BREATHING BASED RELAXATION TOOLS IN AN AMBULATORY SETTING

A Thesis

by

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ABSTRACT

Due to the increase in the work-place stress and stress related ailments, various treatments have been developed in the last decade to help people train relaxation skills (Stein 2001). Among them, deep breathing has been shown to be effective in helping users relax. In this study, we aim to investigate two modalities of breathing assistance: biofeedback and pacing signals. We study the transfer of deep breathing relaxation skill to a stressful task, their efficiency in assisting the users lower their breathing rate, and usage statistics. We also aimed to study the effect of including of a casual game with the treatment modality on these factors. To this end, we implemented four relaxation interventions, namely, visual biofeedback (VBF), pacing (PACE), game biofeedback (GBF), and game with pacing (GPACE).

First, we conducted a controlled study in a laboratory setting to study the transfer of relaxation skill to a stressful task immediately after the treatment. Our results showed that all the four treatment interventions were able to help the participants lower their breathing rates compared to a control group (casual game only); however, only the GBF group showed statistically significant reduction compared to the control group. Further, the biofeedback groups (VBF, GBF) aided the participants to maintain their breathing rate lower than the pacing groups (PACE, GPACE) during the treatment. The effect of game inclusion on skill transfer is still inconclusive, due to ambiguity caused as a result of the higher variance in the average breathing rate during the post treatment stressful task using the non-game groups (VBF, PACE) than the game groups (GBF, GPACE).

Then, we performed experiments in which the participants included the intervention into their routine and performed them in a real-world setting. We found that the usage of the GBF intervention was significantly higher than the VBF intervention. However, no significant difference in the usage was found between the other interventions. And, participants found the game interventions significantly more enjoyable than the non-game interventions supporting the choice of including a game with treatment modality to minimize attrition. Further, we observed that higher amount of training is needed for the game groups than then non-game groups. Using the GBF intervention, if the user is trained well to control their breathing rate, it is more likely that they control their breathing rate during the treatment sessions as well, whereas the participants in the other treatments did not show the same. Finally, this study failed to show difference in skill transfer between groups due to a few drawbacks in the design of the protocol.

Results from our studies are still inconclusive; however they indicate that all the four treatments are beneficial in assisting participants relax. Game biofeedback seems to be marginally better than the other interventions in terms of skill transfer; however more data is needed to reach a definitive conclusion. Our studies, showed a few drawbacks in the design of the experiments that need to be addressed in future studies to provide conclusive results and definitive comparison between the interventions.

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NOMENCLATURE

BR	Breathing rate
BPM	Breathes per minute
VBF	Visual biofeedback
PACE	Pacing
GBF	Game Biofeedback
GPACE	Game with pacing
CWT	Color word test
KOM	King of math
pre-test	Pre treatment assessment
post-test	Post treatment assessment

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1. INTRODUCTION

Fast paced workplaces in the era of information work are accompanied by constant interruptions (e.g., emails, text messages, phone calls), which can lead to frustration, higher time pressure, and effort (Mark, Gudith et al. 2008). People tend to breathe shallowly while dealing with these unavoidable tasks (Stone 2008), and frequent, shallow breathing patterns can lead to imbalanced levels of oxygen and carbon dioxide within the body (Haldane, Meakins et al. 1919). This imbalance can lead to stress and anxiety (Ley and Yelich 1998) further leading to serious health impacts (e.g., hypertension (Kulkarni, O'Farrell et al. 1998), diabetes (Cohen, Janicki-Deverts et al. 2012), and obesity (Dallman 2010)), mood, and productivity. Therefore, learning to avoid shallow breathing and maintain calm when exposed to stressors is paramount to reduce these negative health outcomes. One solution for this is *deep breathing*, a voluntary slow breathing technique proven to increase relaxation by restoring balance to oxygen and carbon dioxide levels and to the nervous system (Martarelli, Cocchioni et al. 2011).

With the increase in the usage of mobile phones, various easily accessible, cost effective, and self-guided interventions have been developed over the past decade to help people relax and self-regulate. Applications such as meditation, deep breathing guides, and games (Reinecke 2009, Collins and Cox 2014) have been developed to help people relax. Breathing guides such as paced breathing and biofeedback[1] games in particular have

[1] Biofeedback is the process where real time information about a bodily function is used to train a user to acquire control of that function.

been shown to be effective in inducing relaxation (Moraveji, Olson et al. 2011, Al Osman, Dong et al. 2016, Sonne and Jensen 2016, Cheng, Croarkin et al. 2019). Biofeedback games that penalize shallow breathing have been shown to effectively teach self-regulation in the presence of stressors (Parnandi, Ahmed et al. 2013). Furthermore, Parnandi and Gutierrez-Osuna (2015, 2017) showed that self-regulation skills learned using biofeedback games transfer to a different stressful task immediately after the biofeedback is removed

Need statement: Though biofeedback games are effective in relaxation skill transfer (Parnandi, Ahmed et al. 2013, Sonne and Jensen 2016), using them requires an additional sensor, which increases costs, and the treatment has a steeper learning curve. Paced breathing, on the other hand, is inexpensive and intuitive, but it is still unclear whether relaxation skills learned using paced breathing transfer to other stressful tasks. Moreover, the majority of the studies investigated the effectiveness of mobile-based interventions based on these two modalities in when the treatment is performed in a controlled laboratory environments (Vaschillo, Vaschillo et al. 2006, Bouchard, Bernier et al. 2012, Parnandi, Ahmed et al. 2013, Parnandi and Gutierrez-Osuna 2015, Parnandi and Gutierrez-Osuna 2017, Cheng, Croarkin et al. 2019). The efficacy of paced breathing and biofeedback games in an ambulatory setting is yet to be studied.

Research agenda: In this work, we study the effectiveness of mobile-based relaxation interventions in a laboratory and in an ambulatory setting. We studied four interventions: game biofeedback (GBF), visual feedback (VBF), pacing (PACE), and game with pacing (PACE). First, we performed controlled experiments in a laboratory setting, where we assessed skill transfer immediately after the treatment. Then we performed experiments in ambulatory setting, where the treatment session of the protocol was performed outside the laboratory similar to how it is meant to be performed in real life usage.

1.1 Specific research goals

The research goals for this thesis are summarized as follows:

1. Develop relaxation interventions in a 2x2 factorial fashion using relaxation modality (biofeedback vs pacing signal) as the first factor, and the game inclusion (no game vs game) as the second factor.
2. Evaluate and compare the four treatment interventions in a controlled laboratory setting.
3. Evaluate the interventions when the treatment in performed in a real world ambulatory setting

1.2 Summary of findings

To determine the effectiveness of the treatment interventions, we analyze the controlled and the ambulatory study separately. Results from the controlled study show that:

- Biofeedback groups had lower average breathing rate than the pacing groups during the treatment.
- Adding game to pacing made it harder for participants to control their breathing rate during the treatment. However, participants were still able to show similar level of control over their breathing rate when game was added to biofeedback.

- All treatments showed lower breathing rate than control during post-test. However, GBF showed significant reduction than control and GPACE. Therefore, skill transfer is possible with all the treatments.

In turn, results from the ambulatory study show that:

- Game biofeedback was used a significantly higher number of times than visual feedback. However, no differences were found between the usage of other treatments
- Game based interventions (GBF, GPACE) were found to be perceived as significantly more enjoyable than the non-game interventions (VBF, PACE).
- Participants needed more training for the game-based interventions than non-game interventions.
- The participants in the GBF groups who were able to lower their breathing rate to the effective breathing rate range ($5.1 \leq BR \leq\ 6.9BPM$) during training were more likely to control their breathing rate during in the treatment sessions than the other treatment interventions.
- Skill transfer to a stressful task after performing treatment in an ambulatory setting is still inconclusive and needs further research

1.3 Outline

The rest of the manuscript is organized as follows. Section 2 provides a background of the stress and relaxation physiology, reviews previous works that used mobile applications for heath and self-regulation. Section 3 provides an overview of our system and the design of the interventions and the stressors we used in this work. Section

4 discusses the controlled experiments and their results. Following that, in Section 5, we discuss the protocol and the results for the ambulatory experiments. In Section 6, we discuss the implications of the presented results. Finally, in Section 7 we discuss the limitations of our work and present ideas for future work and conclude in Section 8.

2. BACKGROUND AND RELATED WORK

In this section, we first review the effects of stress on human physiology and how the physiology changes with the help of relaxation treatments, followed by a review of the physiological markers that can be used to measure stress. Then, we give a brief account of prior works using mobile games for health, and discuss some specific works that uses mobile games and deep breathing exercises for relaxation and self-regulation. Finally, we discuss a few recent works that concentrate on the acquisition and transfer of relaxation skills and propose how our work helps the research in this field.

2.1 Stress and stress management

Stress is the body's response to external demand or stimulus. Stress response is the ability of the body to adapt while facing stressors to obtain physiological homeostasis[2] (Selye 1956). Stress can be positive or negative; positive and motivating stress is termed eustress, and debilitating stress is termed distress. Stress can be positive as it helps us to stay alert in dangerous situations and stay focused. Increased arousal can improve performance till a certain point (optimal stress level), beyond which it effects performance and health in a harmful manner. This is known as the Yerkes-Dodsen law (Cohen 2011), and it provides an empirical relationship between arousal and performance – see Figure 1. Negative stress can be short term (acute stress), which lasts for less than a few minutes, or

[2] Homeostasis is the body's ability to maintain stability in response to external fluctuations.

long term (chronic) such as work stress which can last for days and longer. Chronic stress can lead to harmful physical health problems such as coronary diseases (Kivimäki, Virtanen et al. 2006), diabetes (Harris, DeShazo et al. 2010), and obesity (Dallman 2010). In addition to the various health hazards, stress is one of the main concerns from an economic perspective. Every year loss of productivity due to stress causes fiscal loss in the order of 300 billion dollars[3].

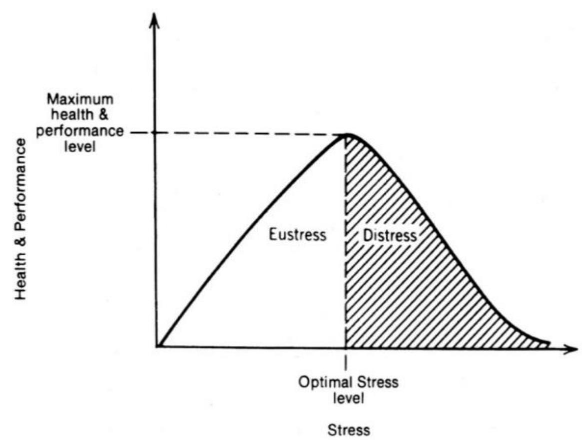


Figure 1 Yerkes-Dodsen relationship between stress and health/performance (Everly and Lating 2002)

Exposure to stressors invokes the '*flight or fight*' response of the sympathetic branch of the autonomic nervous system (ANS). This response is characterized by increased heart rate, breathing rate, pupil dilation, and more (Bakewell 1995) .The parasympathetic nervous system tries to counter this effect, helping reduce the negative

[3] https://www.healthline.com/health-news/stress-health-costs#4

effects of stress on the human body and reach homeostasis. This is known as the relaxation response, and is characterized by the reduction in heart rate, breathing rate and arousal.

Though breathing is a simple function of the body, it has profound effects on a person's physiological state and can be used to attain the relaxation response (Russo, Santarelli et al. 2017). Shallow breathing (12-24 breaths per minute) initiated from the upper chest (Calais-Germain 2006) leads to an imbalance in the blood oxygen levels, affecting the nervous system balance (Marieb and Hoehn 2007), and leads to stress. Deep or Diaphragmatic breathing (around 6 breaths per minute), on the other hand, is initiated from the abdominal area and is shown to increase the parasympathetic nervous activity restoring balance, and assists in attaining a calm and relaxed state (Marieb and Hoehn 2007).

2.1.1 Effects of stress on physical and mental heath

Stress has harmful effects on the health and the overall wellbeing of a person. Constant exposure to stress can reduce quality of life due to insufficient recovery (Van Hooff, Geurts et al. 2006), sleeping disorders (Åkerstedt, Knutsson et al. 2002) and exhaustion (Schaufeli and Bakker 2004). Chronic stress can lead to various negative health outcomes such as obesity (Dallman 2010), hypertension (Kulkarni, O'Farrell et al. 1998), increased risk of coronary disease (Kivimäki, Virtanen et al. 2006), lowered immune function (Kiecolt-Glaser, McGuire et al. 2002) and premature aging of genes (O'Donovan, Tomiyama et al. 2012). Studies have shown that number of negative coping behaviors such as smoking and alcoholism and substance abuse (Crum, Muntaner et al. 1995) can be caused due to stress.

Stress can also affect the mental health of the individual profoundly. Stress affects multiple areas of the brain (hippocampus, pre frontal cortex, and amygdala), affecting both the short and long term memory (Bremner and Narayan 1998). It can also impair spatial and verbal memory (Luine, Villegas et al. 1994), impact learning capability (Sapolsky 2003), lower attention span and cognitive performance (Linden, Keijsers et al. 2005). Prolonged exposure to stress can also lead to depression (Mazure and Maciejewski 2003), post-traumatic stress disorder (Vasterling and Brewin 2005) and bipolar disorder (Hammen and Gitlin 1997).

2.1.2 Stress management methods

Stress management methods have been classified into primary, secondary and tertiary methods (Richardson and Rothstein 2008). Primary interventions aims on identifying and eliminating the source of stress. Secondary interventions aim on lowering the subject’s arousal on exposure to stressors. Secondary methods can be therapeutic or developmental methods. Therapeutic methods help in inducing a relaxed state, whereas developmental methods help also in improving the perception of stress and teach self-regulation in response to certain stressful events. Finally, tertiary interventions aim to reduce the impact of stress through rehabilitation programs. In this work, we focus on developmental secondary interventions. Various developmental methods exist such as cognitive behavioral therapy (CBT), yoga, meditation, biofeedback and deep breathing.

CBT is a psychotherapy that aims to increase the adaptive coping mechanisms in response to stressors. During a CBT session, a therapist works with the patient to identify the negative thoughts and behaviors, and helps the patient in replacing them with new health behaviors. CBT has been shown as an effective treatment for stress related mental disorders, depression and anxiety (Beck 2011). But CBT based methods are time consuming and have to be performed in the presence of a trained clinician, making them costly in terms of both time and money (Richardson and Rothstein 2008). Further, the patient has to follow a strict training regimen, which results in high attrition rates (Henriques, Keffer et al. 2011).

Mind-body relaxation techniques such as yoga and tai-chi have been shown to be effective as self-guided relaxation interventions (Esch, Duckstein et al. 2007). Mindfulness methods such as meditation, yoga and mindful breathing have been studied as relaxation interventions in health individuals, and in people suffering from specific stress related issue (Smith, Richardson et al. 2005, Cutshall, Wentworth et al. 2011). But these methods also suffer from high dropout rates (Rose, Buckey Jr et al. 2013) due to the lack of motivation and the unengaging nature of the exercises (Davis and Addis 1999). Further, these techniques are performed in a quite environment, which may not generalize to real world scenarios (Cannon-Bowers and Salas 1998).

With technological advancements, various technology based methods have also been developed as treatment interventions for stress management. For example, meditation apps, biofeedback, virtual reality (VR) applications have been built. VR methods allow the user in immersive training via an artificially generated scene, making the training more engaging (Wood, Webb-Murphy et al. 2009). But these methods are still costly due to the specialized hardware and software involved. Traditional biofeedback systems monitor various physiological signals of the patient (heart rate, electro dermal activity and breathing rate) and present them to the user (Stein 2001). While effective for relaxation, these biofeedback displays tend to be non–intuitive to the users and also suffer from attrition due to their monotonic nature.

2.2 Games for health and stress management

Video games are engaging by nature and are very popular. Video games have been shown to improve mood and reduce the effects of stress. For example, Russoneillo et al. (2009) found that playing video games lead to improvement in positive mood and reduced stress. Collins and Cox (2014) studied the effect of digital games in stress recovery. They showed that the total duration spend on playing games in a week is correlated with overall recovery. They attributed this to the detachment from stress that the players experience.

Games have also been shown to improve learning (Cordova and Lepper 1996) by enhancing motivation, leading to higher attention to training and higher retention (Ricci, Salas et al. 1996). The key features the advantageous for learning include interactivity, goal directed action, challenge, player control, and dynamic visual (Garris, Ahlers et al. 2002). Moreover, games that are designed for the general public and are fun and easy to play for short periods of time such as 5 – 20 minutes are ideal for physiological training appeal to a majority of the population. Further, playing casual games was shown to improve positive mood and reduce stress (Russoniello, O’Brien et al. 2009).

Video games have been a part of the health care industry and have been used in a therapeutic context to improve health since the 1980s (Szer 1983). For example, Krichevets et al. (1995) developed a computer game to help children with Erb's palsy improve arm control. The authors concluded that this form of treatment was more successful than traditional physiotherapy as it takes advantage of the children's motivation to win in the game. Games have also been used as a form of distraction during painful procedures, such as chemotherapy, and to control side effects such as nausea and high blood pressure (Redd, Jacobsen et al. 1987, Vasterling, Jenkins et al. 1993).

