adaptation) and its effect on the game. Towards the end of the treatment session, the variance observed in the *GBF* group was similar to the *VBF* group, suggesting that participants were able to follow the biofeedback and control their breathing. A few participants in the *VBF* group reported that they focused more on the gameplay than on the biofeedback display; see section 5.4 for user comments. This division in attention between gameplay and biofeedback may have led to the high variance observed in their breathing responses. Finally, BRs for participants in the control group are flatlined during the six treatment sessions, indicating that the game alone had no effect on breathing behavior.

5.1.2 *Electrodermal activity (EDA)*

Next, we compared EDA in terms of the number of skin conductance responses per min ($SCR_{\#}$). Results are shown in Fig 6. As with BRs, participants in the four groups had a low $SCR_{\#}$ during paced breathing (indicative of relaxation), followed by a notable increase during pre-test (consistent with the introduction of a stressor). $SCR_{\#}$ decline during treatment for all participants, including those in the *control* group, which suggests some degree of habituation to the game. However, only the *XBF* group maintained a low $SCR_{\#}$ at post-test, whereas the other three groups showed an increase relative to treatment.

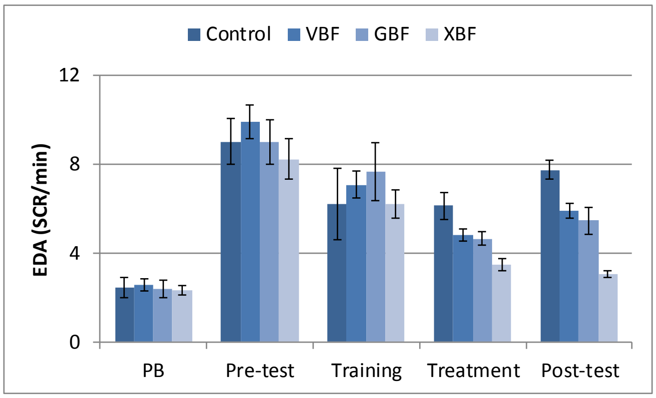

Fig 6 Average EDA (SCR/min) during paced breathing (PB), pre-test (CWT 1), treatment, and post-test (CWT 2 and KOM) for all the groups.

One-way ANOVA on the increase in $SCR_{\#}$ between pre- and post-tests shows a statistically significant difference between the four groups: $F(3,20) = 3.65, p < 0.05$. A 2-

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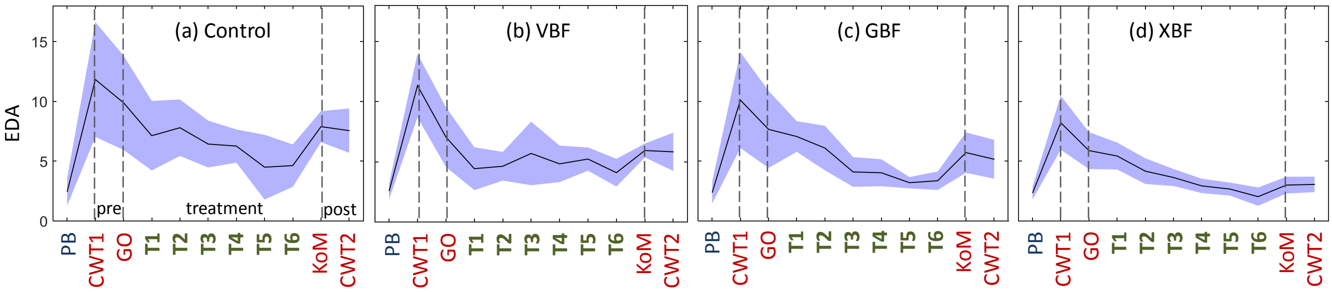

Fig 7 Average EDA (SCR#/min) during the course of the experiment (a) *control* (b) *visual (VBF)* (c) *game biofeedback (GBF)* (d) *combined (XBF)*. Shaded bands indicate one standard deviation.

way ANOVA with the two biofeedback mechanisms (visual vs. game adaptation) as factors indicated strong main effects (VBF: $F(1,20) = 4.47, p < 0.05$; GBF: $F(1,20) = 6.48, p < 0.05$,), and no interaction effects ($F(1,20) = 0.01, p < 0.9$).

