PHYSIOLOGICAL SELF REGULATION WITH BIOFEEDBACK GAMES

A Dissertation

by

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ABSTRACT

Mental stress is a global epidemic that can have serious health consequences including cardiovascular diseases and diabetes. Several techniques are available to teach stress self-regulation skills including therapy, meditation, deep breathing, and biofeedback. While effective, these methods suffer from high drop-outs due to the monotonic nature of the exercises and are generally practiced in quiet relaxed environment, which may not transfer to real-world scenarios. To address these issues, this dissertation presents a novel intervention for stress training using games and wearable sensors. The approach consists of monitoring the user’s physiological signals during gameplay, mapping them into estimates of stress levels, and adapting the game in a way that promotes states of low arousal. This approach offers two key advantages. First, it allows users to focus on the gameplay rather than on monitoring their physiological signals, which makes the training far more engaging. More importantly, it teaches users to self-regulate their stress response, while performing a task designed to increase arousal. Within this broad framework, this dissertation studies three specific problems. First, the dissertation evaluates three physiological signals (breathing rate, heart rate variability, and electrodermal activity) that span across the dimensions of degrees of selectivity in measuring arousal and voluntary control in their effectiveness in lowering arousal. This will identify the signal appropriate for game based stress training and the associated bio-signal processing techniques for real-time arousal estimation. Second, this dissertation investigates different methods of biofeedback presentation e.g.

visual feedback and game adaptation during gameplay. Selection of appropriate biofeedback mechanism is critical since it provides the necessary information to improve the perception of visceral states (e.g. stress) to the user. Furthermore, these modalities facilitate skill acquisition in distinct ways (i.e., top-down and bottom-up learning) and influence retention of skills. Third, this dissertation studies reinforcement scheduling in a game and its effect on skill learning and retention. A reinforcement schedule determines which occurrences of the target response are reinforced. This study focuses on continuous and partial reinforcement schedules in GBF and their effect on resistance to extinction (i.e. ability to retain learned skills) after the biofeedback is removed. The main contribution of this dissertation is in demonstrating that stress self-regulation training can be embedded in videogames and help individuals develop more adaptive responses to reduce physiological stress encountered both at home and work.

DEDICATION

Dedicated to my family.

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1. INTRODUCTION

In 2014, 64% of employees in the U.S. reported high levels of stress and this number is continually growing (APA 2016). Workplace stress impacts quality of life and can have serious health consequences. In fact, the World Health Organization has deemed job stress a global epidemic (DeVries and Wilkerson 2003). Recent advancement of mobile technology has further exacerbated this problem. Mobile technology allows for a nearly constant connectedness of employees with their work leading to increasingly non-standard work hours blurring the boundaries between work and home. This provides flexibility to the employees to work at the time and place of their convenience and improves productivity for the employer. While beneficial, it has been reported that employees who stay connected find it difficult to psychologically detach themselves from work and work-related pressures (Stawarz, Cox et al. 2013). This leads to a number of negative consequences such as insufficient recovery (Sonnentag 2001), exhaustion (Schaufeli and Bakker 2004), and more critically, stress (APA 2016). Constant exposure to work related stress causes a number of health problems ranging from sleep deprivation (Åkerstedt, Knutsson et al. 2002) to negative coping behaviors including smoking (Kouvonen, Kivimäki et al. 2005) and alcohol abuse (Crum, Muntaner et al. 1995). Chronic stress can lead to lowered immune function, memory impairment, obesity, diabetes, depression, and cardiac diseases (Goldstein 1995, Kivimäki, Virtanen et al. 2006, Dallman 2010). It severely impacts employers by reducing worker productivity and increased healthcare costs. As an example, workplace stress has been estimated to cost $300 billion to the US economy alone (Leiter and Maslach 2011).