2.2.1 Mobile games for health and stress management

Recently, mobile phones are becoming a useful tool in delivering interventions for improving health due to their increasing technical capabilities and everyday usage (Klasnja and Pratt 2012). Mobile games can be used to help users maintain their health in an immersive and enjoyable way. For example, mobile applications and games are being developed to improve health and to educate users about healthy lifestyle. Baghaei et al. (2016) designed an Android game called Diabetic Mario – based on the famous 2D platformer game Mario Brothers – to educate children about diabetes. Their studies, conducted over a span of one week, showed that children improved their knowledge of healthy diet and lifestyle. Games have also been developed to help people make healthy food choices and track calorie intake to maintain a healthy lifestyle and assist in losing weight (Grimes, Kantroo et al. 2010, Harris, DeShazo et al. 2010). Mobile games have also helped in the treatment of speech-language pathologies. For example, Hair et al.

(2018) used automatic speech recognition algorithms in a mobile game called Apraxia World, which assists in remote treatment of childhood apraxia. Games based on smartphone's internal sensing capabilities, such as GPS and Bluetooth, can help increase socialization and outdoor activity. For example, the commercial augmented reality game Pokémon Go utilizes GPS sensors to involve participant's movement into the game play. A study conducted over a period of 30 days showed that Pokémon Go helped increase physical activity by more than 25% compared to prior activity level (Althoff, White et al. 2016).

2.3 Deep breathing for relaxation and self-regulation

Deep breathing has been used in various studies as a relaxation tool (Martarelli, Cocchioni et al. 2011, Blandini, Fecarotta et al. 2015, Perciavalle, Blandini et al. 2017, Cheng, Croarkin et al. 2019). Inhaling and exhaling affects the oscillations of the heart rate through a process known as respiratory sinus arrhythmia (RSA). The beat-to-beat (R-R) interval is shortened during inhalation and is prolonged during exhalation (Strauss-Blasche, Moser et al. 2000, Yasuma and Hayano 2004). High amplitude of heart rate oscillations imply higher relaxed state when an individual performs deep breathing at the resonant frequency of the cardiovascular system (CVS), which is close to 0.1 Hz (6 BPM) (Vaschillo, Vaschillo et al. 2006).

A study involving college students showed that performing deep breathing successfully improved the participants' mood and reduced stress levels (Perciavalle, Blandini et al. 2017). Martarelli et al. (2011) showed that deep breathing was able to reduce heart rate, increase insulin, and reduce glycaemia and anti-oxidant levels all of which are associated with relaxation. Various tools and protocols that assist the user in performing deep breathing by means of a pacing signal have been developed to help users relax and self-regulate. Pacing signals are simple breathing aids that dictate a breathing pattern using audio or visual cues. *Deep Breaths* is a mobile tool that provides the user with a stationary pacing signal in order to attain a relaxed state (Hair and Gutierrez-Osuna 2017). *Paced Breathing*[4] is a commercial application available on Google Play Store, where the user can set different breathing patterns that allows the user to achieve resonance breathing rate that maximizes relaxation. Cheng et al. (2019) showed that experimental groups using visual guided deep breathing obtained larger standard deviation of beat-to-beat intervals and normalized low frequency power of heart rate variability (HRV) as compared to a control group with no mindful breathing, which are indications of a relaxed state (Shaffer and Ginsberg 2017). Moraveji et al. (2011) studied the influence of peripherally integrated respiration pacing methods into the user's desktop screen, and found that the participant's respiration rate decreased significantly when the screen brightness updated according to a pacing signal.

Various studies have shown the effectiveness of biofeedback games in helping users relax and also learn self-regulation in the presence of stressors (Parnandi, Ahmed et al. 2013, Al Osman, Dong et al. 2016, Sonne and Jensen 2016, Van Rooij, Lobel et al. 2016). Sonne and Jenson (2016) used a breath-controlled game, *ChillFish*, to treat children with attention-deficit hyperactivity disorder (ADHD). In *ChillFish*, children controlled the

[4] https://play.google.com/store/apps/details?id=com.apps.paced.breathing&hl=en_US

size of a puffer fish by controlling their breathing. Breathing slowly makes the puffer fish bigger, allowing them to collect more rewards. The authors reported a significant increase in HRV, when compared to activities like talking and playing Pacman. Lobel et al. (2016) developed a horror-themed biofeedback game called *Nevermind* to improve the player's emotion regulation skills in the face of a stressful situation. The authors designed the game such that negative arousal amplifies the game's horror setting using heart rate biofeedback. The authors reported anecdotal evidence collected from three participants, but a comprehensive analysis of the effects of game play has not been presented. Osman et al. (2016) implemented ubiquitous biofeedback to track mental stress using HRV in a game named *Botanical Nerves*. In this game, the health of a tree is dependent on the status of the player's autonomous nervous system. Hence, the tree wilts when the player is feeling stressed, and grows greener when the player is relaxed. In ubiquitous biofeedback, biological monitoring is not time bound to the duration during which the application is used. The author's short-term experiments showed that the game scores and tree health were correlated with the user's relaxation. Their extended experiments, carried over a period of five days, showed that participants assigned to the biofeedback group had a healthier tree compared to the non-biofeedback group, indicating the participants were relaxed for longer duration during the five days.

In recent years, the reduced cost of VR headsets has made them a viable platform to deliver stress training with enhanced engagement and immersion. As an example, Van Rooji et al. (2016) developed an underwater virtual reality biofeedback breathing game called *DEEP*, which utilizes the player's breathing in the game play in order to promote an immersive relaxing experience. In their experiments, the authors showed that with a seven-minute gameplay session, the participants reported lower anxiety scores when compared to the baseline session. Kosunen et al. (2016) developed a game called *RelaWorld*, which combines neurofeedback[5] with virtual reality to provide an immersive meditation system. They compared neuro feedback versus no feedback, and virtual reality headset versus computer screen to assist with two types of meditation. They found that the combined neurofeedback with a head mounted display provided the users with a deeper relaxation, feeling or presence, and a deeper level of meditation.

2.4 Biofeedback games for skill transfer

Skill transfer is the ability to effectively transfer the skills learned with assistance on a task to a different task with no assistance. A few studies have investigated whether relaxation skills learned with biofeedback games could be transferred to another task, performed without biofeedback (Larkin, Zayfert et al. 1992, Leahy, Clayman et al. 1998, Goodie and Larkin 2006). Larkin et al. (1992) studied skill transfer using heart rate feedback and contingent reinforcement. In their study, participants were shown their heart rate as a peripheral visual cue and a score contingency was imposed to improve the reinforcement of the participant's ability to maintain their heart rate lower. Participants were assigned to one of the three experimental groups: score contingency (SC), visual feedback (FB), and a combined strategy (SC-FB). They showed that SC-FB and SC groups

[5] Neurofeedback is a type of biofeedback that displays real-time brain activity to help teach the user self-regulation of brain activity.

had significantly lower heart rate both during game play without feedback and while performing a novel mental arithmetic task. Bouchard et al. (2012) studied whether a stress-management technique known as immersion and practice of arousal control training (ImPACT) was better than 'training as usual' when delivered to military personnel. In ImPACT, soldiers were exposed to a stressful situation through immersion in a horror/first person shooter game, where they try to learn skills with the use of biofeedback. Their study, with 60 participants, showed that the ImPACT group obtained better self-regulation skills compared to the control group, measured through salivary cortisol and heart rate. The ImPACT group also obtained better task performance than the control group. Lewis et al. (2015) studied the impact of heart rate variability biofeedback in stress relaxation training to counter Post Traumatic Stress Syndrome (PTSD) and depression symptoms. They used a relaxation training protocol known as pre-deployment stress inoculation training (PRESTINT), which is a slow paced-breathing training supported by HRV biofeedback in a simulated combat-training exercise. The authors showed that the participants were more relaxed as observed using HRV in a post-training combat simulation designed to heighten arousal.

Parnandi et al. (2013) developed a respiratory biofeedback game named *Chill-Out* that penalizes fast and shallow breathing by increasing the game difficulty to enforce deep breathing skills. An experimental study with the biofeedback game showed that participants were able to control their breathing in a subsequent stressful task, as compared to a control condition. In later studies, Parnandi and Gutierrez-osuna (2015, 2017) studied various biofeedback strategies to increase the skill acquisition and transfer to a subsequent stressful task. They compared various game biofeedback strategies, such as visual feedback, game adaptation, and combined biofeedback, to study which would promote better relaxation, skill acquisition, and skill transfer. The authors concluded that using a combined strategy of visual feedback and game adaptation provided higher skill retention than the other conditions. They showed that the game adaptation allows the participant to reduce their breathing rate whereas the visual feedback helps in maintaining it at the desired breathing rate range. The authors also observed that the combined strategy leads to the fastest acquisition of deep breathing skills.

2.5 Summary

In most of the above-mentioned studies the treatment stage of the experiments is generally performed under the control of the study staff. However, when using casual mobile applications as treatment interventions, there is a need to study the efficiency of these tools in real-world ambulatory settings. In addition, the attrition characteristics of these tools needs to be studied, since the treatments must be continued for a long term in order to have lasting effects. Therefore, in this work, we study relaxation interventions when the treatment is performed in both a controlled and an ambulatory setting.

3. DESIGN OF TREATMENT INTERVENTIONS AND STRESSORS

This chapter presents an overview of the game and the game mechanics, and describes four different interventions used in this work, their design and their implementations. We also briefly describe the apparatus used to deliver the interventions and the sensing equipment that was used in the biofeedback interventions and for measuring the physiological state of the user. Finally, we describe the stressor used as part of our experiments to function as assessment tasks pre- and post- treatment.

Relaxation treatment interventions need to aid in controlling a certain physiological function of the body to promote relaxation. In this study, we used two breathing based methods as relaxation aids. The first is breathing-based biofeedback, which provides information to the user about their breathing rate, and the second is an audio pacing signal that dictates the breathing rhythm for achieving more relaxation. Finally, we also use a casual game to act as a mild stressor.

	Biofeedback	**Audio Pacing**
Game	Game Biofeedback (GBF)	Game with Pacing (GPACE)
No game	Visual Biofeedback (VBF)	Pacing (PACE)

Table 1 2x2 design of experimental groups using biofeedback vs pacing as the first factor, and no game vs game as the second.

We designed our treatment interventions in a 2x2 factorial design with two factors (factor 1: biofeedback vs pacing signal, and factor 2: Casual game vs No game). Table 1 shows the four resultant interventions: Visual Biofeedback (VBF), Pacing (PACE), Game

Biofeedback (GBF), and Game with Pacing (GPACE). GBF and GPACE deliver the modalities embedded with the game to train in the presence of a stressor whereas VBF and PACE deliver biofeedback and pacing signal with no mild stressor respectively.

3.1 Game

We adapted a clone of the casual puzzle-type mobile game Scale[6] in this work. The player is initially presented with a square arena (see Figure 2), with a ball bouncing inside it with a randomly initialized direction and location.

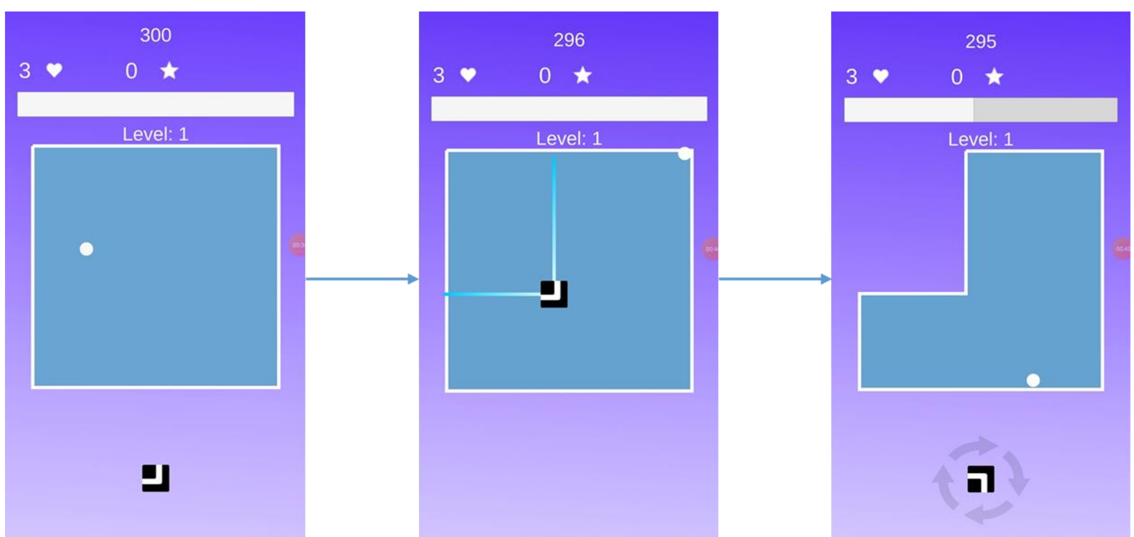


Figure 2 Screen shots of the casual game (scale)[7]. A square arena is initially presented to the user. Then on placing the tile in the arena, the arena gets chopped.

[6] https://play.google.com/store/apps/details?id=com.qbk.games.scale
[7] For more details on the game mechanics refer to: https://youtu.be/1z9q4UGBSWw

The objective is to chop the arena and restrict the ball using the tiles at the bottom as shown in Figure 2. These tiles can cut the arena based on their shape by projecting diving rays towards the ends. For example, a right-angle tile facing the fourth quadrant cuts off the arena present in the fourth quadrant centered on the point it was placed – see Figure 2. The game uses 6 different tiles. Figure 3 shows the actions of each tile. The default speed of the ball and the projection lines (V_0) are set such that it takes them one second to cross the full arena.

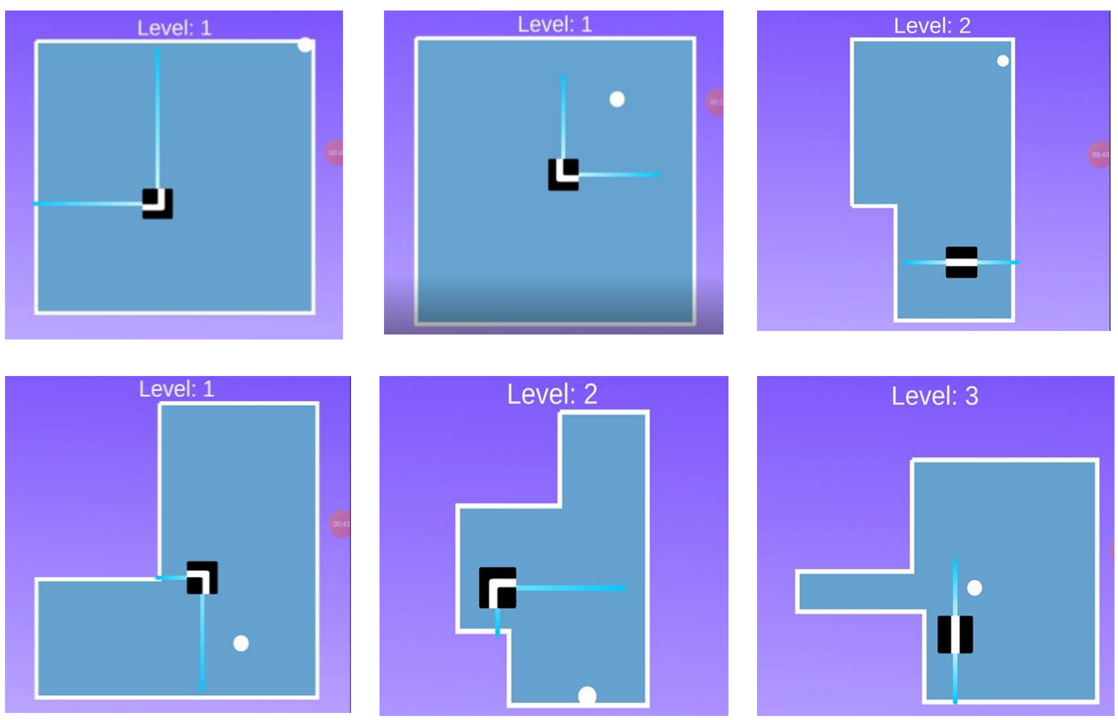


Figure 3 Six tiles used in the game and their actions.

If the ball hits the dividing rays while they are growing (i.e., before the arena is cut off), the player loses a life – see Figure 4. Therefore, the player must vigilantly place the tiles in order to maximize the removed area at the same time escaping the motion of the ball.

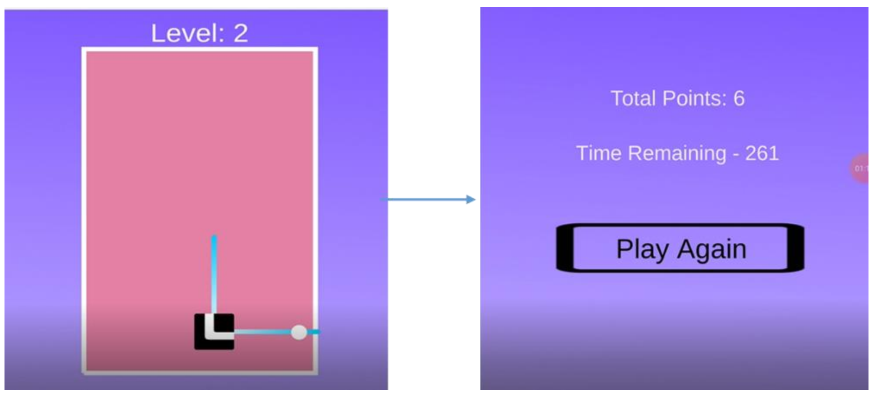


Figure 4 The first image shows ball intersecting the diving ray leading to a loss of life. Loss of three lives shows the second image where the user can choose to play again.