Fig 7 shows the time course of $SCR_{\#}$ for each group during the experiment. As the treatment progresses (T1-T6), the *GBF* and *XBF* groups show a gradual decrease in arousal following the higher values observed during pre-test. Participants in the *control* group also showed a decrease in $SCR_{\#}$, though not as consistent as that on the *GBF* or *XBF* groups –see error bands. No particular trends were observed for *VBF* biofeedback during treatment: participants in this group are able to lower their $SCR_{\#}$ within the first session (T1) and maintain it throughout the treatment. Two factors can explain this result. First, visual biofeedback is relatively intuitive, whereas game biofeedback is provided through changes in the game. As such, visual biofeedback is easy to grasp within a single treatment session. Second, visual biofeedback does not affect the game, whereas game biofeedback increases the game difficulty when BRs increase beyond the target rate. This introduces a learning curve for participants in the *GBF* and *XBF* group. However, only the *XBF* group had post-test arousal levels similar to those obtained during the initial paced breathing session, which indicates stronger skill transfer than in the other three groups.

5.1.3 *Heart rate variability (HRV)*

Finally, we assessed HRV levels for participants in the four groups. As shown in Fig 9 and Fig 8, the four groups display a high HRV during the initial paced breathing session followed by a reduction during pre-test; these results are consistent with those obtained on BR and EDA. During treatment, participants in the three biofeedback groups (*VBF, GBF*, and *XBF*) experience a gradual rise in HRV, whereas participants in the *control* group only show a marginal increase. Of note, for participants in the *XBF* group, HRV continues to increase during post-test, reaching the baseline level attained during the initial paced breathing session. In contrast, participants in the *GBF* and *VBF* groups show a drop in HRV during post-tasks relative to the values attained at the end of the treatment, the drop being more significant in the case of *VBF* –see Fig 9(b, c). One-way ANOVA of HRV differences between pre- and post-test shows no statistically significant differences among the four groups: $F(3,20) = 1.04, p < 0.39$. A 2-way ANOVA fails to show any significant main effects (visual: $F(1,20) = 0.7, p < 0.41$; GBF: $F(1,20) = 0.16, p < 0.7$),) or interaction ($F(1,20) = 2.15, p < 0.15$).

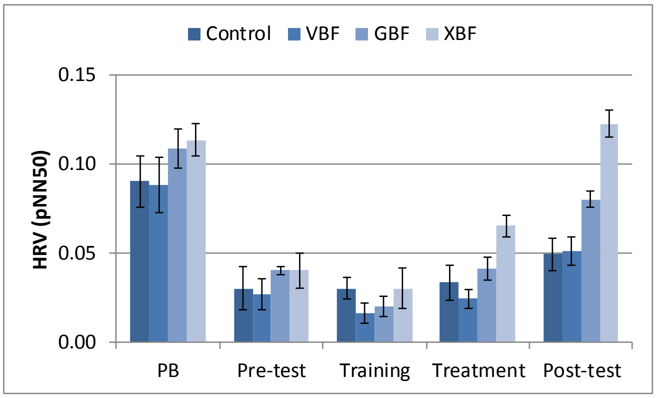

Fig 8 Average HRV (pNN50) during paced breathing (PB), pre-test (CWT 1), treatment, and post-test (CWT 2 and KOM) for all groups.

5.2 Pace of learning

In a second set of analyses, we examined differences in pace of learning, measured as the amount of time participants needed to reach and maintain an average BR below 8 bpm for an entire (5 min) treatment session. All participants in the *GBF* and *XBF* groups were able to bring their BR down to that level within the six treatment sessions (T1-T6), compared to only one participant in the *VBF* group and none in the *control* group. Direct comparison between the *XBF* and *GBF* groups shows a faster acquisition of deep-breathing skills for *XBF* (an average of 3.33 sessions) compared to *GBF* (4.16 sessions). Though most participants in the *VBF* group could not reach the 8 bpm mark, Fig 5 shows that they were able to lower their BR during treatment, albeit at a slower pace than *XBF* and *GBF*. Perhaps, then, additional treatment sessions may have allowed *VBF* participants to acquire the deep breathing skills.