A number of interventions have been developed to teach self-regulation skills to individuals, including at the workplace. These include cognitive behavioral therapy (CBT), biofeedback, meditation, yoga, and breathing exercises (Richardson and Rothstein 2008). Although these interventions have been shown to be effective in mitigating stress, they suffer from several shortcomings. For example, CBT, which is a form of psychotherapy (Beck 2011), is performed under the supervision of a trained mental health clinician making it an expensive and inaccessible for most. In biofeedback, electrodes are attached to the patient’s body to monitor key physiological variables and the resulting signals are displayed on a visual display (Stein 2001). This allows the user to see the immediate effects of stressors on their physiology and regulate their stress response, though visualizations (especially those of electrodermal activity (EDA) and electroencephalogram (EEG)) tend to be non-intuitive to many users (Pallavicini, Algeri et al. 2009). Self-guided interventions, including meditation and yoga, suffer from high dropout rates (Rose, Buckey et al. 2013) due to the unengaging nature of the exercises and lack of motivation (Davis and Addis 1999). In addition, most of these methods suffer from the limitations that these require the user to adhere to strict training protocol making it challenging to follow the regimen (Henriques, Keffer et al. 2011). More importantly, these techniques develop self-regulation in quiet, controlled settings, which may not generalize to stressful real world scenarios where it is really needed (Driskell and Johnston 1998).

Need statement: There is a need for a stress management technique that is intuitive, inherently engaging, and teaches stress regulation under the influence of stressors.

Since one of the main factors in inducing stress is the increasing use of mobile technologies (Derks and Bakker 2012), this dissertation explores whether these technologies can be used to build resilience to stress and reduce the overall negative effects. In fact, in recent years a number of technology based interventions have been developed allowing for stress self-regulation and these methods have been found to be as effective as face to face therapy in a number of studies (Proudfoot, Goldberg et al. 2003, Titov, Andrews et al. 2010). Example of technology-based interventions include bio/neurofeedback devices (Rosenthal, Alter et al. 2001, Thompson and Thompson 2007), meditation apps (Clinic 2009), Virtual reality (VR) methods (Pallavicini, Algeri et al. 2009, Wood, Webb-Murphy et al. 2009), and videogames (Reinecke 2009, Russoniello, O'Brien et al. 2009, Collins and Cox 2014). These methods are well suited for the issue of stress management since they are cost-effective (economy of scales), can provide personalized training to users, maintain privacy, and can be performed at the time and place of user's choosing.

Among the existing tools, videogames appear ideally suited for stress exposure training i.e. teaching stress management under the presence of stressors and retention of these skills beyond training. Videogames are designed to increase arousal (Buckley and Anderson 2006, Reinecke 2009), therefore a stress management program embedded in a videogame can help combat stress (i.e. lower user's arousal) while performing an arousal inducing task, a form of stress desensitization. As an added benefit, videogames are extremely popular across a wide variety of users (Williams, Martins et al. 2009). In fact, researchers have used videogames to increase patient's motivation during painful and repetitive procedures (Patel, Schieble et al. 2006) and for a variety of medical conditions (Lieberman 1997). Given the repetitive nature of videogames, they have been used to as instructional games to promote skill learning and practice (Lieberman 1997, Rosas, Nussbaum et al. 2003). Finally, videogames have been shown to lead to recovery and recuperate from stress and strain following work related fatigue due to the sense of detachment (Fritz and Sonnentag 2005, Reinecke 2009). Given that videogames are inherently engaging and useful in recovery, they are a viable candidate for stress training. However, while videogames have shown promise in healthcare and fitness applications, they have not yet been extensively studied as a stress-management tool. This is the focus of this dissertation. Namely, this dissertation proposes a new category of intervention that combines the appeal of video games and the availability of wearable sensors with instrumental conditioning[1] to allow individuals to practice biofeedback-based stress reduction anywhere, anytime. The proposed approach, termed *game biofeedback (GBF)*, consists of monitoring the user's physiology during gameplay and adapting the game in a way that rewards relaxing behavior. During a GBF session, users play a game while wearable sensors measure their stress levels. These stress levels are then used to modify gameplay parameters with a proportional-derivative controller in a