After 50% of the area is chopped off, the player advances a level and the screen zooms to fit the arena. The player is scored according to the sum of levels completed, e.g., after finishing level 4, the player has 10 points: one point for level 1, two points for level 2, etc. In each game session, the user has three lives. If player loses all the lives, an end game screen is shown where the player can choose to play again. The new game starts from level 1 but the score from the previous game play is carried over. The game was developed using the Unity game engine[8].

[8] https://unity.com/

3.2 Biofeedback based interventions

Our biofeedback framework comprises of three major components, a sensor to measure physiological states, a feedback controller, and a dynamic user interface. Figure 5 shows a high-level view of the biofeedback framework. During a treatment session, the user plays the game while their breathing rate data is captured using a wearable sensor. These signals are then transmitted to a mobile phone via Bluetooth. The feedback controller uses the breathing rate data to modify the user interface (for example visual display or adapting the game difficulty) and deliver the feedback information to the player. We use breathing rate biofeedback, as it has been shown to be more effective in inducing relaxation during treatment and promoting greater skill retention than heart rate variability or electro dermal activity biofeedback, due to the higher level of voluntary control the user has over their breathing (Parnandi and Gutierrez-Osuna 2015). We use a Zephyr Bioharness[9] chest strap worn around the sternum to obtain average breathing rate estimates every second. In this section, we describe game biofeedback (GBF) and visual biofeedback (VBF) imple mented with and with the inclusion of the game respectively. The feedback controller and the user interfaces of these two adaptations differ and are described in the following sections.

[9] Zephyr bioharness : https://www.zephyranywhere.com/#

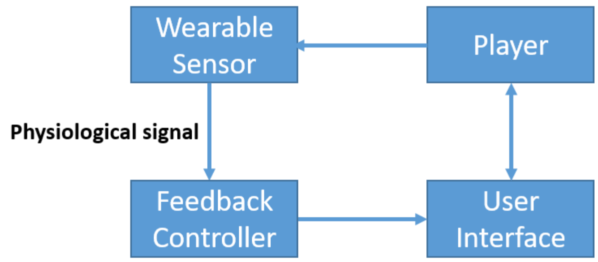


Figure 5 High level view of the biofeedback mechanism used in our experiments. A wearable sensor provides the breathing rate estimate to the feedback controller, which dynamically modifies the user interface.

3.2.1 Game biofeedback

The game biofeedback adaptation uses instrumental conditioning as its core mechanism. In instrumental conditioning, we present the user with rewards or penalties based on their response. Game biofeedback adaptation uses the negative reinforcement instrumental conditioning (NR-IC), where the target behavior (staying calm and relaxed) eliminates the occurrence of an averse stimulus (increased game difficulty). Under the NR-IC system, the player must try to control their arousal so as to keep the game difficulty lower and progress in the game and score higher. NR-IC has been shown to increase the likelihood of the target behavior to be repeated in the future (Domjan 2014).

The adaptation for this intervention is inspired by the Combined Biofeedback described in (Parnandi and Gutierrez-Osuna 2017). Biofeedback is delivered in two ways, first in the form of game adaptation, and second using peripheral visual cues. Game adaptation is performed by altering the difficulty of the game with the player's breathing rate. The difficulty of the game is controlled by changing the speed of the ball and the number of balls in the arena. To control the speed of the ball, we adapt the time the ball takes to travel one full arena width. The scaling factor (α : the ratio of the time taken for the ball to travel the arena at a breathing rate BR (T_{BR}) and the default travel time (T_0)) is a piecewise linear function with respect to the breathing rate – see Figure 6.

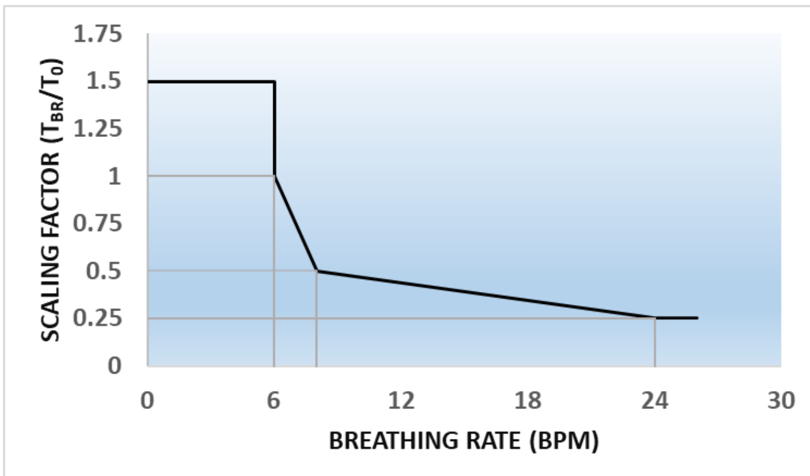


Figure 6 Relationship between the scaling factor ($\boldsymbol{\alpha} = \frac{T_{BR}}{T_0}$) and the breathing rate.

For breathing rates less than 6 BPM, the travel time of the ball (T_{BR}) is $1.5 * V_0$ but drops to T_0 just above 6 BPM. At 8 BPM, the travel time is $0.50 \times T$, and at 24 BPM it is $0.25 \times T_0$. In addition, we add a ball to the arena if the player's breathing rate is above 6 BPM and increasing. We remove one of the balls at random if the player's breathing rate is above 6 BPM *but decreasing*, to remove the averse stimulus for not reacting negatively to the stress caused by the added difficulty (Negative Reinforcement-Instrumental

Conditioning[10]). Table 2 shows the summary of the game adaptation with respect to the breathing rate and the rate of change.

Along with the game adaptation, the system shows a numerical indicator of the breathing rate and an arrow indicating whether the breathing rate is decreasing (green and downwards) or increasing (red and upwards) – see Figure 7. Further, a text prompt "*Please try and relax*" is shown at the bottom of the screen if the player's breathing rate is constantly increasing for more than 30 seconds.

	$\boldsymbol{BR \leq 6}$	$\boldsymbol{BR > 6}$
$\boldsymbol{\Delta \mathrm{BR} < 0}$	$N_b = 1, T_{BR} = 1.5T_0$	$N_b = 1, T_{BR} = \alpha T_0$
$\boldsymbol{\Delta BR \geq 0}$	$N_b = 1, T_{BR} = 1.5T_0$	$N_b = 2, T_{BR} = \alpha T_0$

Table 2 Summary of the effect of breathing rate and its rate of change on the number of balls in the arena ($\boldsymbol{N_b}$) along with the ball travel time ($\boldsymbol{T_{BR}}$). Scaling factor ($\boldsymbol{\alpha}$) for BR > 6 is obtained from Figure 6.

[10] Instrumental conditioning is the process of rewarding or penalizing user based on their response to modify a target behavior. Negative reinforcement is when the target behavior is strengthened by removing an averse stimulus (Skinner 1965)

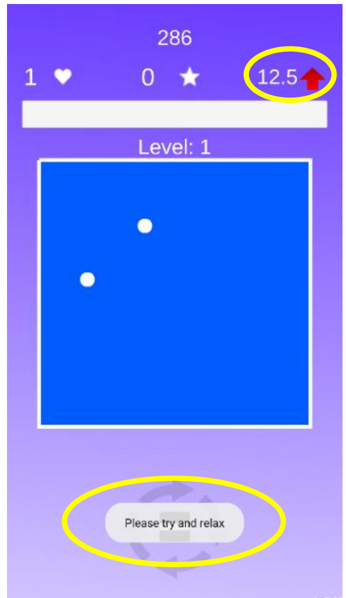


Figure 7 Visual feedback shown peripherally in the game biofeedback adaptation

3.2.2 Visual biofeedback

Visual biofeedback (VBF) is a straightforward application of biofeedback, where the user is provided with their physiological information (breathing rate in this case). We deliver this in the form of a visual cue using a numerical indicator of the player's breathing rate. To make the biofeedback more obvious, the number's font color changes to green when the breathing rate (BR) is in the desirable range ($BR \leq 6\ BPM$), yellow while approaching the desirable range ($6BPM < BR < 12\ BPM$), and red when the breathing rate is far from the desirable range ($BR > 12\ BPM$). Figure 8 shows a screenshot of the visual biofeedback application.

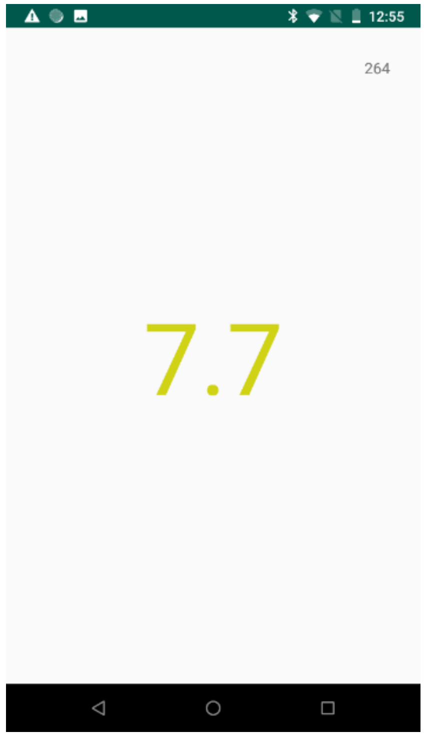


Figure 8 Screen shot of the visual feedback application

3.3 Pacing signal based interventions

Pacing signals are breathing aids that dictate a pattern for the participant to follow, e.g., when to inhale and when to exhale. These signals are often delivered in a visual or auditory fashion. For example, a visual pacing signal could be relatively simple, such as having a horizontal line move upwards gradually during inhalation and downwards during exhalation. Cheng et al. (2019) in their experiments used a video pacing signal with a smiley face with petals appearing around it during inhale phase and disappearing during the exhale phase. Figure 9 shows an example of a pacing signal used in the Android application Paced Breathing.

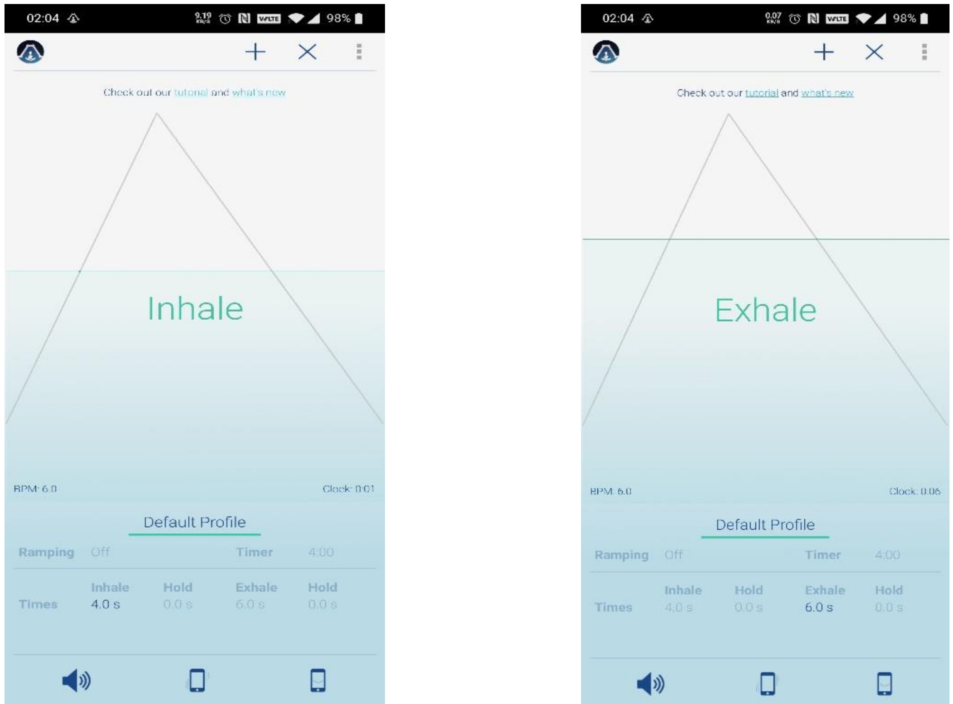


Figure 9 Example of a visual pacing signal depicted using a horizontal line moving up and down. (a) Inhale phase (b) Exhale phase. The screenshots were taken from the Paced breathing application available on google playstore

Another way to deliver the pacing signal is by modulating the intensity of a wave. For example, Moraveji et al. (2011) delivered the pacing signal by modulating the brightness of the screen in which a primary information task was being done. Pacing signal can also be delivered using audio cues, by increasing and decreasing the intensity or pitch of an audio signal or by simply delivering the instructions such as '*breathe in*' and '*breathe out*'.

In our work, we used an audio pacing signal delivered using an increasing intensity of a relaxing sound pulse during inhalation and reducing it during exhalation. The inhalation duration was set to 4 seconds and exhalation to 6 seconds (6 BPM). We used this frequency as prior works has shown that the cardiovascular system has a resonant frequency of 0.1 Hz (6 BPM) (Vaschillo, Vaschillo et al. 2006), and shorter inhalation and longer exhalation lead to higher respiratory sinus arrhythmia (Strauss-Blasche, Moser et al. 2000) causing higher relaxation. In the following sections, we describe the two pacing signal based interventions: Pacing (PACE) and Game with pacing (GPACE).

3.3.1 Game with pacing

We implemented this adaptation to test the effect of using guided deep breathing in the presence of a primary task (the game). We provided the same pacing signal (4 seconds for inhale and 6 seconds for exhale) as background audio during with the game. The speed of the ball remains unchanged during game play, and only one ball is present in the arena. Moraveji et al. (2011) showed that participant's respiration rate decreased significantly by providing a respiration pacing guide in a visual peripheral manner while performing a primary information work task. Thus, our intervention can be thought of as providing the respiration guide peripherally, in the form of audio cues while the primary task is the game.

3.3.2 Pacing

For this intervention, we developed a simple application that plays the auditory pacing signal that increases in intensity for four seconds (inhale) and decreases in intensity for six seconds (exhale) till it reaches the original intensity level. The audio pacing signal is played, with a text in the center that says, “Inhale for 4 seconds and exhale for 6 seconds”.

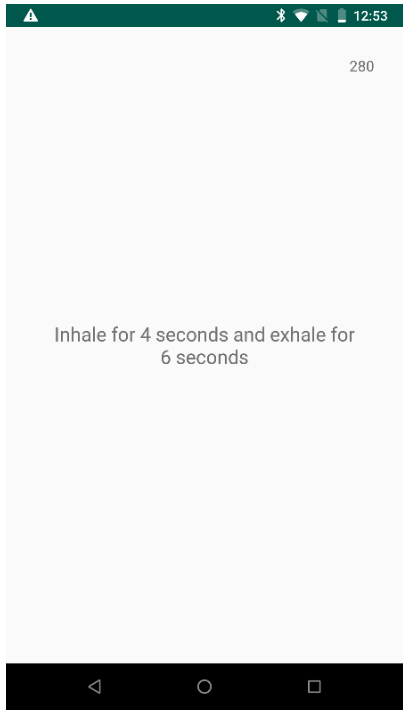


Figure 10 Screenshot of the pacing application

3.4 Software architecture

All the interventions were developed on a Google Nexus 6P running Android 8.0.1. The architecture can divided into four layers: application, application framework and libraries, Android libraries and Android Linux kernel. The intervention runs on the top most application layer along with some necessary Bluetooth libraries for the sensors. The application layer is built on top of the Android application framework which handles basic activity functionality such as closing and opening the application, resource management such as how much ram and power to utilize for the application and some other frameworks that help in Wi-Fi and Bluetooth connectivity through APIs. These APIs are used by the application to scan for Bluetooth based devices, pair with them and establish a connection. Then, there is the Android libraries such as the SQLite that handles storage, OpenGL that helps render the screen, media manager, and many more. The whole stack is built on the default Android Linux kernel that runs on top of the hardware.

In the case of our treatment interventions, the application module connects with the Bioharness sensor via the Bioharness Bluetooth module and queries for the physiological information. This data is then used for modifying the application in the case of visual feedback and game biofeedback.

Figure 11 (a-d) show the Android architecture of the visual biofeedback, game biofeedback, pacing and game with pacing applications. The Bioharness Bluetooth sensor libraries consist of various classes that help connect the Bioharness device and to query and stream physiological data. *BT client* manages the Bluetooth connectivity. *ConnectedListener* class is responsible for interfacing with the Bioharness and for processing the data packet from the Bioharness and parsing the input stream to obtain the showing needed data. *BTComms* class is used to read the data from an input stream and write to an output stream. *PacketTypeRequest* class contains the methods to enable and disable different packets of data that are streamed (for example, BR, R-R etc.). A code snippet for connecting to the Bluetooth device is provided in APPENDIX A.