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5.3 Performance results

To assess participant performance, first we examined differences in CWT scores before and after treatment. As shown in Fig 10(a), all groups showed an increase in CWT score during post-test, a result that may be attributed to learning effects. The *VBF* and *control* groups showed a larger increase (17.33 and 16.33 points, respectively) than the *GBF* and *XBF* groups (9.17 and 12.17 points, respectively). However, 1-way ANOVA fails to reveal any statistically significant differences between the four groups: $F(3,20) = 0.57, p < 0.64$. Performance in the KOM task was higher for the *VBF* and *control* groups than for the *GBF* and *XBF* groups -see Fig 10(b), but this difference was not statistically significant: $F(3,20) = 0.83, p < 0.49$.

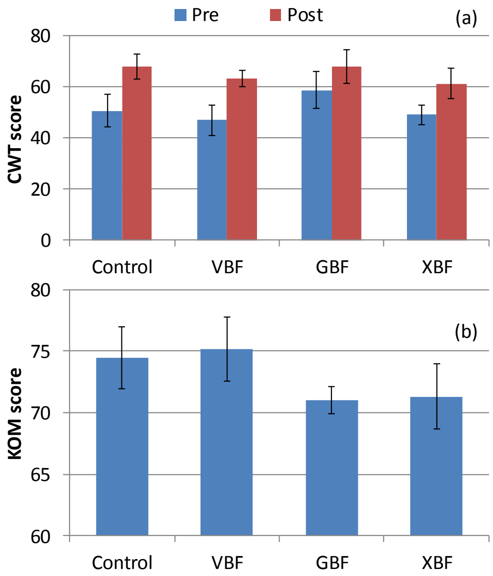

Fig 10 (a) Average CWT scores during pre- and post-tests. (b) Average KOM scores

In summary, participants in the *control* and *VBF* groups showed larger improvements in CWT and higher performance during KOM than the other two biofeedback groups. Considering that the *control* and *VBF* groups had a higher level of arousal during post-task, it is possible that high arousal could have facilitated both tasks. However, correlation analysis between performance scores and arousal at post-test reveals only a weak positive correlation; see Table 1.

	BR	HRV	EDA
CWT2	0.13	-0.06	0.234
KOM	0.06	-0.05	0.182

Table 1 Pearson correlation coefficient ρ between arousal at post-test, and performance in CWT2 and KOM

5.4 Subjective analysis

In a final analysis, we examined subjective assessments provided by participants at the conclusion of the experiment. Participants in the *VBF* group found it difficult to increase their relaxation score, as indicated by the comment "[I] *kept forgetting about relaxation score improvement even though it was mentioned after every single game*". Another participant in this group mentioned that "*the BR on the top was helpful, but many times I was not looking at them, especially during difficult levels*". Two participants in this group also recommended using auditory feedback to indicate their BR level, instead of a visual display. These comments indicate that participants in the *VBF* group preferred an additional mechanism (auditory in this case) to provide biofeedback that complements visual biofeedback. Participants in the *GBF* group also indicated the need for a display of their current BR level; as noted by one participant in reference to the auto-shooting penalty for fast breathing: "*I could see the game change but some indication right before they* [bubbles] *start shooting would have been nice, say 5 sec. This would have allowed me to control my breathing*". Similarly, another participant commented that "*it was easy to maintain slow breathing once you knew how slow it needs to be; during the game I was not sure how much I need to slow down my breathing rate.*" One participant in the *XBF* group echoed sentiments expressed by participants in the *VBF* group regarding auditory feedback: "*it was helpful that my breathing was shown on top of the screen; auditory tone would also have been helpful.*" Another participant noted the need for more training: "*more practice of deep breathing will be good*". In contrast, participants in the *control* group did not find the game particularly useful for relaxation: "*I don't know if playing frozen bubble game helped me in any way to stay relaxed. I think paced breathing was more effective.*" Overall, participants responded positively towards the GBF treatment and indicated that they would use it frequently if the system was available to them. Altogether, these comments provide directions for future