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[1] Instrumental conditioning refers to the modification of behavior based on the consequences of voluntary actions. It uses reinforcement (i.e. rewards or penalties) to modify (i.e. increase or decrease) a behavior.

positive feedback loop, such that high levels of arousal lead to increasingly more difficult gameplay, whereas lower levels of arousal result in more fluid gameplay. Unlike conventional biofeedback training, where feedback is explicit, GBF provides an implicit form of feedback through subtle changes in gameplay. For example, increases in heart rate variability (an indication of relaxation) could be used to improve certain characteristics of the game, e.g., better road conditions/visibility in a car racing game. This allows users to focus on the gameplay experience rather than on monitoring their physiological signals, which makes the training more engaging (i.e. stealth learning). Furthermore, since videogames are designed to increase arousal (Buckley and Anderson 2006), the proposed intervention allows the user to practice self-regulation during a stress-inducing task, a form of stress inoculation that may transfer to real-world scenarios.

Research agenda: The research agenda of this dissertation is to build a biofeedback game based system to teach stress management skills to individuals in an engaging way and in the presence of stressors.

1.1 Research challenges

Integrating physiological sensors with games for stress training poses many research questions; to allow for depth of study, this dissertation has focused on three of them. The first question pertains to the physiological signal that should be used for biofeedback to best teach relaxation skills. The choice of signal is important for two reasons. First, humans have different degrees of voluntary control over physiological signals; for example, breathing rate (BR) is under complete voluntary control while electrodermal activity (EDA) is under minimal voluntary control. Second, physiological modalities have varying degrees of selectivity in measuring autonomic arousal; for instance, EDA is a highly selective indicator of arousal while BR is not an accurate measure of arousal. As such, the different physiological signals allow for examining the tradeoff between these factors (i.e. degree of voluntary control and selectivity in indicating arousal) and determine their effectiveness in teaching relaxation and promoting skill transfer. Furthermore, raw physiological measures have large variability both across participants and over time. This indicates the necessity of robust signal processing methods for real-time estimation of arousal on a smartphone.

The second question deals with closing the loop in the biofeedback system and presenting the physiological information to the user. Traditional biofeedback systems present the signals on a visual display. In contrast, GBF offers novel ways in which the feedback can be integrated in a game (e.g., game adaptation). An ideal biofeedback mechanism in a game should 1) improve a user's perception of certain visceral states (e.g. high arousal), 2) guide the user to relaxation by providing the necessary information during gameplay, and 3) not affect performance on the task, i.e., gameplay. These points indicate that selecting an appropriate biofeedback mechanism is critical.

The third and final question deals with retention of relaxation skills –once the biofeedback is removed. Skill retention over time depends not only on the training method and dosage requirements but also on the reinforcement schedule. A reinforcement schedule determines which instances of the target responses are reinforced or penalized and can be categorized into continuous and intermittent reinforcement.

Thus, as a final goal, this dissertation investigates the persistence effects of GBF and studies the resistance to extinction of deep-breathing skills. Resistance to extinction refers to the ability to maintain learned skills once biofeedback is removed. This study will evaluate the effectiveness of continuous and partial reinforcement schedules in game biofeedback by their effectiveness in teaching self-regulation skills and improving resistance to extinction.

1.2 Specific research goals

The research questions investigating the effectiveness of the game biofeedback approach can be summarized into the following four research goals:

1. Develop and validate an adaptive biofeedback game for building self-regulation skills in an individual. This will serve as a proof of concept for the proposed GBF approach.
2. Evaluate the effectiveness of various physiological signals spanning across the dimensions of degrees of selectivity in measuring stress and voluntary control in their ability in reducing arousal with GBF.
3. Develop different methods of biofeedback presentation during gameplay and investigate their effectiveness in lowering arousal during gameplay.
4. Study the effect of reinforcement scheduling of biofeedback in games in teaching relaxation skills and increasing resistance to extinction.

