Chill-Out: Relaxation Training through Respiratory Biofeedback in a Mobile Casual Game

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Abstract. We present Chill-Out, an adaptive biofeedback game that teaches relaxation skills by monitoring the breathing rate of the player. The game uses a positive feedback loop that penalizes fast breathing by means of a proportional-derivative control law: rapid (and/or increasing) breathing rates increase game difficulty and reduce the final score of the game. We evaluated Chill-Out against a conventional non-biofeedback game and traditional relaxation based on deep breathing. Measurements of breathing rate, electrodermal activity, and heart rate variability show that playing Chill-Out leads to lower arousal during a subsequent task designed to induce stress.

1 Introduction

The World Health Organization has deemed job stress a global epidemic [1]. Job stress can have serious health consequences; it contributes to the obesity epidemic worldwide [2] and promotes a host chronic diseases, specifically cardiovascular disease –the leading cause of death in the developed world [1]. Stress can also have a profoundly negative effect on mental health, an under-acknowledged growing health problem around the world. Thus, reducing job stress could help reduce a number of negative health outcomes, increase the quality of life for workers, and result in an economic benefit for employers, e.g., increased worker productivity, reduced healthcare costs; as an example, workplace stress has been estimated to cost $150-300 billion to the US economy alone [3].

A number of techniques have been developed to help individuals self-regulate the impact of stress, including various forms of meditation, deep breathing and biofeedback [4]. Deep or diaphragmatic breathing (DB) is among the easiest and most intuitive evidenced-based methods for reducing stress [5]. Essentially, DB addresses the autonomic nervous system imbalance that arises following exposure to a stressor and activation of the sympathetic nervous system. As DB recruits the parasympathetic nervous system, action of the sympathetic nervous system becomes inhibited leading to a calmer, more relaxed state [6]. Many of the stress management programs delivered in workplace settings demonstrate that DB substantially reduces the

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symptoms of stress [4]. Biofeedback techniques are also used frequently as components of worksite stress management programs. Biofeedback allows patients to see changes in their physiology (e.g., skin conductance, heart rate) while they perform relaxation exercises, and can be effective, provided that the patient adheres to the training regime. Although beneficial, however, these traditional programs may not be sustainable since they require prolonged and substantial commitments of time and other resources from both workers and employers [7]. In addition, these techniques teach subjects 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].

Thus, there is a need for treatment techniques that are inherently engaging and that promote relaxation in the presence of stressors. Video games appear ideally suited for this purpose: they are tremendously popular (53% of adults age 18 and older play video games, both men and women [9]), and are very effective at manipulating arousal levels [10, 11]. Early research showed that even short and "easy" deep relaxation exercises could positively impact workers' cardiac autonomic function [12]. Consequently, relaxation exercises embedded in a videogame and played frequently for a few minutes each session may allow workers to achieve sustained health benefits while also maintaining their productivity over the long term. As a step towards our goal of relaxation training, we present Chill-Out, a novel method that combines biofeedback and adaptive games. Our approach combines an open-source casual game (Frozen Bubble) with a proportional-derivative positive feedback controller [13] that modulates game difficulty to reward slow breathing patterns and penalize high or increasing breathing rates. We compared the approach against a non-adaptive game and deep breathing (DB). We hypothesized that Chill-Out would lead to (1) better transfer of DB skills, (2) a reduction in physiological arousal, and (3) improved performance, all measured during a subsequent stress-inducing task.

2 Methods

We use concepts from classical control theory to model the process of adapting the videogame in response to the player's breathing rate. Illustrated in Fig. 1(a), a control loop consists of (i) the plant we wish to control, (ii) a sensor that measures the plant's output, and (iii) a controller that seeks to minimize the difference between the desired and actual output. When applied to game adaptation, the plant becomes the player, whose breathing rate we seek to regulate, the feedback loop consists of a respiratory sensor, and the controller is an algorithm that modulates the game's difficulty accordingly –see Fig. 1(b).