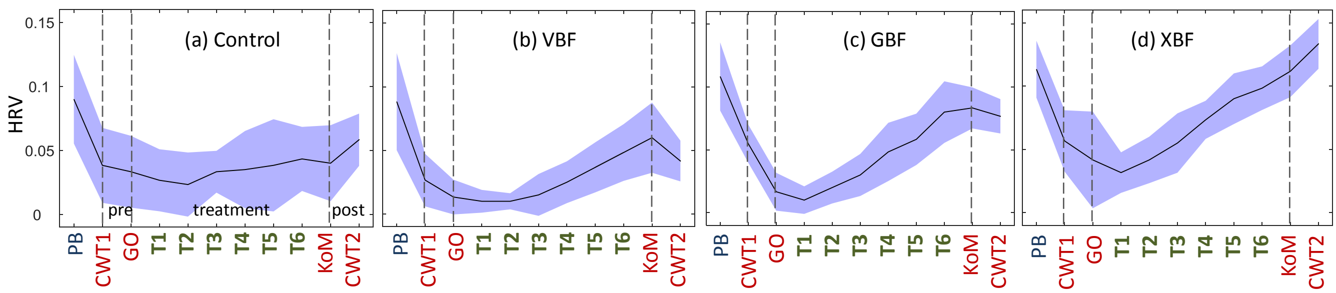

Fig 9 Average HRV (pNN50) during the course of the experiment (a) *control* (b) *visual (VBF)* (c) *game biofeedback* (*GBF*) (d) *combined (XBF)*. Shaded bands indicate one standard deviation.

work to make GBF-based treatments more effective.

6 Discussion

Key to any biofeedback intervention is to present physiological information in a way that not only improves the patients' awareness of their internal state (e.g., high arousal), but also guides them towards a more desirable one (e.g., low arousal or relaxation). This paper sought to evaluate the effectiveness of three forms of biofeedback (*VBF*, *GBF*, and their combination) to promote relaxation and transfer of relaxation skills. In *visual* biofeedback, physiological information is presented directly to the user via a visual display, without any form of game adaptation. Thus, *VBF* is equivalent to traditional biofeedback, where stress levels are used only for visualization. In contrast, in *GBF*, physiological information is embedded into the game (i.e. the game adapts based on player's physiology), but not overtly presented to the player. Our experiments indicate that *GBF* outperforms *VBF* in terms of lowering arousal during treatment (skill acquisition) and transferring these skills to subsequent stressful tasks not used during treatment. Our experiments also indicate that delivering both forms of biofeedback simultaneously leads to better skill acquisition and skill transfer than delivering them in isolation.

6.1 Skill acquisition and retention

Skill transfer was higher for the *GBF* and *XBF* groups than for the *VBF* group, a result that can be explained in terms of instrumental conditioning. In instrumental conditioning, a reinforcement is used to modify (increase or decrease) a behavior. In this context, GBF can be viewed as a form of avoidance conditioning [57], which uses negative reinforcement to increase a behavior (deep breathing in our case) to avoid the occurrence of an aversive stimulus (game penalty).

Skill acquisition with game biofeedback and games in general may also be explained from a neuronal perspective. Performing goal directed tasks, i.e. playing a videogame, leads to dopamine[8] release in the striatum of the brain [58]. Dopamine release is an indicator of memory storage events and attention [59], and is also involved in learning stimuli or actions that predict rewarding or aversive outcomes. A study on the effects of videogame play on striatal dopamine release found a monotonic increase in dopamine levels during gameplay and the levels stayed higher (compared to baseline) after the gaming session ended [58]. Since dopamine release is associated with memory storage, videogames may facilitate better learning of relaxation skills. It may further assist in detecting physiological stress triggers (i.e. improving perception of stress), and reinforcing relaxation behaviors.

Our study shows that the two game-adaptation treatments (*GBF*, *XBF*) led to better transfer of relaxation skills during the subsequent stress-inducing tasks than visual biofeedback did. This can be explained via *stimulus generalization*, where a conditioned behavior (slow deep-breathing) learned in response to a stimulus (game penalty) is elicited in response to another similar stimulus (stress inducing post task) [60]. The skill transfer result is also consistent with previous studies on *contextualized learning*, a mechanism that couples learning with real-life experience and context [61]. According to this view, combining virtual objects (e.g., videogames) with real-world tasks (e.g., deep breathing) provides meaning to otherwise abstract physiological information [62]. This allows the player to internalize the relaxation process while performing a task, which leads to improved transfer of skills. To maximize retention of skills to subsequent tasks, First Principle of Transfer is also relevant [60]. It states that "*when stimuli and responses are similar in two situations, maximal positive transfer*[9] *occurs*" [60, 63]. This suggests that, to maximize transfer, training should be done within a number of different contexts.