1.3 Summary of findings

The aim of this dissertation is to present the game biofeedback approach and determine its effectiveness in teaching stress self-regulation and promoting skill transfer. To evaluate the effectiveness of the GBF approach a number of studies were conducted as part of this dissertation. Table 1 presents an overview of the studies and their contributions in addressing the specific research goals stated in Section 1.2.

Table 1 Studies and contributions in this dissertation

#	Chapter	Contributions
3	Design and validation of the game biofeedback approach	(1) Describe the GBF approach including the game, game adaptation, and arousal estimation methods. (2) Validate the GBF approach in teaching relaxation skills and promoting skill transfer through a pilot study.
4	Physiological modalities for relaxation skill transfer In biofeedback games	(1) Explore the tradeoff between voluntary control and selectivity in measuring arousal by bio-signals. (2) Identify the physiological signal most suited for stress training with GBF.
5	Visual biofeedback and game adaptation in relaxation skill transfer	(1) Design and develop three GBF methods: visual biofeedback, game adaptation, and combined. (2) Evaluate the biofeedback methods by their effectiveness in improving skill learning and retention. (3) Study the pace of learning for the GBF and control group in terms of acquisition of deep breathing skills.
6	Reinforcement scheduling in game biofeedback	(1) Implement partial and continuous reinforcement methods in GBF. (2) Evaluate the effect of scheduling of reinforcement in GBF based training to maximize skill transfer.

1.4 Dissertation outline

The rest of the dissertation is organized as follows. Chapter 2 discusses the stress response and human body's response to stress, reviews prior work on stress-management tools and discusses the usage of videogames in healthcare and arousal reduction applications. Chapter 3 presents an overview of the GBF approach – including the choice of game, physiological correlates of stress and signal processing methods for arousal estimation. This chapter also evaluates its effectiveness in teaching relaxation skills against a control and standard treatment through a pilot study. Chapter 4 investigates various physiological signals for GBF stress training. Chapter 5 closes the feedback loop and evaluates different ways of presenting the biofeedback information back to the user. Chapter 6 studies the scheduling of reinforcement in GBF and compares continuous and partial biofeedback reinforcement in improving resistance to extinction. Chapter 7 concludes this dissertation and presents future directions for the GBF approach.

2. RELATED WORK

2.1 Stress and the human body

Stress is the body's response to any demand (internal or external) or stimulus (Selye 1956). Stress response, also known as resilience, is body's ability to adapt successfully when facing acute stress or trauma and regaining physiological homeostasis[2] (Charney 2004). When a stressful situation arises, a series of events begin in the hypothalamus of the brain leading to the secretion of the stress hormones (cortisol). The secretion of stress hormones lead to the increase in the availability of energy substrates in the body and allow for adaptation depending on the demands of the situation (Lupien, McEwen et al. 2009).

The presence of a stressor gives rise to what is known as the '*fight or flight*' response of the sympathetic branch of the autonomic nervous system (ANS) (Bakewell 1995). This is characterized by increased heart rate, breathing rate, pupil dilation, eccrine gland activities, and decreased immune function (Clark, Rager et al. 1997); see Figure 1. To counter this effect, the parasympathetic nervous system (PNS) –one of the two branches in the ANS—is activated. PNS is antagonistic to the sympathetic nervous system (SNS) and works to induce relaxation and conserve energy. It inhibits the SNS to maintain or regain homeostasis. It helps mitigate the negative effects of the stressor on the body and help reach homeostasis. This is known as the relaxation response, which is

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[2] Homeostasis refers to the body's ability to regulate its physiological systems to maintain stability in response to external fluctuations.

physiologically characterized by reduction in arousal, cortisol levels, heart rate and breathing rate.