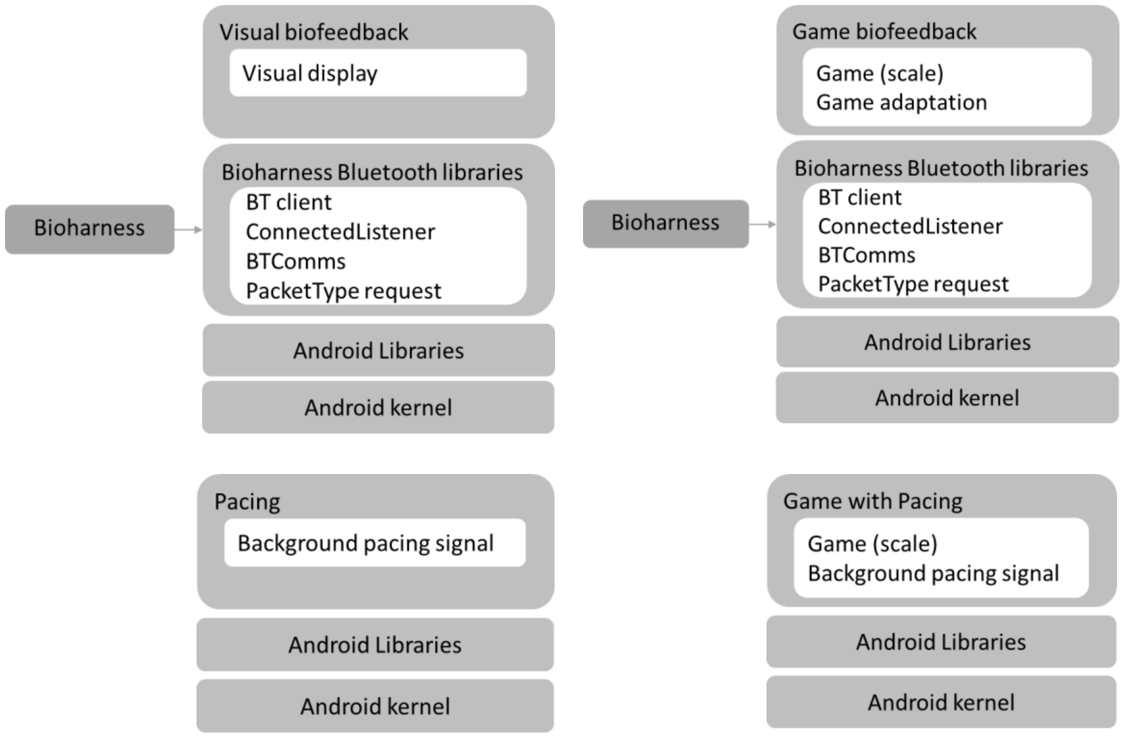
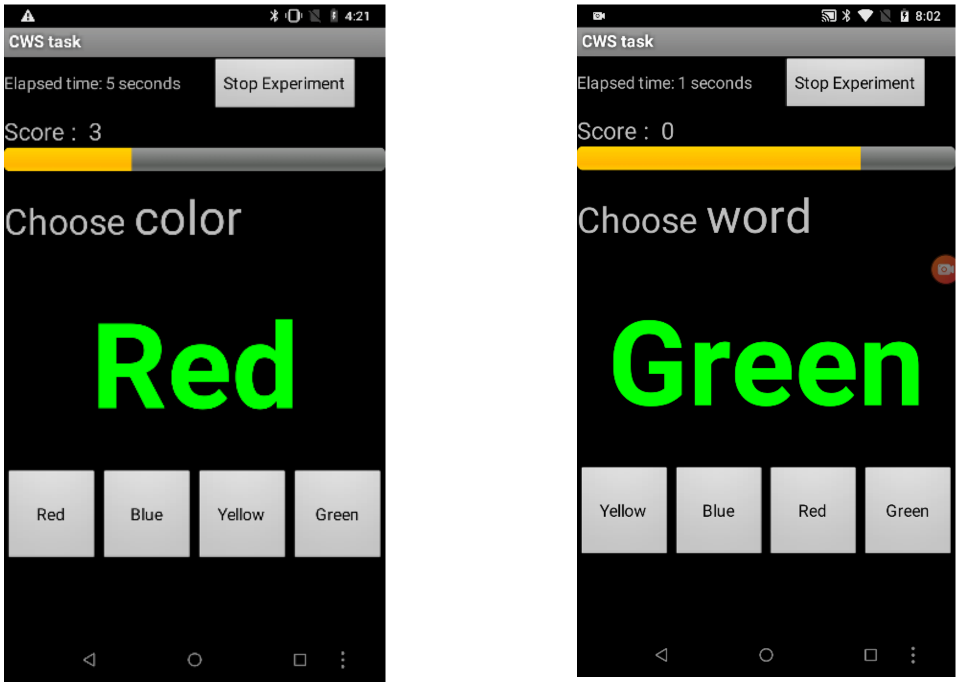


Figure 11 Android architecture of the (a) Visual biofeedback application (b) Game biofeedback application (c) Pacing application and (d) Game with pacing application

3.5 Stressors

To compare the skill transfer of the treatments we used two assessment tasks: the Stroop color word test (CWT) (Stroop 1935), and a mental arithmetic task. The Stroop CWT is widely used to induce arousal through cognitive work load. We used a modified version of the CWT. In the conventional CWT, four color words (red, blue, green, and yellow) are shown in a different ink (e.g., **red**) and the participant is asked to choose either the displayed word or the ink color displayed. Our method switches between congruent and incongruent modes – see Figure 12– every 30 seconds. In congruent mode, the word and the ink color were the same, whereas in incongruent the work and ink color differ.

Further, the location of the answer buttons is also jumbled every time. Every correct answer increases the score by one while wrong answer decreases it.



(a) (b)

Figure 12 Color word test (CWT) operating in (a) incongruent mode, (b) congruent mode

The second assessment task is a mental arithmetic game, King of Math (KOM), available on Google Play store[11] . In this application, the player tries to score as high as they can by answering basic arithmetic tasks such as additions, multiplication, and fractions in a limited time. As the level increases, the level of difficulty of the arithmetic

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[11] King of math on play store : https://play.google.com/store/apps/details?id=com.oddrobo.kom

increases. The participants are presented with four answer choices – see Figure 13. We used a mixed setting in the game, which shows an assortment of questions based on various math concepts. Each level has ten questions, and the score is based on the number of questions correctly answered by the participant. Additionally, if the participant commits three mistakes, they are not allowed to progress and the level restarts. The stressors are provided by a prior work by Parnandi and Gutierrez-Osuna on biofeedback games (2017).

Figure 13 King of math (KOM) in mixed setting.

4. CONTROLLED STUDY

In the previous section, we presented the design of four relaxation interventions and their implementations. In this section we use those interventions to perform a controlled experiment in the lab. Biofeedback has been shown to be effective in helping users learn and transfer deep breathing skills (Bouchard, Bernier et al. 2012, Parnandi and Gutierrez-Osuna 2017). However, the skill transfer effect of using pacing as a treatment intervention is unclear. Using this controlled study, we aim to study if using the pacing signal lead to transfer of deep breathing skills. Further, we use the controlled study as a proof of concept to show the skill transfer using game biofeedback. Finally, we also aim to study the effect of game integration into a relaxation modality on the transfer of skill to a stressful task. In this study, post-test task is performed immediately after the treatment to assess skill transfer.

The studies were designed in a between-subjects fashion to minimize fatigue (due to performing all the tasks), carryover (due to first treatment interfering in the second), and learning effects (better performance in the assessment tasks due to unexplained factors of the treatment interference) (Budiu 2018). The participants were randomly assigned to a treatment condition (VBF, PACE, GBF, or GPACE) or to a control group (Game only). The treatments used in the studies are as follows:

- *Visual Biofeedback* (VBF): Participants are shown their breathing rate numerically and number's font color changed based on their proximity to the target breathing rate (6 BPM).

- *Auditory pacing* (PACE): Participants are provided with an audio breathing guide set to 4 seconds inhale and 6 seconds exhale.
- *Game biofeedback* (GBF): Participants played a casual game that adapts according to the participant's breathing rate, and provides visual cues to help control the breathing rate.
- *Game with pacing signal* (GPACE): Participants played a casual game accompanied by an audio breathing guide set to 4 seconds inhale and 6 seconds exhale.
- *Game only* (Control): Participant played the casual game with no modifications.

4.1 Protocol

We recruited 30 participants (16 males, 14 females) using the Texas A&M University bulk mail service. The participants were all university staff and students, in the age range of 18-35 years. Only participants with no prior account of anxiety or depression were recruited. Participants had experience using mobile phones and playing causal mobile games but had no experience with biofeedback applications. The Texas A&M University Institutional Review Board[12] approved our experiments prior to conducting the studies.

The participants were greeted and asked to read the informed consent document thoroughly and then their signatures were collected before starting the experiments. Participants were asked to place the Zephyr Bioharness chest strap snugly around their

[12] Institutional Review Board approval number: IRB2019-0218D

sternum and were asked to assume a comfortable seating position. The participant performed all the tasks on a Google Nexus 6P running Android 8.0.1 (Oreo).

The study consisted of five stages: Pre-treatment assessment (Pre-Test), Paced Breathing, Game Training, Treatment, and Post-Treatment assessment (Post-Test). A high-level diagram, describing an experimental session is shown in Figure 14.

- Pre-Test: Participants performed the modified Stroop CWT for 3 minutes – see section 3.5 for more details. Participants had 3 seconds to answer each question. This task was performed in order to measure the participant's arousal under stress without training.
- Paced Breathing: Participants followed an audio breathing guide set to 4 seconds inhale and 6 seconds exhale. This task was performed for 3 minutes. This task was performed to expose participant to the breathing pattern, and train them to perform deep breathing using an audio guide.
- Game Training: Participants played an unaltered version of the game, *scale* for 3 minutes. The purpose of this task was to familiarize the participant with the game mechanics.
- Treatment: Participant is assigned to one of the five groups (control, PACE, VBF, GBF, GPACE) and they performed the corresponding treatment for 6 sessions, each session lasting 5 minutes, with a 30-second to 1-minute break between sessions. If the participant was assigned to one of the groups involving game, they were told their game score between sessions and were asked to improve it.

- Post-Test: Participants performed the CWT again for 3 minutes, but the difficulty was increased (2 seconds to answer instead of 3 seconds) to account for the learning effects from the first time the test was performed.

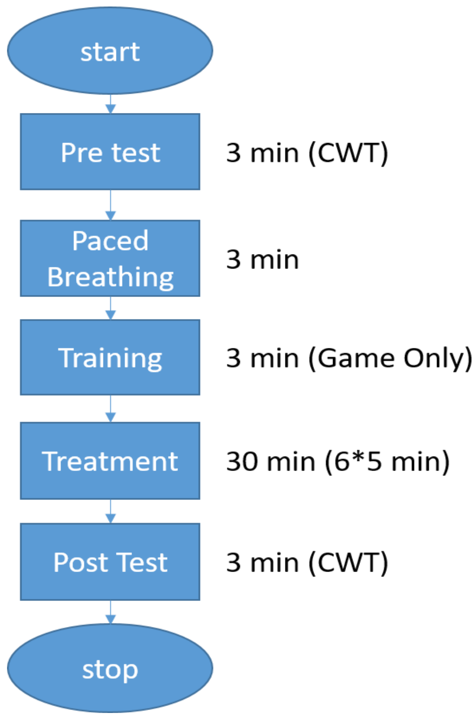


Figure 14 Pilot study experimental protocol with five phases and their respective durations. In treatment, the participant is assigned to one of the 5 groups (Control, VBF, PACE, GBF, and GPACE).

For this study, we used breathing rate (BR) and subjective results to study the evidence of skill transfer. To ensure a fair comparison between the game groups, we needed to keep the difficulty level of the games similar across all game groups (control, GBF, and GPACE). GBF group has dynamic control over the game difficulty based on the breathing rate, whereas the Control and GPACE groups do not modify the difficulty level of the game. To make the game equally challenging for all three conditions, we employed a yoked design, where we first conducted the experiments for the GBF group and recorded the ball speed during treatment. We then set the ball speed for the Control and the GPACE groups as the average speed during GBF.

4.1.1 Instructions

We gave the participants various instructions throughout the experiments. The pre-test and post-test instructions were adapted from a prior work by Parnandi and Gutierrez-Osuna (2017). The instructions are listed below.

Before treatment:

Common to all groups:

- *"Relax, try to breathe slowly and maintain your breathing rate around 6 BPM. Use the 4 second inhale and 6 seconds exhale pattern you learned during the paced breathing."*

Specific to each group:

- PACE: *"Try to breathe by following the pacing signal provided."*
- VBF: *"The number on the screen changes as you control your breathing rate. Please try to keep the number around 6."*
- GBF: *"The game difficulty will be affected by your breathing rate. The higher the breathing rate, the more difficult the game gets. Also, your breathing rate, and whether it is increasing or decreasing, is also shown. Breathe slowly at 6 BPM so that game stays easy."*

- GPACE: *"Try and play the game and breathe by following the background pacing signal."*
- Control: "*Stay calm and do your best in the game.*"

After treatment: *"Stay calm and relaxed using the breathing skills you learned during the treatment and try to do your best in the assessment task."*

4.2 Results

4.2.1 Breathing rate

Figure 15 shows the average breathing rates for all the groups at all stages of the protocol: Pre-Test (CWT1), paced breathing (PB), Training (TRAIN), Treatment (TREAT) and Post-Test (CWT2) phases. The five groups had approximately the same average breathing rates (pairwise two sample t-tests showed no statistically significant differences) during the CWT1, PB and TRAIN sessions of the protocol. We observed an average of 20 BPM across all groups during Pre-Test, which is expected due to the mild stressor delivered by the CWT. We also observed breathing rates around 6 BPM during PB, which shows that all participants were able to follow the pacing signal successfully. As the participants of all groups have the same initial state, fairness is ensured in the comparison of self-regulation skill transfer.

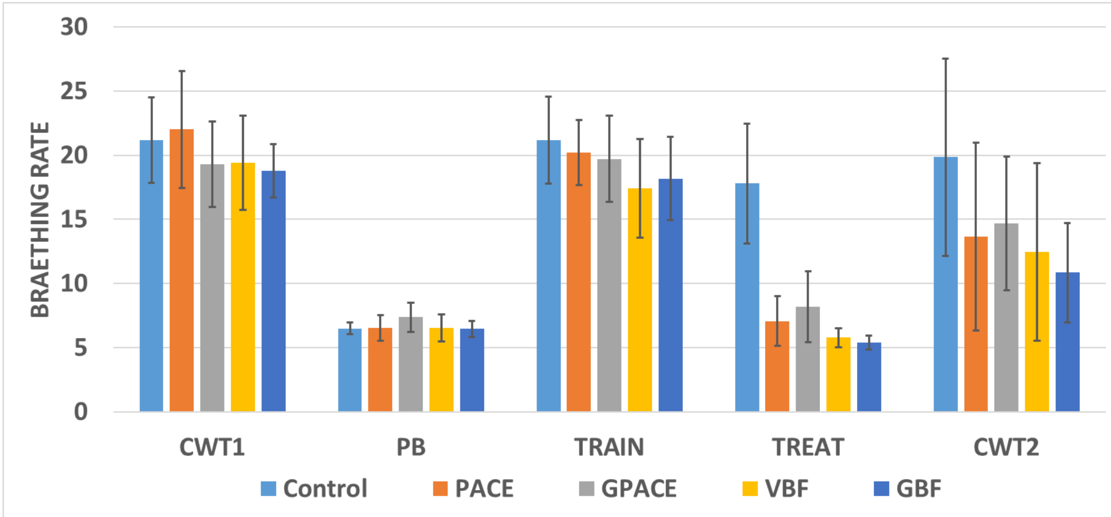


Figure 15 Average Breathing rate per group during the Pre-Test (CWT1), paced breathing (PB), Training (Train), treatment (TREAT) and Post-Test (CWT2).

During the treatment phase, all the treatment conditions were able to lower the participant's breathing rates significantly when compared to the Control group. Pairwise two sample t-tests on the average treatment breathing rate (6 sessions x 6 samples = 36 samples) between the groups showed that (1) GBF has an average breathing rate during treatment that is significantly lower than PACE ($t(70) = 4.72, p = 0.00001$) and GPACE ($t(70) = 5.6, p = 0.00003$), and (2) VBF also has an average breathing rate significantly lower than PACE ($t(70) = 3.64, p = 0.0005$) and GPACE ($t(70) = 4.96, p = 0.000004$). Further we also found significant difference between PACE and GPACE ($t\ (70) = 2.54, p = 0.013$), but no difference between VBF and GBF($t\ (70) = 1.71, p = 0.09$). From the above comparisons, we conclude that both biofeedback groups had an average treatment breathing rate lower than both the pacing groups. Further, including a game into biofeedback did not result in any difference in the average breathing rate during treatment, whereas including game into pacing increased the average breathing rate, showing that the game and the pacing signal worked against each other and made the treatment harder to follow.