We also found that the *XBF* treatment leads to fastest acquisition of deep breathing (see Fig 5), followed by *GBF*. All the participants in these two groups were able to reach the target BR within the 6 training sessions. In contrast, only 1/6 participants in the *VBF* treatment and none in the *control* treatment could reach the target BR. On further analysis, however, we found that 4/6 participants in the *VBF* group were able to lower their BR to 10 bpm and maintain it during treatment. This suggest the need for longer treatment sessions that continue until the participant acquires deep breathing skills –as opposed to the fixed length treatment session used in our study. This is similar to the paradigm in [10], which used a dual stopping criterion for the training -participants had to reach the target HR or complete three 2-hour sessions, whichever happened first. In our assessment, the *control* group did not acquire relaxation skills, an expected result since videogames are generally designed to increase the arousal levels rather than relax [8].

6.2 Task performance and multi-tasking

Our results indicate that participants in the *VBF* and *control* groups attained marginally higher test scores during the post-tasks than those in the *GBF* and *XBF* groups (though the differences were statistically insignificant); see Fig 10. Taken together with the physiological indicators, we may infer that higher arousal leads to higher task performance. However, correlation analysis showed only a weak positive correlation between arousal and performance; see Table 1. This observation can be explained by the Yerkes Dodson law [64], which governs the relationship between arousal and performance levels. It states that the relationship between performance levels and arousal is not linear and instead follows an inverted-U relationship: arousal increases with physiological arousal up to a point beyond which the stress becomes excessive, diminishing the performance. Additional insight into par-

[8] Dopamine is a neurotransmitter that allows the modulation of information passed between sections of the brain.

[9] Positive transfer: learning in one situation facilitates learning or performance in another situation.

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ticipant's performance and cognitive workload can be obtained by analyzing their reaction time and number of mistakes during the post-tasks. Unfortunately, we did not collect this information in the current study, but plan to do so in future studies.

Our proposed treatment requires that participants perform two tasks concurrently: control their breathing and play the game. This can lead to task interference and negatively impact performance in both tasks [65]. A number of studies [66, 67] have shown that multi-tasking results in lower performance on individual tasks, largely due to increased mental workload, increased working memory demands, and task switching overhead. However, our results show that the two game-adaptation treatments (*GBF* and *XBF*) lead to improved performance on the deep breathing task while achieving only marginally lower performance on the post-tests than the *VBF* and *control* groups. Multi-tasking performance can be improved if one task provides additional information for completing the other task –as opposed to competing for resources [68]. Such seems to be the case in our GBF interventions, where BR information is dynamically integrated in the game. Such integration makes the cues indicating high BR more salient, thus allowing for more efficient dual-task performance. Finally, prior work [65] has shown that dual task performance improves if the two tasks utilize resources from separate dimensions (e.g., visual and auditory) as opposed to both competing for the same resource. This is consistent with participants' suggestions that we use auditory feedback. Thus, combining auditory and visual channels for biofeedback may reduce task interference and improve performance.

7 Limitations and Future Work

Our study has a number of limitations, including a short training period in a lab setting, cognitive stressors that cannot capture the complexity of real-world scenarios, and a focus on short-term skill transfer. Thus, further work is needed with longer (multi-session) training in real-world, ambulatory settings to determine the long-term persistence of game biofeedback. In our work, we did not investigate user's experience levels during gameplay. Researchers have shown that physiological measures correlate with gameplay experience and can be used to increase user engagement and immersion [69]. Further work is required to study user engagement in the context of relaxation skill transfer. Finally, our study was conducted with a (relatively) small group of participants. A power analysis on the breathing rate results indicated a power of 54% to 98% for the various treatment conditions when compared with the control group. We also calculated the required sample size to detect a statistically significant difference in the mean breathing rate before and after the treatment across the four groups. We based the estimated required sample size computation using the standard parameters (α = 0.05, power = 80%) and effect size of 1.09 - 2.63 for the four groups (computed using Cohen's method [70]). This resulted in a sample size of 12 participants per group. Future work will involve experimental trials with a larger sample size in real world settings.

Our study has focused on promoting slow breathing, a technique known to enhance parasympathetic activity and help move the body towards a relaxed state. Future studies will explore additional respiratory parameters. A possible alternative –or complement to BR, is the ratio of expiration to inspiration (E/I ratio). Breathing with a short inspiration period followed by a long expiration period leads to higher HRV than breathing with a long inspiration followed by a short expiration [51]. Rapid inspiration inhibits the vagal activity and increases the phasic heart rate, while exhalation activates the vagus nerve, decreasing the heart rate. This represents a promising direction for future work, where game biofeedback may be used to train users to reach a higher E/I ratio.