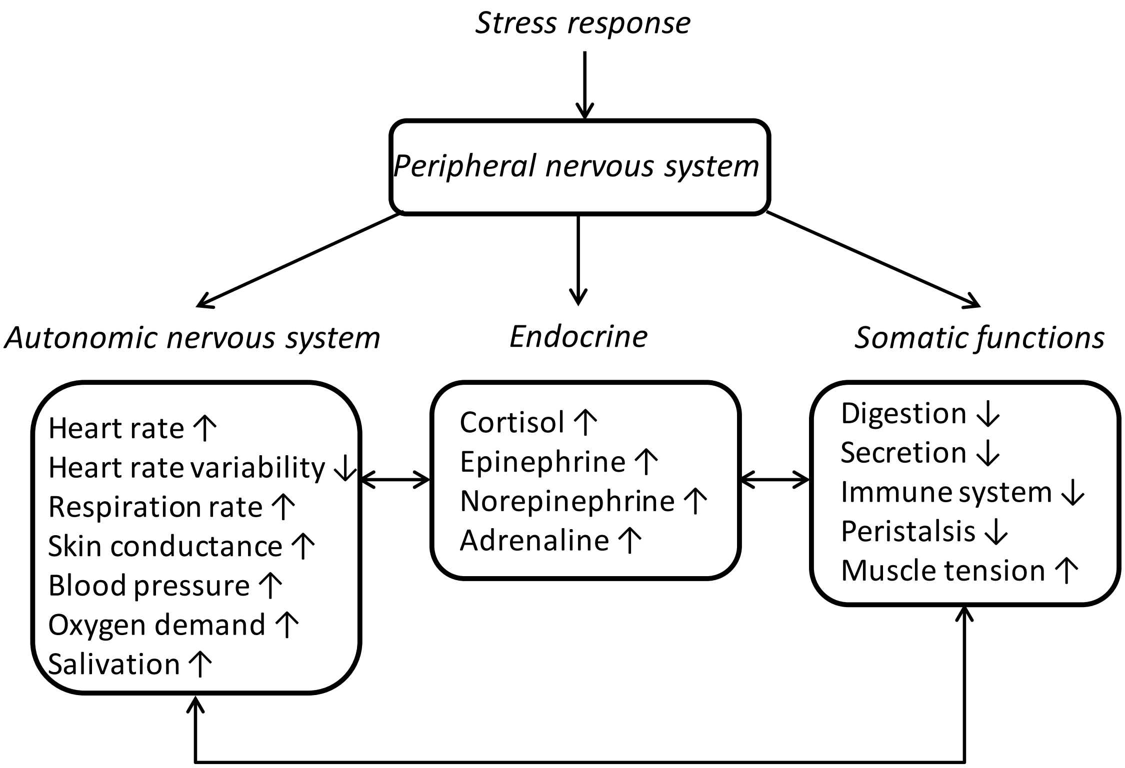

Figure 1 Effect of stress on the human body

2.1.1 Effects of stress on health

Stress is a serious problem around the world and is constantly rising (ADAA 2015). Stress affects both the health and overall quality of life. Constant exposure to stress leads to a number of negative effects including tiredness and insufficient recovery (Van Hooff, Geurts et al. 2006), sleeping disorders (Åkerstedt, Knutsson et al. 2002), and burn outs and exhaustion (Schaufeli and Bakker 2004).

Continuous exposure to stress (i.e. chronic stress) can lead to negative health consequences e.g. obesity (Dallman 2010) and pathological aging[3] (Bremner and Narayan 1998). Stress is also associated with increased hypertension (Vrijkotte, Van Doornen et al. 2000), lowered immune function (Kiecolt-Glaser, McGuire et al. 2002), premature aging of genes (O'Donovan, Tomiyama et al. 2012) and 50% increased risk of coronary heart disease (Kivimäki, Virtanen et al. 2006). In an influential study, Epel et al. (2004) found that chronic stress increases the rate of telomere[4] shortening and damage. Not surprisingly, stress is considered a major health issue, as serious as infectious disease such as AIDS, and one that negatively impacts our daily lives (DeVries and Wilkerson 2003). Along with the negative effect on health, studies have also shown that stress leads to a number of negative coping behaviors including smoking (Kouvonen, Kivimäki et al. 2005) and alcohol and substance abuse (Crum, Muntaner et al. 1995) further exacerbating the adverse health consequences. Finally, stress is also related with low physical activity and increased body weight leading to poorer health conditions.