Then, we compared the average breathing rate during the CWT2 phase to determine which group was able to control their breathing rate the most. From Figure 15, we noticed that the average breathing rate for the control group does not change from the initial breathing rate (two sample t-test showed no significant difference). All treatment groups have a lower average breathing rate than the control group, though pair wise two-sample t-tests between the control group and the experimental groups revealed that only GBF had a statistically significant reduction in average breathing rate ($t(10) = 2.56$, $p = 0.028$). Further, pairwise two sample t-tests between the experimental groups showed that GBF had significantly lower average breathing rate than GPACE ($t(10) = 3.1$, $p = 0.01$) as well, but failed to show differences with any other groups. Further, we did not observe any significant differences in the pairwise comparisons of other groups. Therefore, it is conclusive that in groups with game involved (control, GBF and GPACE), GBF is be the best treatment as it helped participants lower their breathing rate significantly both during treatment and final assessment. However, we are unable to show significant differences between GBF and PACE, or GBF and VBF. All the groups resulted in a reduction of breathing rate from CWT1 to CWT2 implying some level of skill transfer but, statistical significance was seen only in the case of GBF. This is due to the high variance in the average breathing rates of the non-game groups (VBF, PACE) in the final assessment.

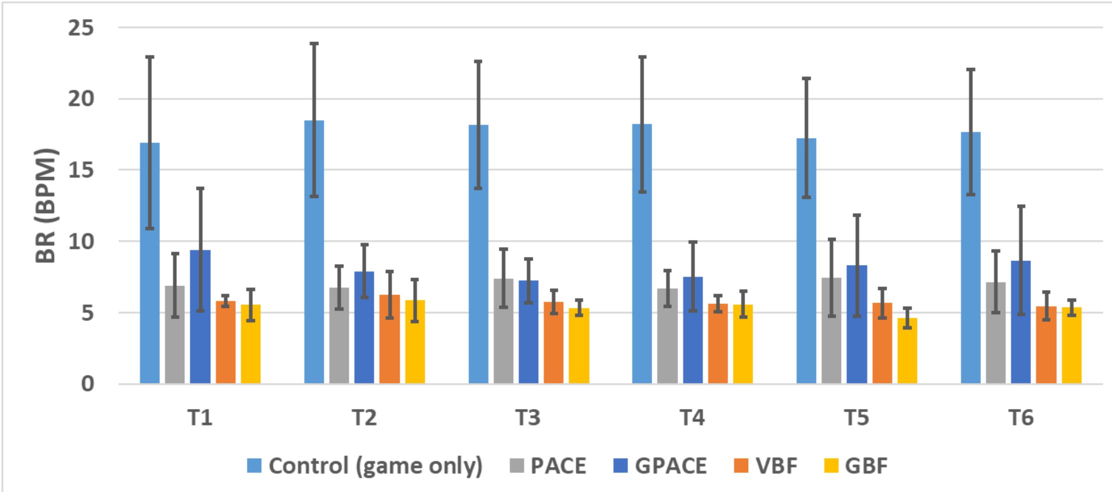


Figure 16 Average breathing rate trend during the six treatment session for control and all the experimental groups.

Figure 16 shows the trend of average breathing rate during the six treatment sessions for all the groups. T-tests between the consecutive treatment sessions in a group did not reveal any significant differences for any of them. The control group has an average breathing rate close to 19 BPM with a very high variance, followed by GPACE with an average breathing rate close to 8 BPM then PACE around 7 BPM. Finally VBF and the GBF groups were able to aid the participants in controlling their breathing rate very close to 6 BPM on an average.

Another interesting find was that the difference in the average breathing rates between the post-test CWT and pre-test CWT showed lower spread for the groups with the game and higher spread for groups without the game. The same trend holds for the absolute values of the average breathing rates during the post-test CWT (CWT2) – see Figure 17. This reason for this effect is ambiguous and could be a consequence of the low sample size used in the study, or could be a characteristic of non-game interventions. More participants need to be recruited so that this ambiguity can eliminated to reach a conclusion.

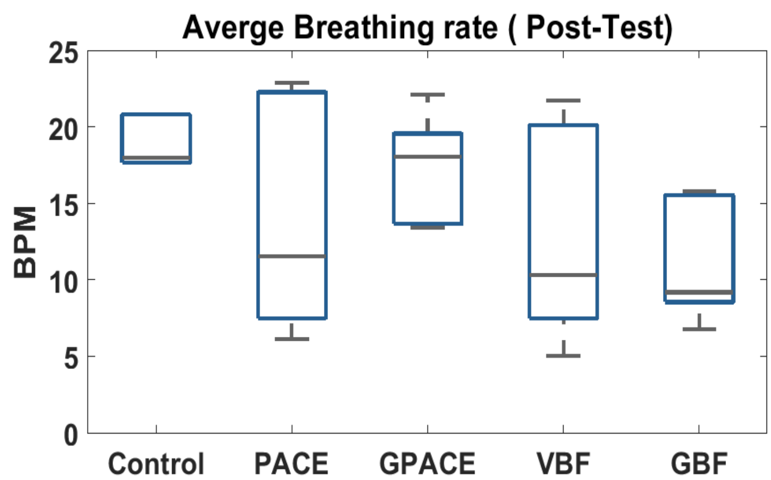


Figure 17 Box plot of the average breathing rate during the Post-Test CWT (CWT2)

4.2.2 Survey and subjective analysis

At the conclusion of the experiment, participants were asked to fill a survey regarding their experience with the treatment. We asked how enjoyable the participant found the treatment on a scale of 1-5. Figure 18 shows the perceived enjoyment for all the groups in the study. From the figure we observe that participants in the game groups had more positive response than the participants in the non-game groups.

Pairwise 2-sample t-tests on the groups showed that GBF was perceived as more enjoyable than VBF ($t(10) = 4.02, p = 0.002$), PACE ($t(10) = 5.72, p = 0.0001$) but not GPACE or control. However, GPACE was perceived as more enjoyable than PACE ($t(10) = 3.06, p = 0.01$) but not VBF. No difference was noticed between PACE and

VBF. No significant difference was noticed between control and GBF, control and GPACE, and control and VBF. However, we noticed a difference in perceived enjoyment in control and PACE ($t(10) = 2.55, p = 0.02$). This shows that GBF is perceived more enjoyable than any non-game interventions, but GPACE was perceived more enjoyable than PACE only, and not VBF. On the other hand GBF and GPACE were perceived to provide similar level of enjoyment, and so did VBF and PACE.

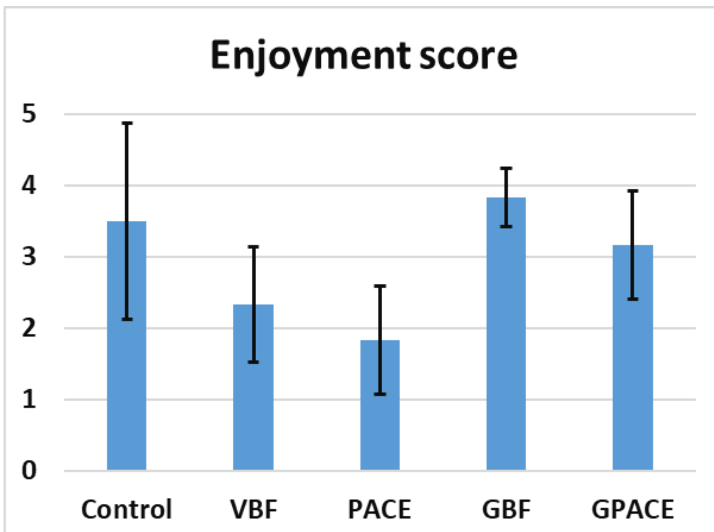


Figure 18 Enjoyment score reported by the participants on a scale of 1-5.

Further, t-test on the perceived enjoyment of all the game groups combined versus all the non-game groups combined showed that the game groups are perceived more enjoyable than the non-game groups irrespective of the treatment modality included ($t(28) = 4.34, p = 0.0001$). This supports the choice of including a game with any breathing modality (biofeedback, pacing) to make it more appealing to the users.

Finally, we examined the subjective assessments provided by the participants. Participants in the VBF groups found it easy to control their breathing rate, as mentioned by the comments "*It was easy to control breathing because the screen showed your breathing rate*". A participant in the PACE groups mentioned *"It's too monotonic and I got bored after the second trial"* indicating that pacing signal would lead to boredom and distraction when repeated multiple times. Participants in the GBF found the biofeedback integration helpful in controlling their breathing rate as mentioned by the comments, *"I like the idea that you can control the game with your breathing and score more points"*, and another participant mentioned "*The game play was fun and the pop-ups and the breathing rate indicator were helpful*". Further, participants in the GPACE groups found, the pacing signal distracting from the game play as one mentioned "*I kept switching back and forth between playing the game and breathing*". Another participant mentioned *"After 3-4 trials I just felt like only playing the game or breathing"* indicating that the pacing signal though integrated into a game, was still having the effect of monotonicity and boredom. When the participants from GBF and GPACE groups were asked if they were able to concentrate on the game, all 6 participants from GBF answered yes, but only 3 from GPACE answered yes. This is an indication of the game and the biofeedback mechanism acting together to help the participant perform both tasks better, whereas the pacing signal working against the game play causing a distraction from it. Finally, a participant in the control group mentioned *"I was more relaxed during paced breathing and the game didn't really help me relax"* which shows that the game by itself though it acts as a distraction, does not provide any means of relaxation.

5. AMBULATORY STUDY

Relaxation interventions are mostly studied when the treatment is performed in a controlled setting. Therefore, it is more likely that the participants pay more attention towards performing the treatment sessions. However, without the supervision of the study staff, it is not necessary that the user perform the treatment in the intended way and as a result not benefit from the treatment. Further, some treatment interventions could appeal to the user better than the others. This is a very important feature of casual mobile based interventions as they are self-driven and need to be appealing to the user, so they would use it for multiple sessions and not get bored or frustrated causing an increase in attrition. In the ambulatory study, we aim to study these factors. The primary objective of this study to analyze the usage statistics of the treatments and analyze the performance of the interventions in helping the users control their breathing rate in an ambulatory setting. Following that we also tried to find evidence of skill transfer as a secondary objective.

In this study, we only considered the four experimental groups (VBF, PACE, GBF, and GPACE) but not the control group. In the laboratory experiment, only the experimental conditions were able to aid the participants in reducing their breathing rates to approximately 6 BPM during the treatment sessions, whereas the control condition (only game) did not help in controlling the participant's breathing rate. Further, the control group has no enforceable breathing modality. Therefore, we discarded the control group as analyzing it in ambulatory setting would not be different than just playing a game.

5.1 Protocol

We divided the experiment into three stages, Pre-Treatment, Treatment, and Post-Treatment. The complete protocol of the experiment is shown in Figure 19. Pre-Treatment has four tasks: Baseline, Pre-Treatment assessment (Pre-Test), Paced Breathing, and Training. We recruited 36 participants (15 male, 21 female) in the same way as the controlled study – section 4.1.

- Baseline: Participants watched a short relaxing video for two minutes[13].
- Pre-Test: Participants performed the CWT for five minutes (See Section 3.5 for more details). In this task the participant has a 3-second response time.
- Paced Breathing: Same as paced breathing in the controlled study. See Section 4.1.
- Training: Participants are assigned to one of the four groups (PACE, VBF, GBF, and GPACE) and they performed the corresponding treatment to learn the mechanics of the treatment intervention.

Once training was finished, participants left the lab and went about their day as usual, while incorporating the assigned treatment intervention into their routine. Participants were given a Nexus 6P smartphone with the corresponding application installed. For participants in the pacing groups, we provided headphones so the sound would not inconvenience people around them. The participants were asked to perform the assigned treatment intervention whenever they saw fit during the day. Each treatment

[13] The relaxing video named *'Alaska's wild, Denali'* (2014), which was shown to induce a neutral physiological response (Jeon 2017). This was done to allow the participant to relax and minimize the variance in the results due to carryover effects from external factors.

session took 5 minutes. This treatment stage starts once the participant stepped out of the lab and ends once the participant returned to the lab at the end of the workday (approximately 7 hours). The participants wore the Bioharness chest strap for the whole duration of the experiment.

In the Post-Treatment stage, the participants performed three tasks, Baseline, Final Treatment, and post-test.

- Baseline: Same as the initial baseline session.
- Final Treatment: Participant performs the treatment task for a final time.
- Post Test: Participant performs the CWT again, and also an unseen mental arithmetic task (KOM), each for 3 minutes – see Section 3.5. The response time in CWT is reduced to 2 seconds.

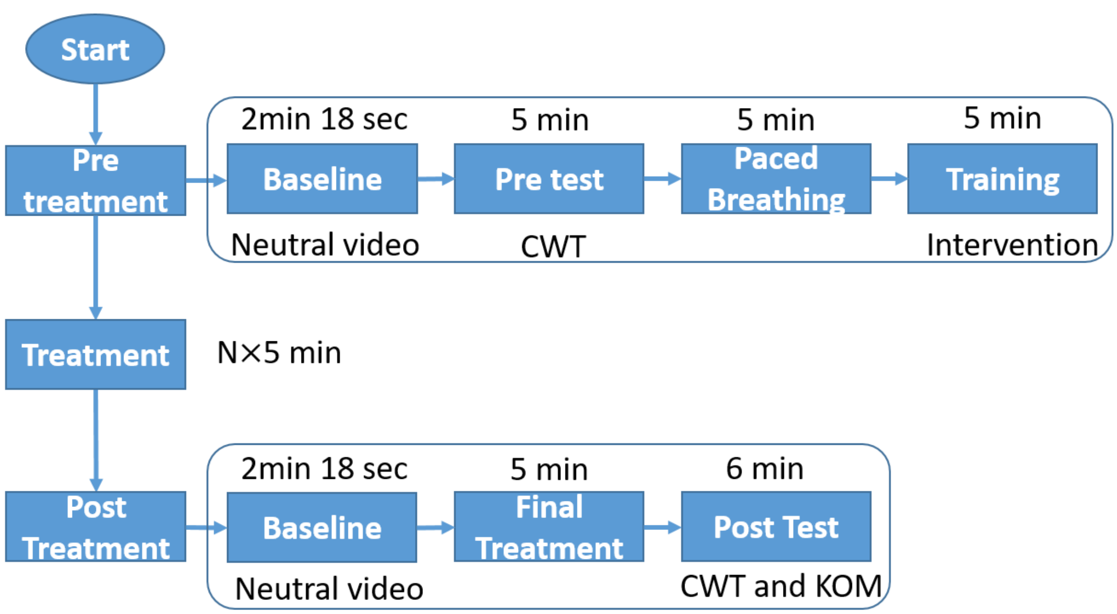


Figure 19 Experimental protocol for the ambulatory study with all the tasks and their respective durations. N in the treatment phase is the number of times the participant

used the application. The participant is assigned to one of the four groups (VBF, PACE, GBF, or GPACE) in the training and treatment tasks.

5.1.1 Effective breathing range

The four treatments aim to assist participants in lowering their breathing rate and maintaining it at approximately 6 BPM. The sensor used provides average breathing rate instead of instantaneous breathing rate, which takes 45 seconds to converge to the average estimate with a ± 1 BPM accuracy (BioHarness 2019). Further, the resonant breathing frequency is participant-dependent and can range from 5.5 BPM to 6.5 BPM (Vaschillo, Vaschillo et al. 2006). Considering the above reasons, we established a 15% margin around 6 BPM $6\ BPM \pm 0.9\ BPM\ (15\%)$ as the effective breathing rate range.

5.2 Results

In this section we first look into the usage statistic of each intervention, i.e. the number of times the treatment intervention was used by participants and the participant's self-reported scores. We use these to conclude on the adherence to treatment. Then, we look into the effective dosage, to see how effectively the participants used the treatments and further, the average breathing rate during the treatment sessions. Then, we look for possible effects of skill transfer to an already seen task and a new task. Finally, we look at subjective and survey results.

5.2.1 Adherence to treatment

Figure 20 show the number of times a participant used the treatment throughout the 7-hour treatment stage. Before t-tests, we analyzed differences in the variance of each group. Pairwise f-tests and Bartlett's and Levine's tests failed to reject the null hypothesis ($p > 0.05$), which shows that the variances of all the groups are similar. As the variance in all the groups is similar, we performed 2-sample t-tests to analyze the differences in the means of the groups. We noticed a significant difference in the means of the GBF and VBF groups ($t(16) = 2.14,\ p = 0.043$). However, we did not observe a significant difference between GPACE and PACE, VBF and PACE or GBF and GPACE. Though significant differences was not observed between most groups, the average number of times the treatment was used was the highest in the case of GBF, followed by GPACE, then PACE and finally VBF. This trend shows that game interventions were preferred over non-game interventions. More differences might become evident when a higher sample size is user or if treatment is extended for more than one day.