When comparing arousal levels during the two post-tasks, we found that participants had higher arousal during KOM -a novel task, relative to CWT (used during both pre- and post-test). This is in agreement with Goodie and Larkin [10], who showed that participants' ability to lower HR reactivity degraded during a novel task. This also indicates the necessity for training within a number of contexts to facilitate higher skill transfer to novel tasks.

Finally, when exposed to similar stressful conditions, different individuals react differently [71]. Therefore, a single solution for stress self-management is unlikely to work for all users. The effectiveness of game biofeedback may depend on a number of factors, including task complexity, multi-tasking capabilities, or individual's perception of visceral/physiological states. For some participants, a multidimensional program, as suggested in [2, 72], might be better suited. These programs consist of activities including meditation, exercise, videos/animations, and videogames to deliver self-guided stress management training and therefore may cater to a wider population.

Future work will also involve detecting user stress levels in real world scenarios and triggering an intervention when needed. This is also known as just-in-time (JIT) behavioral intervention and would require development of other signal processing and estimation methods for stress detection in the wild. Prior works have studied the effectiveness of wearable sensors and mobile devices for stress detection [73, 74]. Sano and Picard [73] presented physiological markers for stress recognition using wearable sensors and smartphones. The authors performed correlation analysis between the subjective measures and the sensor data. Experimental results indicated a strong correlation between the subjective and objective measures of stress. Giakoumis et al. [74] focused on bio-signal features to improve stress detection accuracy. The aim of this study was to extract features that reduce between subject variability observed in physiological measures, which in turn influences the performance of emotion and stress recognition methods. The novel feature set (including EDA derivative, interbeat interval signature, and Legendre and Krawtchouk moments) showed a significant increase in stress detection accuracy compared to existing methods using conventional features. In future, we will aim to integrate these stress detection methods with game bio-

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feedback to provide stress training as/when needed.

Recent studies have explored the use of physiological measures as a way to capture facets of the player's gameplay experience; these measures can then be transformed into control signals to adapt game parameters, in what has been described as a biocybernetic loop [75]. Future work will involve combining the three dimensions: user's physiology, engagement, and performance level in game adaptation to develop novel affective systems. This approach may also be used to help players achieve and maintain flow [76], the cognitive state that leads to deep enjoyment. Flow can be achieved by achieving a balance between player's ability/skill level and game difficulty. Tracking user's arousal, performance level and game challenge level will allow for dynamically adapting the game to drive the player towards a state of flow. Prior work by Konrad, et al. [72] has shown the importance of balancing self-efficacy (not too difficult) and maintaining motivation (not too easy) to maximize compliance and development of self-regulation skills. Future work will study self-efficacy, motivation, and challenge levels in the context of game biofeedback with an aim to maximize the acquisition and retention of deep breathing skills while maintaining engagement in the game.

8 Conclusion

The effectiveness of biofeedback games depends on a number of variables, a few of which have been examined in past research. These include game genres [28], game difficulty [77, 78], score contingency [39], sign of feedback gain (e.g., positive vs. negative) [79, 80], type of feedback control (proportional-derivative, proportional-integral-derivative) [81], and physiological signal for biofeedback (e.g., HR, EDA, EEG) [12, 82]. This paper has explored an additional dimension of game biofeedback: whether feedback should be delivered through a visual channel or through subtle changes in the game. Specifically, we compared how these two forms of biofeedback can facilitate the acquisition and transfer of deep-breathing skills. We used concepts from instrumental conditioning to replace stress responses with relaxing behaviors. Our results indicate that biofeedback delivered through game adaptation is more effective than visual biofeedback, and that a combination of the two is more effective than either form of biofeedback in isolation. This result can have practical significance to game developers and researchers interested in integrating biofeedback into games.

Our study examined the effect of a short-term treatment on breathing behavior (i.e. deep breathing). Such brief treatments are relevant in both home and workplace settings with time constraints. Early research showed that even short and "easy" deep relaxation exercises can positively impact workers' cardiac autonomic function [83]. Consequently, relaxation exercises embedded in a videogame and played frequently for a few minutes each session may allow users to achieve sustained health benefits while also maintaining their productivity over the long-term and improving overall quality of life.

9 Acknowledgements

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