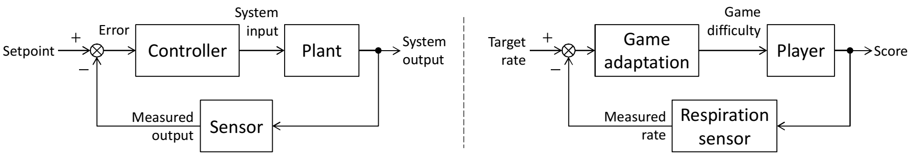


Fig. 1. Block diagram of (a) a classical feedback control system, and (b) our adaptive physiological game

In this work, we use a positive feedback control law where states of non-relaxation, which we define as those with breathing rates higher than 6 breaths per minute (brpm) and increasing ($BR > 6 \wedge \Delta BR > 0$), are penalized by increasing the game difficulty; breathing rates lower than 6 brpm are not penalized. We use a proportional derivative (PD) control law to adapt the game:

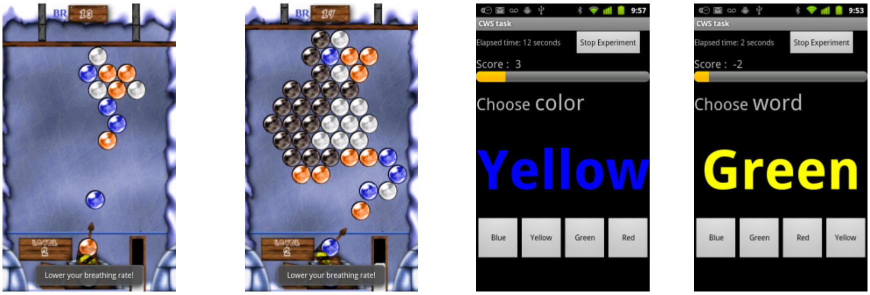
$$d(t) = K_p\, \epsilon(t) + K_d\, d\epsilon(t)/dt \tag{1}$$

$$\epsilon(t) = \begin{cases} b(t) - b_0 & (b(t) > b_0) \wedge \big(b(t) > b(t-1)\big) \\ 0 & otherwise \end{cases} \tag{2}$$

where $d(t)$ is the game's difficulty level, and $\epsilon(t)$ is the error in the current breathing rate $b(t)$ relative to the desired rate $b_0 = 6$. The term K_p is a proportional gain that causes the game difficulty to increase when the respiratory rate is higher than the desired value. Likewise, the term K_d is a derivative gain that adjusts the game difficulty based on the rate of change in respiration; adding a derivative term reduces overshoot and helps stabilize the process. Our implementation uses $K_p = 0.5$ and $K_d = 1$, values that were determined empirically.

2.1 Integration with a Casual Game

Selection of a suitable game genre is critical because it is the activity through which players learn to regulate their breathing rate. A few genres (e.g., first-person shooter) are unsuited due to their violent content and their possible connection with aggressive behavior. A few other genres require long time commitment (e.g. role playing, strategy), which makes them best suited for a specialized segment of the population, such as hardcore players [14]. A few of the remaining genres (e.g., quiz, board games) also lack the dynamic content that would be required to develop adaptive gameplay. The ideal game for physiological training belongs to what have been described as casual games: "*games developed for the general public,... appeal to people of all ages, gender and nationalities, … are fun and easy to play, … and are usually played for a short period of time, from 5 to 20 minutes*" [15].



Elapsed time: 12 seconds

Score : 3

Choose color

Yellow

Elapsed time: 2 seconds

Score : -2

Choose word

Green

(a) (b) (c) (d)

Fig. 2. (a-b). Screenshots of the Frozen Bubble game. (c-d) Screenshots of the modified Stroop CWT used as pre- and post-tasks.