2.1.2 Effects of stress on mental health

Stress also has a profoundly negative effect on mental health, an under-acknowledged growing health problem around the world. According to the WHO, by year 2020 stress related mental issues will be the second most debilitating condition in

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[3] Normal aging is a result of natural maturation processes. In contrast, pathological aging is due to other factors such as diseases or trauma.

[4] Telomeres are DNA–protein complexes that cap chromosomal ends leading to chromosomal stability and provide a way for explaining human longevity (Epel, Blackburn et al. 2004).

the world lead only by ischemic heart disease (Kalia 2002). It impairs spatial and verbal memory (Luine, Villegas et al. 1994) and negatively impacts one's ability to learn (Sapolsky 2003). Stress affects a number of areas in the brain including hippocampus, amygdala, prefrontal cortex (Bremner and Narayan 1998). Stress including the perception of stressful tasks and situations affect both short- and long-term memory (Bremner and Narayan 1998), lowers attention span and cognitive performance (Linden, Keijsers et al. 2005). The effects of prolonged exposure to stress are known to cause mental disorders and is a major risk factor for depression (Mazure and Maciejewski 2003), anxiety (Shin and Liberzon 2010), post-traumatic stress disorder (Southwick, Rasmusson et al. 2005), and bipolar disorder (Hammen and Gitlin 1997).

2.1.3 Effects of stress on performance

Constant exposure to stress leads to exhaustion, burnouts (Etzion 1984) and negatively impacts performance (Schaufeli and Bakker 2004). The relationship between stress and performance is governed by the Yerkes-Dodson Law (Yerkes and Dodson 1908); see Figure 2. The law states that as arousal increases the performance levels increase; this type of stress is termed as *eustress*. Eustress is beneficial as it keeps people alert in demanding situations and focused to meet challenges. At the optimal arousal level, performance reaches its peak. However, if the arousal level keeps increasing beyond this point, performance deteriorates; this region is termed as *distress* and is bad for health and performance. To summarize, stress impacts the quality of life (ADAA 2015), performance, and results in increased absenteeism leading to a further loss of productivity (Colligan and Higgins 2006). In all, stress is estimated to cost U.S. economy approximately $300 billion annually in healthcare costs and lost productivity (Leiter and Maslach 2011).

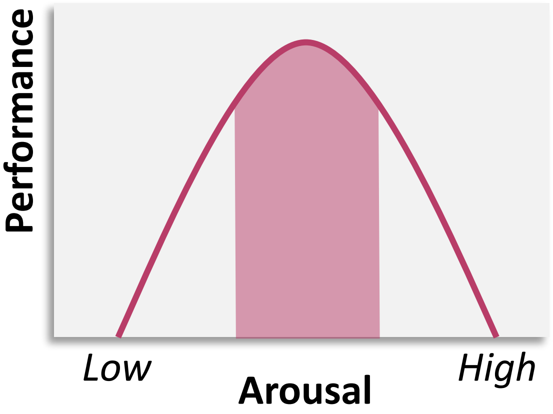

Figure 2 The relationship between arousal level and performance according to the Yerkes Dodson law.