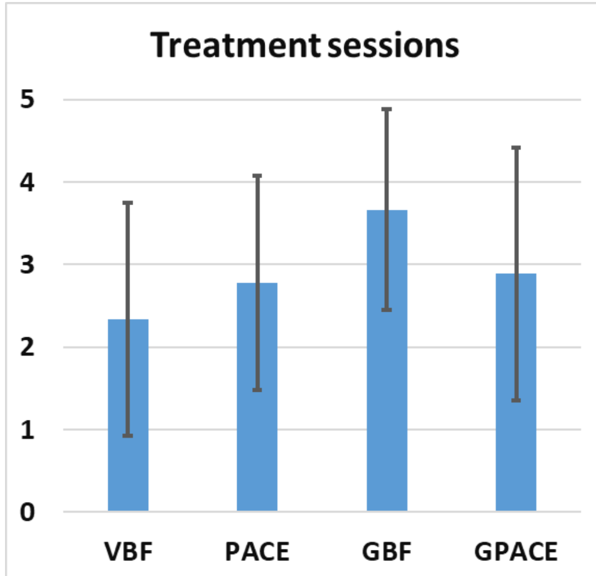


Figure 20 Average number of times the treatment intervention was used during the treatment stage

Figure 21 shows the self-reported engagement and enjoyment scores for the four groups on a five point scale. Engagement describes the action of being involved in the task, whereas enjoyment is the process of taking pleasure in the task. To see the effect of game inclusion into a treatment, we performe 2-sample t-tests on the engagement and enjoyment scores with game groups versus non-game groups. This revealed that participants found GPACE ($t(42) = 2.07,\ p = 0.044$) and GBF ($t(21) = 2.28, p = 0.032$) more enjoyable than PACE, but no significant difference was observed in comparison to VBF. Further, combining both game groups and both non-game game groups revealed a significant difference in the enjoyment score ($t(20) = 2.98, p = 0.007$), but no significant difference in the engagement score. This shows that differences between non-game and the game groups in terms of enjoyment are evident but engagement needs to be studied further. This result bolsters the fact that high drop-outs were seen in unengaging tasks such as mindfulness training and meditation due to lack of motivation and initiative, as shown in (Davis and Addis 1999, Rose, Buckey Jr et al. 2013). Games can counter this issue by adding an enjoyment factor.

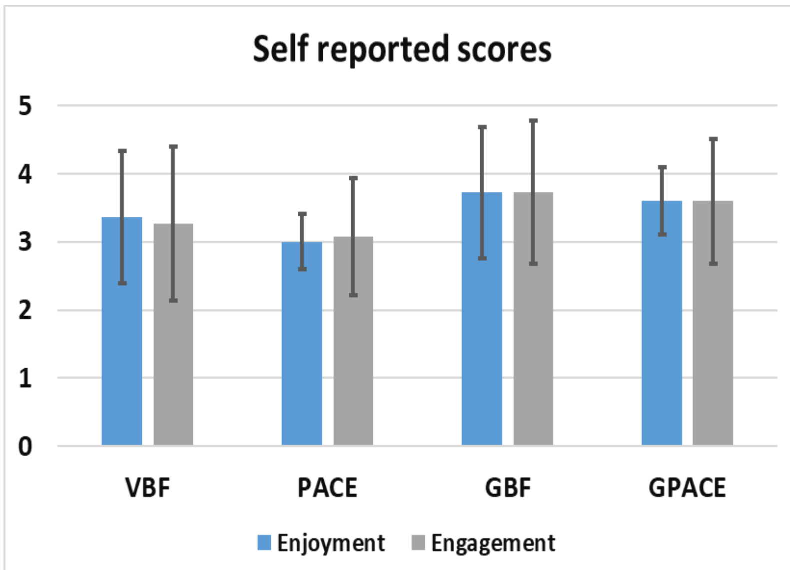


Figure 21 Self-reported enjoyment and engagement scores on a scale of 1-5.

5.2.2 Average training breathing rate

From the controlled study we observed that, for all the interventions, the average breathing rate during the six treatment sessions were very similar. This implies that the participants were able to grasp the mechanisms involved in lowering their breathing rate in the first treatment session and maintain it– see Figure 16. Therefore, in the ambulatory study, we used only one training session before the participant is dismissed. However, in the ambulatory study, we noticed high variability in the average breathing rates during training in the case of GBF and GPACE – see Figure 22, which shows that only a few participants were able to lower their breathing rate to the desired range $(6BPM \pm 0.9BPM)$. But participants in the PACE and VBF groups were able to control their breathing rate and lower it down only with one training session. This can be a result of various factors. First, it could be that the lower sample size used in the controlled study was not able to fairly represent the variability in participant's capability to internalize a certain task. This resulted in an incorrect interpretation of the ease at which participants were able to internalize each task, due to which the design choice of using one training session is unjustified. Further, VBF and PACE are simple tasks, whereas GBF and GPACE are tasks that involve multi-tasking and more practice could be necessary to completely internalize both the game and the breathing mechanism of the task.

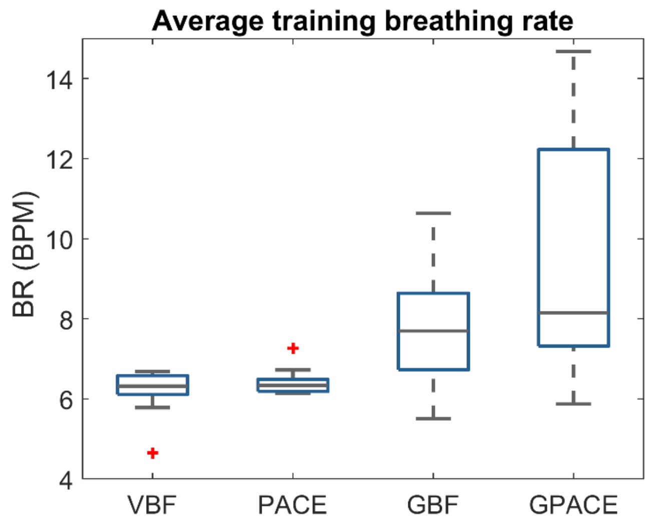


Figure 22 Average breathing rate (BPM) during the training session for all the groups

5.2.2.1 Effect of training on treatment

People approach different tasks with different level of commitment and keenness. Therefore, even though a participant controls their breathing rate during the training and learns the mechanics behind using the treatment intervention, it is not necessary that they use the same amount of commitment in the absence of the study staff. Figure 23 (a-d) show the box plots of the average breathing rate during the training and the treatment sessions for all the conditions considering only the participants that were able to maintain their average training breathing rate in the effective breathing rate range ($6BPM \pm 0.9BPM$). We performed 2-sample welch t-tests for unequal sizes on the training and treatment breathings rate of each group as the variances are dissimilar. We found that the training and treatment average breathing rates are significantly different from each other in the case of VBF ($t(26.14) = 3.21, p = 0.0033$), PACE ($t(17.26) = 3.2, p = 0.005$)

and marginally significant in the case of GPACE ($t(4.8) = 2.19, p = 0.08$), whereas there was no significance in the case of GBF ($t(5.97) = 1.13, p = 0.29$). This shows that in the case of GBF, if the participant is trained such that they are able to hold their breathing rates in the desired breathing rate range, they are more likely to repeat this action and lower their breathing rate during the treatment in the real world setting. However this might not be the case with VBF, PACE and GPACE.

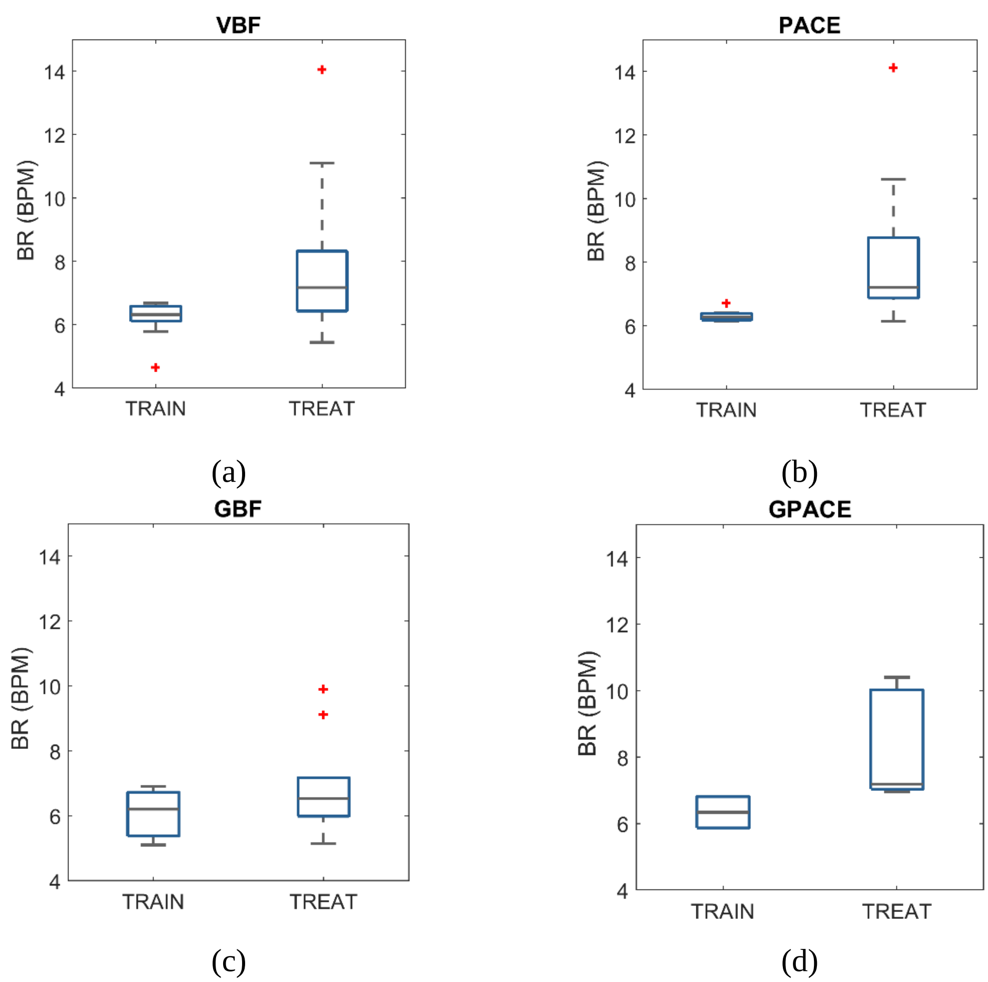
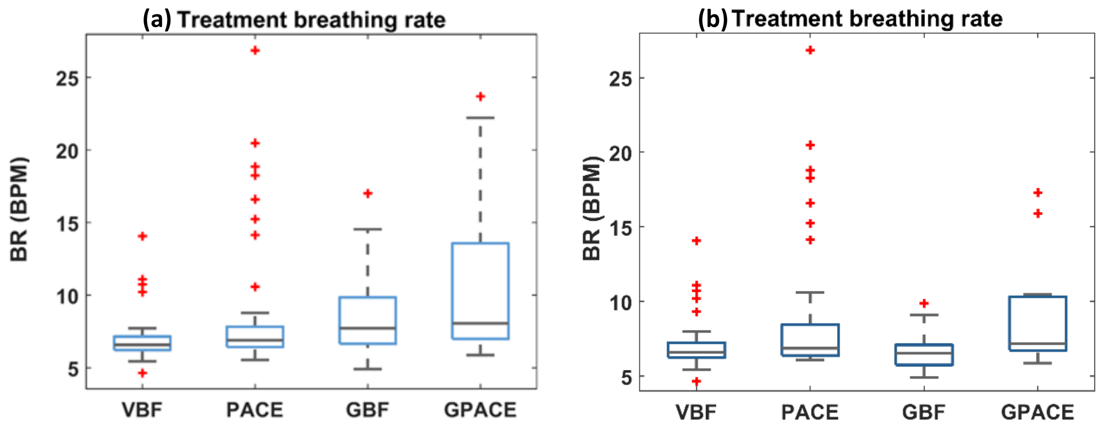


Figure 23 Average breathing rate during the training and treatment session for the participants who were able to maintain the average training breathing rate in the effective breathing rate range ($6BPM \pm 0.9BPM$).

This analysis in our experiments however has a drawback, due to the design of the ambulatory study protocol. Since the protocol involves only one five-minute training session, very few participants were able to reach a level to maintain their average breathing rate in the desired range using GBF and GPACE interventions. However, using the PACE and VBF interventions, almost all the participants were able to reach such level with one session. This lead to a large difference in the number of samples for the GBF and GPACE groups, and the VBF and PACE groups. To rectify this problem, an alternative study needs be designed such that a participant is not dismissed until they learn the mechanic of the intervention so that they control their breathing rate and lower it to the desired breathing range.

Finally, in Figure 24(a-b) we show the effect of training on the average breathing rate during the treatment sessions. Figure 24 (a) shows the average breathing rate during the treatment sessions for all the participants involved. Figure 24 (b) shows the average treatment breathing rates for the participants that were able to maintain their training breathing rate average in the effective breathing rate zone (5.1 $BPM \leq BR \leq$ 6.9 BPM). We notice that the in both cases, average breathing rate in the case of VBF and PACE are very similar whereas GBF and GPACE are different. We observed that if the participant learns the proper technique to control their breathing rate during the training phase, they are more likely to lower their breathing rate during the treatment in the case of the biofeedback groups, than the pacing groups. Factors such as the monotonicity of the pacing signal involved in the pacing groups could be a reason for this.



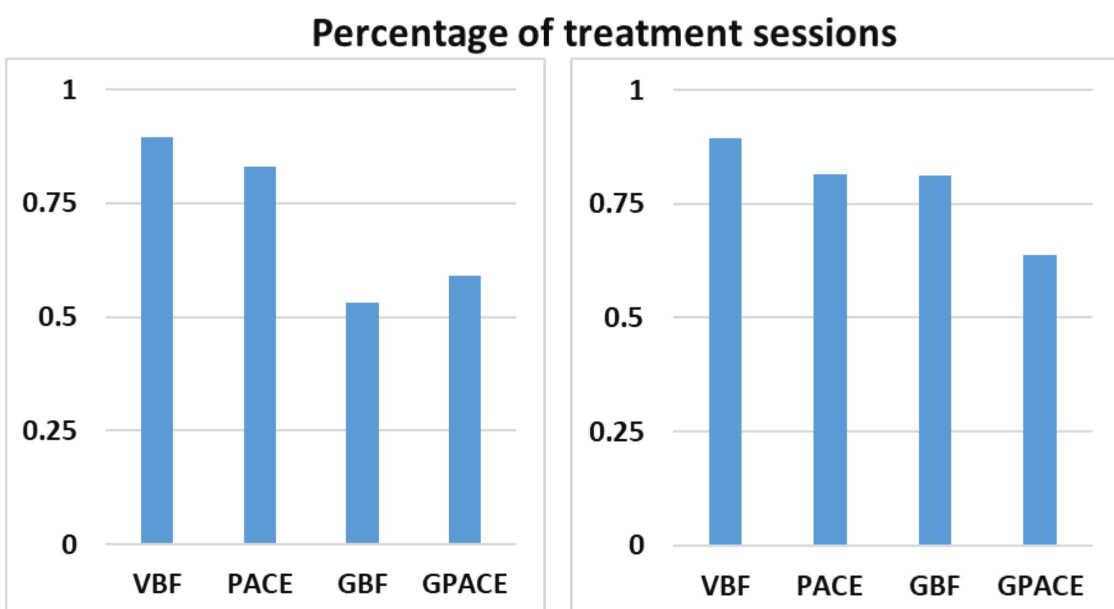
(a) (b)

Figure 24 (a) Box plots of the average treatment breathing rates. (b) Box plots of the average treatment breathing rate using only the participants who were able to lower their breathing rate to the desired range in training.

The results observed in Figure 24 (a) are in contrast with the average breathing rates observed during the treatment session in the controlled study. In the controlled study, GBF and VBF groups showed significantly lower breathing rates during the treatment than PACE and GPACE. VBF group showed similar results, but GBF showed higher average breathing rates than the controlled study. However, the results observed in Figure 24 (b) aligns with the average breathing rates during the treatment session of the controlled experiments (see Figure 15). This shows that if the participants are trained well to lower their breathing rate using a certain intervention, the treatment in the ambulatory setting will be very similar to the treatment in a controlled setting.

5.2.3 Efficacy in lowering breathing rate

In a controlled setting, there is a high chance of the treatment being performed in the desired manner. However, when left to the participant's discretion to use the application, several factors such as the participant's interest level, amount of time they can spend on the task, and their physiological state could affect the way the treatment is used. To assess the effectiveness of the treatment in helping participants lower their breathing rate, we analyzed the average breathing rates during the last 30 seconds of a treatment session. Figure 25 (a) shows the percentage of the total number of sessions where the participants reached the effective breathing range ($6BPM \pm 0.9BPM$). As shown, both non-game interventions were able to do this in approximately 85% of the trials, whereas the game interventions were close to 50% of the time. This is expected, since reaching and maintaining the ideal breathing rate becomes more challenging when an additional task (i.e., the game) is involved.



(a) (b)

Figure 25 Percentage of treatment sessions where the breathing rate of the last 30 seconds was in the effective breathing range ($\mathbf{6}\boldsymbol{BPM} \pm \mathbf{0.9}\boldsymbol{BPM}$) (a) using all the participants. (b) Using only the participants with average training breathing rate in the effective dosage range

Figure 25 (b) shows the percentage of treatment sessions where the participants reached the effective breathing range ($6BPM \pm 0.9BPM$) in the last 30 seconds using only the participants with average training breathing rate in the effective breathing range. We notice that the percentage increases from 50% to 80% in the case of GBF, however very little difference was observed in the case of GPACE. VBF and PACE on the other hand does not show any difference as most of the participants were able to lower their average breathing rate to the desired range during the one training session. This shows that VBF, PACE and GBF helped the participants lower their breathing rate to the effective breathing rate range if trained properly to control their breathing in the training session.