Based on these considerations we adopted Frozen Bubble, a very popular casual game that is also available through a GNU General Public License. Fig. 2 shows a screenshot of the game; the user controls 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 before the ceiling collapses; to do so, the player has to group three or more bubbles of the same color, which causes them to collapse. Frozen Bubble provides a few parameters that are amenable to adaptation, such as auto-shooting rate, how fast the ceiling drops, or angular rate and lag of the cannon. Out of these, we chose the auto-shooting frequency as the game difficulty to be adapted, i.e., parameter $d(t)$ in equation (1), as it demands immediate action from the player. As the breathing rate crosses the threshold ($BR > 6 \wedge \Delta BR > 0$), the auto-shooting frequency increases making it harder to play the game. Hence to make progress on the game, the user must maintain a slow and sustained breathing pattern.

3 Experiments

We validated the approach using an experimental protocol with three phases. During the first phase (pre-task), participants performed a modified Stroop color word test (CWT[1]) for 4 minutes. During the second phase (treatment), participants were randomly assigned into one of three groups, a group that played the biofeedback game (GBF), a baseline group that performed deep breathing (DB[2]), and a control group that played the original Frozen Bubble game without adaptation or respiratory feedback (game only - GO[3]). Following our prior work [11], the duration of the treatment was 8 minutes for the three groups. During the final phase (post-test), participants repeated the CWT for an additional 4 minutes. Prior to the experiments the participants were asked to relax for 5 minutes. We adopted this between-subjects experimental design to avoid ordering effect due to learning or fatigue. Nine participants, (7 male 2 female; age range 22-33 years) participated in the study. Participants reported that they were in good health; none reported excessive drinking

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[1] The CWT is widely used in psychophysiology to increase arousal. In the conventional CWT, participants are shown one of four words (red, blue, green, and yellow) displayed in different ink color, and are asked to choose the ink color of the displayed word; see fig 2(c). To make the task more challenging, our implementation switched between asking for the ink color or the text of the word –see fig 2(d), and also switched between two modes (congruent and incongruent) every 30 s. In congruent mode, the concept and the ink color were the same, e.g., the word "red" in red ink. In 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 sec, and the participant had 3 sec to respond; the response time was reduced to 2.5 sec during post-test to ensure the task remained challenging despite any learning effects from the pre-test.

[2] Participants in the DB condition were asked to follow an audio pacing signal that guided them to breathe at a rate of 6 brpm. None of the participants received prior training in DB.

[3] The game difficulty level in the GO condition was the lowest level (i.e., easiest) in the GBF condition, which GBF participants could only achieve under slow and sustained breathing.

or smoking habits. We received approval from the Institutional Review Board (IRB) prior to the study and consent from individual participant before the session.

We used a Google Nexus-1 smartphone running Android 2.3.6 for the game, pre- and post- CWT, and guided DB. To compare the effectiveness of the adaptive game in managing stress levels, we extracted two physiological measures that are commonly used as indicators of autonomic activity: heart rate variability (HRV) and electrodermal activity (EDA) [16]. When used in combination, these two measures provide a robust index of arousal: changes in EDA and HRV are generally in opposite direction with increasing task demands (e.g. EDA increases while HRV decreases), so simultaneous increases (or decrements) in both variables can be dismissed as noise or motion artifacts [17].

We extracted HRV from a Bioharness BT sensor (Zephyr Tech.), which also provided the respiratory signal for game adaptation. $BR\ and\ \Delta BR$ were updated every second. Our measure of HRV was the root mean square of successive differences (RMSSD) in R-R intervals (sampled at 18 Hz), computed over a 30-second window [16]. We monitored EDA with a FlexComp Infinity encoder (Thought Technology Ltd.) at 32 Hz. Disposable AgCl electrodes were placed at the palmar and hypothenar eminences of the player's non-dominant hand; from this, we extracted the number of skin conductance responses (phasic response) over a 30-second window using a peak detection algorithm with a threshold of 1 mS.

4 Results

Skill Transfer. We compared the three treatments (GBF, GO, and DB) by their ability to transfer the relaxation skill. For this purpose, we analyzed the respiratory signal during pre and post-tests. Fig. 3(a) shows the power spectrum density (PSD) of the breathing waveform for the 9 subjects (light blue: pre-test; dark red: post-test). For subjects in the GBF condition, there is a marked difference in the respiratory PSD before and after game play: the pre-task breathing spectra is broad and shifted towards high breathing rates, whereas the post-task breathing spectra is narrowband and centered on 0.1Hz (6 brpm), the breathing rate rewarded during gameplay. In contrast, the respiratory PSD for subjects in the DB does not show a significant difference before and after treatment, suggesting that the DB skill did not transfer; notice how subject #5 maintained a low respiratory rate during the entire experimental session, which suggests that none of the treatments could have been of much direct benefit. Finally, subjects in the GO condition displayed a high breathing rate pre- and post-test, showing that playing a casual game alone[3] does not encourage a relaxing respiratory behavior.

Similar conclusions can be extracted by analyzing the breathing rate in the time domain over the duration of the experiment –see Fig. 3(b). Subjects in the GBF condition lower their breathing rate during the treatment phase from its initial high value at pre-test and, more importantly, maintain that slow breathing rate during post-test, an indication that the deep breathing skill transferred successfully. Subjects in the DB condition also lower their breathing rate while performing the treatment but,

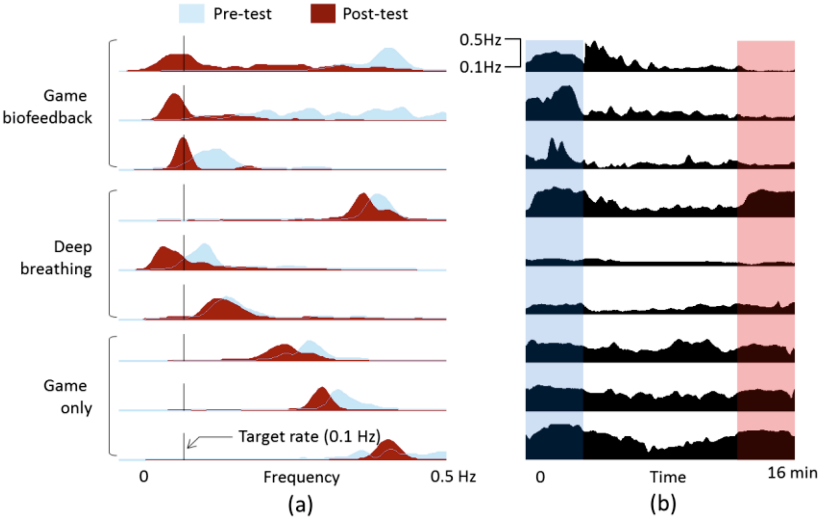

Fig. 3. (a). Power spectral density of the breathing signal during pre-test (light blue) and post-test (dark red); each row represents a participant. (b) Evolution of the breathing rate during the experiments (0.1Hz and 0.5Hz correspond to 6 brpm and 30 brpm, respectively).

unlike GBF subjects, revert during post-test to the high breathing rate shown at pre-test; this is particularly noticeable for subject #4. Finally, the breathing rate for subjects in the GO condition does not change significantly over the duration of the experiment, and never reaches the deep breathing zone.

Physiological Arousal. We also analyzed the subjects' arousal levels, as measured by EDA and HRV. It is important to note that these indirect measures were collected for monitoring purposes and were not used for biofeedback in any way. EDA results for all subjects in the experiments are shown in Fig. 4(a). For subjects in the GBF condition, there is sharp decrease in EDA when going from pre-test to post-test, which indicates that playing the biofeedback game led to a significant reduction in arousal at post-test. In contrast, only 2/3rd of the subjects in the DB and GO conditions had a decrease in EDA, and the remaining 1/3rd experienced an increase in EDA. A 1-way ANOVA of the difference in EDA between pre-test and post-test with treatment (GBF, GO, and DB) as the factor shows statistically significant differences among the three protocols ($p = 0.02$).