5.2.4 Average pre-test and post-test breathing rates

Next, we compare the average pre-test and post-test breathing rates to assess transfer of relaxation skills due to each treatment intervention. For this purpose, one participant in the VBF group and one participant in the GPACE group were removed as they did not perform any treatment session during the day. Figure 26 (a-c) shows the box plot of the average breathing rates during CWT1 (pre-test), CWT2 (post-test) and KOM (post-test) for all the participants. We did not observe any differences between the average breathing rate of pre-test and the post-test tasks. Further, 2 sample t-tests did not yield any significant differences between the groups.

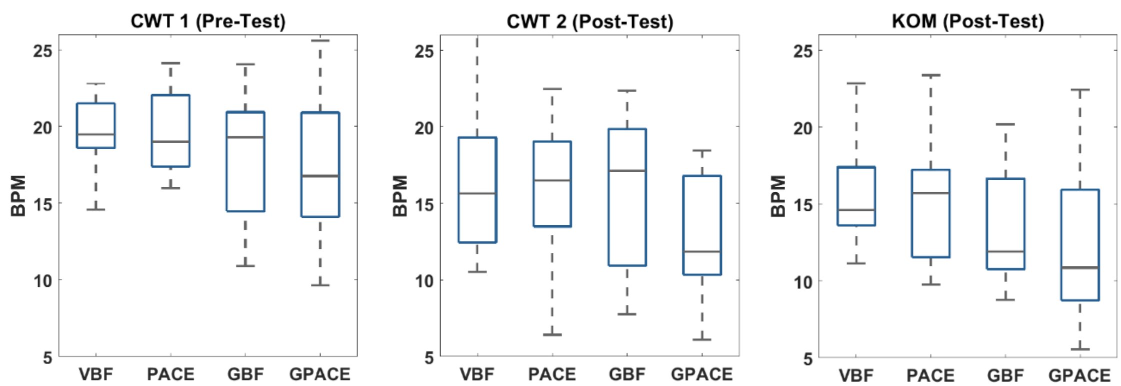


Figure 26 Box plot of average breathing rates during for all the four groups with all the participants included, during (a) CWT 1, (b) CWT 2, (c) KOM

Then we compared the average pre-test and post-test breathing rates considering only the participants who were able to maintain their average breathing rate in the desired range in the training. Figure 27 (a-c) below shows the box plots of CWT1, CWT2 and KOM respectively for the participants with average training breathing rates in the effective breathing rate range ($5.1BPM \leq BR \leq 6.9BPM$). We found significant differences between the CWT1 and CWT2 for GBF ($t(4) = 2.45, p = 0.05$), VBF ($t(14) = 3.35, p = 0.03$) and PACE ($t(14) = 4.2, p = 0.05$) groups but no difference for GPACE. However, the pre-test average breathing rate for the GPACE group was lower than the other three groups. This makes the comparison between the three groups (VBF, PACE and GBF) and GPACE biased against GPACE. Further, none of the groups showed any significant differences between CWT2 and KOM. This suggests the same level of skill transfer to both CWT2 and KOM.

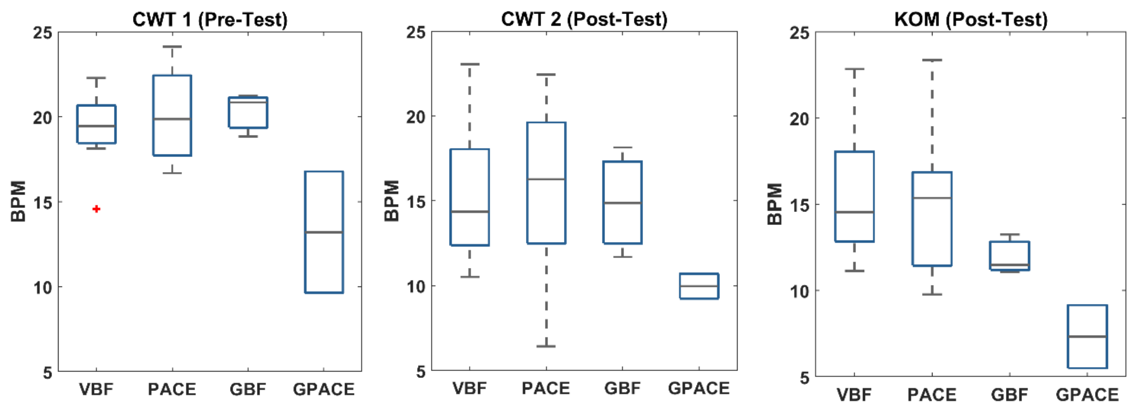


Figure 27 Box plot of average breathing rates using the participants whose average training breathing rate is in the effective breathing rate range ($5.1\ BPM \leq BR \leq 6.9\ BPM$) during (a) CWT 1, (b) CWT 2, (c) KOM

This shows that, in our experiments skill transfer would be possible using three groups, GBF, VBF and PACE, but the results were inconclusive in the case of GPACE. More time under training and treatment would result in better transfer of relaxation skill and provide more noticeable differences between the groups.

This analysis has a few drawbacks. Firstly, GBF and GPACE groups have very limited number of participants with average training breathing rates in the effective breathing rate range. Only three participants in the GBF groups and two in the GPACE group passed this criterion. Therefore their comparison with the VBF and PACE groups is problematic due to the difference in sample sizes. For a better comparison, the participants need to be trained longer so they are able to maximize the benefits from the treatment. Since proving the transfer of relaxation skill was a secondary objective of this study, the design of the protocol is not ideal for this purpose, due to which the results found are still inconclusive.

In ambulatory studies, several factors such as the treatment type, amount of effective dosage, individual capability for internalization, time under training, prior knowledge of games, and breathing techniques play an important role in effecting the skill transfer. Our design does not accommodate for these factors and as a result fails to compare skill transfer between experimental groups. An improved study designed to accommodate for these factors, concentrated specifically on proving skill transfer would be more helpful to study the skill transfer effects of each group and compare them.

5.2.5 Survey results and subjective results

Finally, we assessed the results of the final survey and the subjective results provided by the participants at the end of the experiments. A participant in the VBF group mentioned "(I) *got bored and caught up with something else*" showing that with multiple repetitions, there is possibility that the user would feel VBF monotonous and boring as well. 90 percent of the participants in the PACE group said they felt relaxed at the moment after using the intervention, whereas only 60 percent reported the same in the case of GBF which showed that PACE felt easier for most of the participants and GBF was harder. This is due to the inclusion of the mildly stressful game in GBF. We asked the participants if they were able to perform deep breathing after removing the breathing aid. Then, only 30 percent of the participants in both the PACE and the GPACE groups answered that they were able to perform deep breathing after removing the pacing signal in the presence of a stressor, whereas in the case of GBF and VBF groups, 80 percent answered that they were able to perform deep breathing after removing biofeedback but they felt difficulty in controlling it during a stressful task. This perception is against the results in section 5.2.4, where we observed that there were no statistically significant differences between the post-test average breathing rates of different groups. Finally, two participants of the GBF group mentioned that they needed more practice to do better on the intervention. This is expected due to the increased difficulty level of the task, which involves a steep learning curve and can be very subject dependent.

6. DISCUSSION

Relaxation tools are often tested in a controlled setting so as to prevent most of the external factors affecting the treatment intervention (Goodie and Larkin 2006, Vaschillo, Vaschillo et al. 2006, Parnandi and Gutierrez-Osuna 2015, Parnandi and Gutierrez-Osuna 2017). Therefore, in this thesis we investigate the effectiveness of breathing based relaxation interventions in an ambulatory setting. We designed our experiments in a 2x2 factorial design with the treatment technique as the first factor and a casual game inclusion as the second factor.

Training to stay relaxed in the presence of a stressor for long-term skill retention and transfer employs the principle of systematic desensitization (exposure therapy). Systematic desensitization is used in cognitive behavioral therapy to train for greater self-control in various anxiety provoking situations (Goldfried 1971). In GBF and GPACE, we present the user with a mild stressor (game) and provide them with a relaxation modality. However, in the case of VBF and PACE, we present the user only with the relaxation modality. GBF combines a classical instrumental conditioning (Grant 1964), negative reinforcement (NR-IC) with systematic desensitization. In GBF, the desired relaxing behavior is also strengthened by reducing a negative outcome (game difficulty), to averse stimulus (stress due to increasing difficulty of the game) (Domjan 2014) whereas in the other groups this is not present. Therefore, we saw in our experiments that skill transfer is possible using the four tools, but GBF had a comparatively better effect than the rest, arguably due to the added NR-IC effect in the case of GBF. Further studies that are designed to study skill transfer, which accommodates various influential factors need to be performed to reach a conclusion of skill transfer when treatment is performed in an ambulatory setting.

An interesting observation in the controlled study was that the game groups had a lower variance in the average breathing rate during CWT2 as well as in the difference in the average breathing rates of CWT2 and CWT1 than the non-game groups. One explanation for this could be the low sample size of each group due to which the effect of outliers in dominant. Therefore, even one or two outliers can skew the result in such a way that the spread of the data seems very large. This could be rectified by using a higher number of samples per class, so the outliers can be eliminated.

We also notice that, on the controlled study, GBF had a significantly lower breathing rate than GPACE during treatment. The game based treatments, GBF and GPACE, need the participant to multi-task by controlling their breathing rate and also playing the game simultaneously. Multi-tasking is difficult as it could lead to mental strain, divided attention, and task switching overload (Pashler 2000). In a prior work, Parnandi and Gutierrez-Osuna (Parnandi and Gutierrez-Osuna 2017) showed that game biofeedback intervention allows for better multi-tasking performance as the first task provides information for completing the other task. Breathing rate data is embedded into the game play, affecting it in a positive way by driving the user’s performance during the game play. This turns the single mode of game play into a dual mode, with breathing and motor control over the game. However, in the case of GPACE, the tasks do not contain any information exchange leading to task interference, negatively affecting both tasks (Wickens 2002).

Further, it was also interesting to notice that VBF had significantly lower breathing rate than PACE during the treatment. One explanation for this could be the monotonic nature of the pacing signal. As mentioned in a participant's comment, the monotonic nature of the signal could make the participant lethargic to follow it after some time. In the case of VBF, though, the involvement is not as high as during GBF, a certain degree of involvement is maintained due to the dynamically changing number that displayed the breathing rate. However, from a comment from a participant in the ambulatory study mentions, VBF can get monotonous with extended periods of usage multiple times.

Our controlled study design and analysis is inspired by Parnandi and Gutierrez-Osuna's works on biofeedback games (2015, 2017, 2018), but the experimental groups involved in our study vary from those studies. We use two relaxation modalities and compare a simple straightforward interventions with interventions coupled with a casual game. The GBF (Game Biofeedback) intervention in our study is very similar in implementation as the XBF (Combined biofeedback) proposed by Parnandi and Gutierrez-Osuna (2017), But the results obtained are different. Firstly, the average breathing rate during our treatment sessions was close to 6BPM (see Figure 16) during all the treatments whereas Parnandi and Gutierrez-Osuna's implementation had a gradual reduction in average breathing rates from the first treatment session to the sixth treatment session. Further, the average breathing rate during Post-Test in our experiments was approximately 10.5 BPM, whereas Parnandi and Gutierrez-Osuna's implementation was able to obtain an average breathing rate close to 6 BPM. One reason for these changes is that our implementation of *Scale* and Parnandi and Gutierrez-Osuna's implementation of *Frozen Bubble* differ substantially from each other. Change in the game and the game adaptation mechanism could results in a different approach towards learning involved in the treatment stage. Therefore, it is necessary to choose the game such that the game is suitable for biofeedback implementation as well to see if the desired effect is being achieved. Implementing pilot studies to decide the game that performs best would be a way to achieve this.

Optimal training for long term effects can be time-intensive. Therefore, it is essential that self-guided treatments tools to be characterized with lower attrition rate. A study on predictors of attrition on various protocols showed that lack of engagement and motivation are major contributors to attrition in stress management programs (Davis and Addis 1999). For mobile based interventions with high accessibility and availability, user experience during treatment can highly influence attrition. Therefore, the user is more likely to return to an intervention that causes positive emotional response (for example, excitement) rather than a dull and tedious one. We use the number of times a participant has chosen to use the treatment, and self-reported engagement and enjoyment, to infer the possibility of attrition from the treatment. Observing the histograms in Section 5, the participants are more likely to return to the game-based interventions than the non-game interventions. Further, we noticed a significantly higher usage of GBF over VBF. This preference might be explained by the emotional response joy and intrigue generated playing puzzle games (Ravaja, Salminen et al. 2004).

The efficacy in assisting the user to follow the breathing pattern to relax is an important feature of a relaxation tool. Prior work has shown that maintaining the breathing rate at the resonance breathing rate frequency (generally around 6 BPM) along with shorter inhalations and longer exhalation can lead to maximum relaxation (Strauss-Blasche, Moser et al. 2000, Vaschillo, Vaschillo et al. 2006). Therefore, the treatment that assists in maintaining the average breathing rate close to 6 BPM for a longer duration is likely to induce higher relaxation. In the controlled study, VBF, PACE and GBF were able to aid the participants in lowering their breathing rate close to 6BPM. A significant difference was noticed between the average breathing rate using VBF, GBF groups and the PACE group. However, the difference between the average breathing rates is very low. Therefore, we can conclude that all the three treatments were able to help participants reach 6 BPM and maintain the state.

In the ambulatory experiment analysis, we found that the training session plays a vital role in the effectiveness of the treatment interventions. We observed that training participants to control their breathing rate using VBF and PACE, as almost all the participants were able to control their breathing rate using these interventions in one session. However, using GBF and GPACE very few participants were able to control their breathing rate in one session. We observed that when all the participants were considered in the analysis of average treatment breathing rate, PACE group outperformed the other groups. However, when the participants are filtered based on the average training breathing rate, the biofeedback groups dominate pacing groups. This result is consistent with the result observed in the case of the controlled study. However, more participants need to be recruited and more data needs to be collected to reach a definitive conclusion. Further, since PACE and VBF are simple, they are easy to follow, whereas GPACE and GBF are multi-tasking applications and need practice to control both the tasks. Our experiments train the participants only for a single 5-minute session. Providing longer or number of training sessions before the treatment sessions would probably yield the same result as the result obtained through the controlled study.

7. LIMITATIONS AND FUTURE WORK

In this work, we performed a laboratory study and an ambulatory to investigate four relaxation interventions. We used physiological data collected from 30 participants – 6 per group in the laboratory experiments. Similarly, for the ambulatory study, we collected data using 40 participants – 10 per group. The inferences drawn in both the studies were incomplete as a result of few drawbacks in the design of the study protocols and the sample size used.

In the controlled study, lower sample size lead to ambiguity in the comparison of skill transfer effect between different groups. High variance was seen in the average breathing rate during the post-test task for the VBF and the PACE groups (non-game groups). However, this is not the case with Control, GBF and GPACE groups (game groups). It is still unclear if the high variance is caused due to the low sample size per group, or whether it is an inherent characteristic of the treatment interventions. This caused a difficulty in comparing the different conditions and obtain statistically significant differences. Recruiting more participants to the study should reveal if the high variance in these groups is whether an inherent characteristic of the intervention or a drawback of using few samples. In the future we plan on performing more studies with increased participation to address this issue. Further, the game adaptation can take several forms and needs to be optimized for the best performance in skill transfer. Different types of game adaptations need to be implemented and pilot studies need to be performed with different game adaptations to decide on the best implementation.

The ambulatory study was primarily designed to compare and evaluate the usage of each treatment intervention and assess their effectiveness in aiding the users control their breathing rate in an ambulatory setting. As a secondary goal, we focused on finding an evidence of skill transfer due to each intervention. One major drawback of our approach is that the protocol involves only one training session before the participant is dismissed from the lab. This choice was based on the result from the controlled study, as the participants' average breathing rate during the six treatment sessions were very similar. This showed that most of the participants were able to capture the mechanism of the treatment intervention to lower their breathing rate in the first session and repeat it through out all the sessions. Therefore, we used only one session in the ambulatory experiments for the participants to grasp the mechanisms involved in the treatment intervention. But our results showed that for the GPACE and GBF groups, more training sessions might be needed. This choice was erroneous as the low sample size per group in the controlled study could not have represented the variability in the participants' capability to grasp and learn a new task. An experiment where the participants' breathing rate is monitored in real-time and they are trained until their average breathing rate is close to 6 BPM would balance the difficulty involved in the tasks with the duration of the training session.

To measure the skill transfer due to the treatment interventions, an alternative experiment need to be designed where the dosage of the treatment is more controlled. One such experiment can be where the participants need to perform a minimum number of treatment session during the day. Another such experiment could be where few participants of each experimental group train for different dosage levels (for example 30 minutes, 60 minutes, 90 minutes) spread out during the day. This type of experiment would give a better understanding of the dosage-response relationship of each treatment intervention. This would also give an idea of the effective treatment dosage needed to reach the maximal efficacy, as the benefits of having multiple treatment sessions might saturate at some point. In future studies, we aim to increase the duration of the experiments to (24 hours, 48 hours) and measure skill transfer at various intervals during the experiment.

A study by Parnandi and Gutierrez-Osuna (Parnandi and Gutierrez-Osuna 2018) showed that partial reinforcement in biofeedback improved resistance to extinction of the skill learned using biofeedback after removal of biofeedback. A possible extension to this study is to analyze the long-term transfer of skill and extinction of skill using various biofeedback reinforcement strategies by training over a period of 5 days and testing for skill retention on the 1st and 2nd day after the removal of treatment.