Fig. 4(b) shows the average HRV computed over the duration of the pre-test and post-test segments. HRV increased significantly for subjects in the GBF condition, corroborating results from EDA that indicate lower arousal after completion of the biofeedback game. Two of the subjects in the DB condition also had higher HRV post-test, but the increase is not as marked. HRV for subjects in the GO condition remained largely unaltered. A 1-way ANOVA on the HRV difference between pre-test and post-test with the three treatments as factors also shows a statistically significant difference ($p = 0.01$).

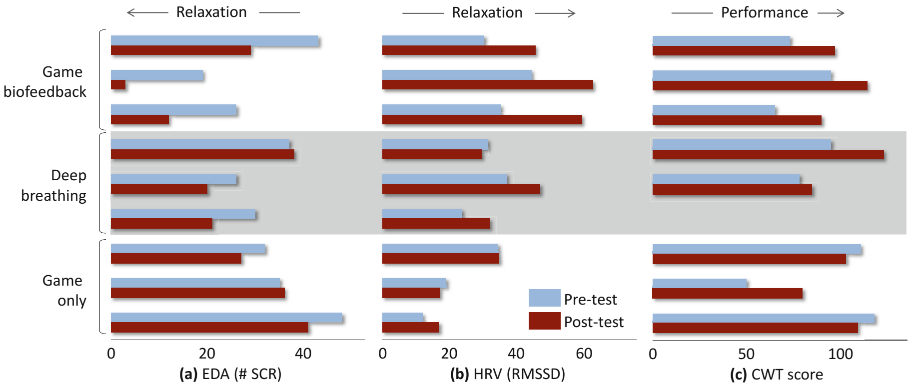

Fig. 4. (a-b). Physiological arousal, measured in EDA and HRV, pre- and post-treatment. (c) CWT scores for 8 subjects; data for subject #6 was corrupted and had to be discarded.

Task Performance. Finally, we analyzed whether the treatment had an effect on performance, measured as the difference in CWT scores between pre-test and post-test. Results are shown in Fig. 4(c) for 8 subjects. Subjects in the GBF and DB conditions had higher CWT scores in the post task, whereas subjects in the GO condition had mixed results. In this case, a 1-way ANOVA shows that the differences among treatments were not statistically significant ($p = 0.40$).

5 Discussion

We have proposed a new strategy for teaching relaxation skills that leverages the broad appeal of casual games. The approach consists of monitoring physiological signals during gameplay, and adapting the game in a way that encourages relaxing behaviors. To test the feasibility of this approach we have developed Chill-Out, a biofeedback game for smartphones that adapts in response to respiratory rate to reward sustained slow breathing. We tested Chill-Out against traditional deep breathing and a non-adaptive non-biofeedback version of the game. Our results show that Chill-Out is more effective than either alternative in transferring deep breathing skills to a subsequent stress-inducing task, and it also leads to significantly lower arousal, as measured by electrodermal activity and heart rate variability.

Chill-Out teaches relaxation techniques while performing a task (i.e. a game) that is designed to increase the user's arousal level [10]. And herein lies the main difference with traditional relaxation training, which encourage practice in quiet settings that do not reflect the environments we encounter in daily life. As a result, our method may lead to better transfer of relaxation skills to other stressful tasks, as demonstrated in our study. This hypothesis is also supported by prior research on stress exposure training in military settings [18], which shows that (for many tasks) normal training procedures do not improve performance when the task is later to be performed under stress.

Future work will test the method with other physiological measures (e.g. HRV, EDA, EEG) as the feedback signal. Additional work is needed to test whether the learning effects observed in our study carry over to subsequent days; longer and repeated training periods beyond the 8-minute treatment in our protocol will likely promote lasting effects. We believe, however, that long-term behavioral changes are not necessary for our approach to be of practical benefit in the workplace; as shown by our study, a single session of Chill-Out leads to reductions in arousal and shows ways in which the practice could be of use in work settings for short-term relief.

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