In our ambulatory study, we analyzed the treatment usage and self-reported enjoyment and engagement scores to correlate with the attrition rate of each treatment. This could be affected by various other personal factors apart from the treatment intervention, such as participant's motivation, daily schedule, and amount of free time. A more detailed treatment attrition study can be performed by considering other factors and using more detailed questionnaires on engagement, enjoyability, and personality. Another direction is to provide the participants with all the treatment interventions and analyze the usage of each intervention over a span of a week. This would allow for an analysis of the attrition of treatments comparatively when the participants are aware of the alternatives available.

Studies by Healy et al. (Healy, Fendrich et al. 1992, Healy, Clawson et al. 1993) showed that for long term skill retention and skill transfer to other tasks, it is essential to design training protocols with varied training conditions. Training in multiple settings would help improve *contextual learning* – see (Ormrod 1990), thereby promoting transfer to a more general condition. Designing treatment protocols that involves multiple game plays, using different game genres such as puzzle, strategy, racing, and action that form different stimulus-response relationships would promote such skill transfer. This could lead to even lower attrition from the treatment, since having multiple options would keep the user engaged for longer periods. Our study just concentrates on using a single treatment intervention (per participant).

All participants in the game biofeedback group answered positively when asked if they would be interested in including a new non-invasive tool to their daily routine to help them cope with stress. This tool would recognize stress markers and prompt the participant with a relaxing casual mobile game application. This tool would require the development of a robust breathing rate estimation algorithm from signals collected from non-invasive monitoring devices (for example, smartwatches). Most smartwatches contain a photoplethysmogram (PPG) sensor, which is often used to estimate the user's heart rate. PPG signals can also be used to infer heart rate variability and average breathing rates. A recent work by Smyth and Heron showed the benefits of providing just-in-time interventions in stress management (Smyth and Heron 2016). Sarker et al. (2017) developed an approach to mine the continuous stream of physiological data from a chest strap sensor to assess stress. A similar approach, coupled with the biofeedback game based on breathing rate estimation from the PPG signal, can be a useful low overhead addition to most people that want to better cope with the stress in their daily lives.

8. CONCLUSION

Self-control and relaxation training have gained a lot of traction due to the increase in workplace stress. If left unchecked, stress could cause many health ailments (Kulkarni, O'Farrell et al. 1998, Dallman 2010, Cohen, Janicki-Deverts et al. 2012). Performing slow and controlled breathing has the ability to help a person relax and restore balance to the nervous system (Russo, Santarelli et al. 2017). However, to remain calm under stress, a person needs to train to stay relaxed. To that end, in our work, we used four breathing based treatment interventions pacing, visual biofeedback, game biofeedback and game with pacing.

First, we performed a controlled study to analyze the transfer of relaxation skill to a stressful task immediately after the treatment sessions. Our results showed that during the post-test the average breathing rate for all the treatment interventions was seen to be lower than the Control (game only) implying that skill transfer is possible with any of the treatment groups. However, GBF was the only group to show statistically significant difference from the control group. Further, GBF and VBF aided participants in controlling their breathing rates better than PACE and GPACE during the treatment sessions. The effect of incorporating game with a treatment modality on skill transfer still inconclusive due to the high variance observed in the average post-test breathing rates in the non-game groups. More participants need to be recruited to reach a definitive conclusion.

Following the controlled study, we performed the ambulatory study. We observed that the usage of GBF intervention was significantly higher than the VBF group. However, we did not observe any differences between GPACE and PACE groups, or the other pairwise comparisons. The participants found the game based interventions to be more enjoyable and engaging than the non-game interventions irrespective of the treatment intervention involved. This supports the choice of using games along with a treatment modality such as biofeedback or pacing to improve treatment adherence. Moreover, our study involved only one training session and as a result high variability was seen in the average training breathing rates in the case of GBF and GPACE implying that these treatments would need more time under training. However, only the participants in the GBF group, who were able to maintain a low breathing rate during training, were able to repeat it again in the treatment stage without the supervision of the study staff. Finally, our study was not able to show any definitive proof of skill transfer. An experiment with an alternative protocol designed specifically to prove skill transfer would be needed.

The two studies performed as a part of this work provided a few conclusive results and a few inconclusive results. However, these studies provided us with directions to improve upon the current treatment interventions and the study designs to reach more definitive conclusions in the future studies. Finally, though the results seemed to point towards GBF being the better treatment strategy, more participants need to be recruited and more data needs to be collected be certain of the comparative distinction between these four interventions. Using any one of these interventions would be beneficial to someone who is suffering from chronic stress and would result in a significantly better relaxation response than just playing a casual game for relaxation.

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APPENDIX B: CONTROLLED STUDY SURVEY

Subject Number:

Background

- Age:
- Gender:
- Occupation:
- How do you feel today?

Very tired | A bit tired | Neutral | A bit energetic | Very energetic

- Do you practice meditation regularly? If so, how often and for how long?
- Do you practice deep breathing regularly? If so, how often and for how long?

Sensor

- Did you find the sensors uncomfortable? If so, how?
- Circle one or more type(s) of sensors you would prefer to use for biofeedback

Chest Strap | Wrist | Glasses | Non-contact

- Do you regularly use any type of physiological sensors (e.g. a heart rate monitor for fitness)?

Protocol design

- Were the instructions clear? If not, which instructions were confusing?
- What was the goal of the tasks?
- Would it be useful if we provided a beat or tempo to guide your breathing?

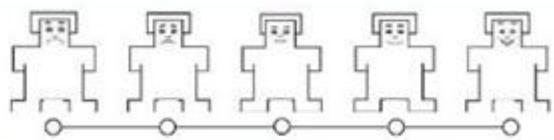
– How hard was it for you to follow the breathing pace during the task?

Very easy ○ — A bit easy ○ — Neutral ○ — A bit hard ○ — Very hard ○

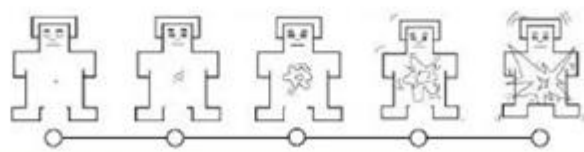
Deep Breathing (Relaxation)

– Did you find the instructions for deep breathing (relaxation) easy to follow? If no, what aspects were unclear?

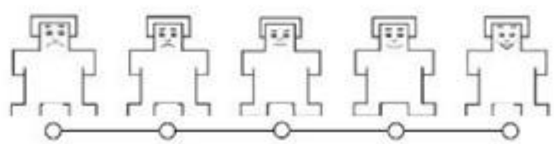
– Valence: How positive or negative did you feel before the deep breathing session?



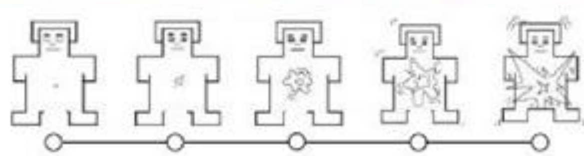
– Arousal: How calm or excited did you feel before the deep breathing session?



– Valence: How positive or negative did you feel after the deep breathing session?



– Arousal: How calm or excited did you feel after the deep breathing session?



– How often would you be likely to practice these deep breathing exercises?

– In which situations or places would you be more likely to practice them?

– How hard was it for you to follow the breathing pace during the task?

Very easy	A bit easy	Neutral	A bit hard	Very hard
○	○	○	○	○

Game

– Video game experience: How often do you play video games per week? For how long each time?

– Favorite video game and type:

– How would you rate your expertise with similar games (e.g. matching games)?

Beginner	Novice	Average	Skilled	Masterful
○	○	○	○	○

– How difficult was it for you to learn to play the game?

Very easy	A bit easy	Neutral	A bit hard	Very hard
○	○	○	○	○

– How did you find the information provided by the user interface, such as breathing rate, game status, etc.?

Very uninformative	Uninformative	Neutral	A bit informative	Very informative
○	○	○	○	○

– Was any aspect of the game (or the instructions) confusing? If so, which one(s)?

– How easy was it to score high on the game?

Very easy	A bit easy	Neutral	A bit hard	Very hard
○	○	○	○	○

– Was any aspect of the game challenging? If so, which one(s)?

– Were you able to concentrate on the game?

– How enjoyable did you find playing the game?

Very boring ○ — A bit boring ○ — Neutral ○ — A bit enjoyable ○ — Very enjoyable ○

– Does playing the game make you feel good? If so, in which ways?

– Would you find a video game like this a good diversion when you are feeling stressed?

– Would you play this game regularly if it were available to you? How often?

– The game you played falls under the genre of puzzles or matching games. What other game genres would you suggest for deep-breathing training?

Check	Game Genre	Example
	Puzzle or matching game	Our game
	Hidden object game	Mystery case files
	Adventure game	Temple run
	Strategy Game or Time Management	SimCity
	Arcade and action game	Candy crush
	Word and trivia game	Scrabble
	Card game	Solitaire

– Please list the things you liked most about this app

– Please list the things you liked least about this app

– Did you notice any inconsistencies in the game? If so please list

– Did you experience any software problems when playing the game? If so, please describe.

Biofeedback in the game

– Was it hard to play the game while you were controlling your breathing rate?

– Did you notice any changes in the game as you adjusted your breathing rate?

– Did you notice any changes in the game with your stress levels?

– Do you like the idea of using wearable sensors as an input to a game? Why? Why not?

– Did you notice any differences in <u>difficulty</u> between pre and post task (Stroop color word test)? If so, please elaborate?

– Did you continue doing deep-breathing while performing the post task (Stroop color word test)? If so, how hard was it to do the two tasks together?

Very easy	A bit easy	Neutral	A bit hard	Very hard
○	○	○	○	○

APPENDIX C: AMBULATORY STUDY SURVEY

Ambulatory study

Form description

Participant number *

Short answer text

Experimental Group *

- ○ VFB
- ○ GBF
- ○ PACE
- ○ GPACE

Gender *

- ○ Female
- ○ Male
- ○ Prefer not to say
- ○ Other...

Occupation *

Short answer text

How do you feel today ? *

- Very Tired
- A bit tired
- Neutral
- A bit energetic
- Very Energetic

Do you practice meditation or mindfulness training regularly ? If so, how often and for how long ? *

Short answer text

Do you practice deep breathing or any kind of breathing exercise ? If so how often and for how long ? *

Short answer text

Sensor

Description (optional)

Did you find the sensor uncomfortable ? *

- ◯ Yes
- ◯ No

Which type of sensors would you prefer ? *

- ◯ Chest Strap
- ◯ Wrist
- ◯ Non -contact
- ◯ Doesn't matter

Do you use any sensors on a regular basis ? (eg: heart rate monitor for fitness tracking) *

Short answer text

Protocol Design

Description (optional)

Were the instructions Clear? If not which instructions were confusing ? *

Short answer text

What task were you assigned to Do ? *

Short answer text

How hard was it for you to follow the breathing pace during the task ? *

	1	2	3	4	5	
Very easy	○	○	○	○	○	Very hard

Did you find the instructions for deep breathing easy to follow ? If no, what aspects were unclear * ?

Short answer text

Assessment Task

Description (optional)

Were you able to maintain your calm while performing the final Color word test ? *

- Yes
- No

Were you able to maintain your calm while performing the King of math task? *

- Yes
- No

Were you able to perform deep breathing while doing the final color word test ? *

- Yes
- No

Were you able to perform deep breathing while doing the king of math ? *

- Yes
- No

How hard was the initial color word test ? *

	1	2	3	4	5	
Very hard	○	○	○	○	○	Very easy

How hard was the final color word test compared to the initial color word test ? *

	1	2	3	4	5	
very hard	◯	◯	◯	◯	◯	very easy

which of the assessment tasks did you find easier ? *

- ◯ color word test
- ◯ king of math

Do you think performing the treatment task multiple times during the day helped you perform deep breathing during the assessment tasks? *

- ◯ Yes
- ◯ No
- ◯ Other...

If the number of sessions during the day were increased. Do you think that would help you remain calm during the assessment tasks? *

- ◯ Yes
- ◯ No

Did playing the game along with deep breathing in the task help you in performing deep breathing along with assessment tasks ? *

- Yes
- No
- NA (No Game)

Did the pacing signal during the treatment help you control your breathing during the assessment tasks? *

- Yes
- No
- NA (No pacing signal)

Did biofeedback during the treatment help you control your breathing during assessment tasks? *

- Yes
- No
- NA (No biofeedback)

Task

Description (optional)

What task were you asked to do during the day ? *

- ◯ Follow Pacing signal
- ◯ Follow Pacing signal and Play the game
- ◯ keep the number on the screen at 6
- ◯ Play the Game while controlling the difficulty level with your breathing

Was it hard for you to follow the breathing pace during the task ? *

- ◯ Yes
- ◯ No

How enjoyable did you find the task *

	1	2	3	4	5	
Very Boring	◯	◯	◯	◯	◯	very Enjoyable

How engaging did you find the task ? *

	1	2	3	4	5	
least Engaging	◯	◯	◯	◯	◯	very engaging

How many times did you perform the task during the day ? *

Short answer text

How many times did you finish the complete session ? *

Short answer text

List some of the reasons that you interrupted the session in the middle *

Long answer text

What type of environment would you prefer to perform the task ? (eg: indoors, outdoors, when you are alone etc.) *

Short answer text

Would you be willing to perform the task in busy location ? (location filled with people) *

- ◯ Yes
- ◯ No

Did performing the task have an effect on reducing the stress you were feeling at that time ? *

- ◯ Yes
- ◯ No
- ◯ Other...

How effective was the task in reducing your stress ? *

	1	2	3	4	5	
Lest effective	◯	◯	◯	◯	◯	very effective

Did doing the task session help you in learning deep breathing? *

- ◯ yes
- ◯ no
- ◯ Other...

How effective was the task in helping you learning deep breathing *

	1	2	3	4	5	
Least effective	◯	◯	◯	◯	◯	Very effective

Would you be willing to perform the treatment task for a few minutes everyday ? (5-10 mins) *

- ◯ Yes
- ◯ No

Did performing the task improve your mood ? *

- ◯ Yes
- ◯ No

Did performing the task during the day improve your day in anyway ? *

- ◯ yes
- ◯ No

In what way did performing the task improve your day ? (If you checked no above answer NA) *

Long answer text

Would performing the treatment task daily help you in remain calm while performing a stressful task? *

- ◯ yes
- ◯ No

Would you like to perform the treatment at any specific times of the day ? or perform it when ever you feel stressed ? *

Short answer text

What time of the day would you prefer to perform the task ? *

- ◯ Early morning
- ◯ around breakfast time
- ◯ between breakfast and lunch
- ◯ around lunch time
- ◯ evening
- ◯ dinner time
- ◯ Before sleeping
- ◯ Other...

GAME

Description (optional)

How often do you play video games ?

Short answer text

What is your favorite type of game ?

- ◯ Puzzle or matching game
- ◯ hidden object game
- ◯ adventure game
- ◯ strategy or time management game (our game)
- ◯ arcade and action game
- ◯ word and trivia game
- ◯ card game

How would you rate you experience in similar type of games?

	1	2	3	4	5	
Beginner	◯	◯	◯	◯	◯	Master

How difficult was it for you to learn to play the game ? *

	1	2	3	4	5	
Very easy	◯	◯	◯	◯	◯	Very hard

How did you find the information provided by the user interface , such as breathing rate, game status etc ?

	1	2	3	4	5	
Very uninformative	○	○	○	○	○	Very informative

Was any aspect of the game (or the instructions) confusing ? If so which one (s)?

Long answer text

How easy was it to score high on the game ?

	1	2	3	4	5	
Very easy	○	○	○	○	○	very hard

Was any aspect of the game challenging . If so which one(s)?

Long answer text

Were you able to concentrate on the game?

○ Yes

○ No

Were you able to maintain breathing pace while playing the game ?

○ Yes

○ No

○ Other...

Would you find a game like this a good diversion when you are feeling stressed ?

- Yes
- No

Would you play this game regularly if it were available to you ? How often would you play it ?

Short answer text

List the things you most liked about the game ?

Long answer text

List the things you least liked about the game ?

Long answer text

Biofeedback

Description (optional)

Was it hard to play the game while you were controlling your breathing rate ?

- Yes
- No
- NA

Were the changes in the game Noticeable when you adjusted your breathing rate ?

- yes
- No
- NA

Did you notice the difference in difficulty level when you were stressed ?

- Yes
- No
- NA

Did playing the game along with biofeedback help you in learning deep breathing ?

- Yes
- No
- NA

How effective was biofeedback in helping you learn deep breathing ?

	1	2	3	4	5	
least effective	○	○	○	○	○	very effective

Pacing

Description (optional)

Were you able to follow the pacing signal ? *

- ○ Yes
- ○ No

Did playing the game along with the pacing signal help you learn deep breathing ? *

- ○ Yes
- ○ No
- ○ NA

How effective was the pacing signal in helping you learn deep breathing? *

	1	2	3	4	5	
least effective	○	○	○	○	○	very effective

Miscellaneous

Description (optional)

Would you be willing to incorporate the treatment into your daily routine ? *

- ◯ Yes
- ◯ No

Would you like a smart watch based sensor system that recognizes you are stressed and gives you a notification to relax and use the treatment. *

- ◯ Yes
- ◯ No