2.2 Traditional intervention for stress management

A number of interventions have been proposed to manage stress, which can be classified as primary, secondary, and tertiary (Richardson and Rothstein 2008). The aim of primary stress interventions is to identify and modify and/or eliminate the source of stress. Secondary interventions, in turn, attempt to lower the arousal level once the subject has been exposed to the stressor. This is done by teaching stress self-regulation skills to the subject. Finally, tertiary interventions are designed to reduce the impact of stressors through rehabilitation or assistance programs. The focus of this dissertation is on secondary interventions. These can be further divided into therapeutic and developmental methods (Moraveji 2012). Therapeutic methods help induce a state of calm in individuals however they are not designed to train the individual to improve perception of stress or to teach voluntary self-regulation skills in response to future stressors. Examples of therapeutic methods include progressive muscle relaxation, eco-therapy, soothing auditory tones, soothing olfaction, and mantras. In contrast, developmental techniques both assist a user in combating the influences of a stressor and also train them to identify certain visceral events (e.g. stressful states) and voluntarily trigger the self-regulation response (e.g. deep breathing). These methods help individuals learn to better self-regulate their stress response in the presence of stressors. This dissertation focusses on developmental methods. In fact, a number of developmental methods already exist for stress self-regulation (Richardson and Rothstein 2008). This includes cognitive-behavioral therapy (CBT), self-guided methods such as yoga, meditation[5], deep breathing, and, biofeedback.

2.2.1 Cognitive behavioral therapy

Cognitive behavior therapy (CBT) is a form of psychotherapy that aims to increase adaptive coping in response to stress and has been shown to be effective in reducing stress (Meichenbaum, Carlson et al. 2001, Beck 2011). CBT techniques include exposure therapy, systematic desensitization, stress inoculation training (SIT), and stress exposure training (SET). CBT explores the relationships among an individual's thoughts, feelings, and behaviors. The core principles of CBT include identifying negative and maladaptive beliefs and actions and replacing them with healthy behaviors

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[5] Yoga and meditation are both therapeutic and developmental (Moraveji 2012).

(Beck 2011). During a CBT session, a therapist works with the user to discover unhealthy thoughts and behaviors. Following this step, the therapist assists the user to replace unhealthy beliefs and behaviors with healthy ones. CBT has been shown to be an effective treatment for mental disorders include depression and anxiety. It has also been used for stress training in the form of SIT and SET (Meichenbaum and Cameron 1989, Driskell and Johnston 1998).

Stress inoculation training is an empirically-validated method for stress training (Meichenbaum and Cameron 1989). The concept of stress inoculation suggests that exposure to stress during training would improve resilience in future stressful scenarios. SIT has been shown to improve perceived control over stress and reduced cortisol response in healthy individual (Gaab, Blättler et al. 2003). Stress exposure training (SET) is an extension of SIT[6] adapted for applied training environments. SET is a three-step stress training method comprising of a) preparatory information (with a clinician), b) skill acquisition, and c) practice of skill under (simulated) stress conditions (Driskell and Johnston 1998). The aim of SET is to prepare an individual to perform tasks effectively under stressful conditions. In fact, SET recommends that the training should be specific to a situation i.e. training should include the stressors expected to be encountered during task performance. Although CBT methods are effective in stress in training, these are resource intensive since they have to be performed under the supervision of trained clinicians, making it cost-prohibitive for most individuals and

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[6] SIT was originally developed to teach coping with physical pain, anger, and phobic responses (Meichenbaum and Cameron 1989).

organizations (van der Klink, Blonk et al. 2001, Richardson and Rothstein 2008). Furthermore, these also suffers from high attrition rate (Henriques, Keffer et al. 2011) due to the requirement of following a strict training regimen.

2.2.2 Self-guided methods

For centuries, yogis have used self-guided methods to promote physical, mental, and spiritual well-being (Khalsa 2007). In recent years, mind-body relaxation techniques such as tai chi and yoga have been shown to be effective as self-administered stress management interventions (Esch, Duckstein et al. 2007). Epel, Daubenmier et al. (2009) found that mindfulness meditation is able to reduce the stress induced damage on telomeres[7] and reduce cell aging. Mindfulness methods (such as meditation, yoga, focused breathing) have been used with both healthy individuals and patients with specific health issues and suffering from stress (Smith, Richardson et al. 2005, Chiesa and Serretti 2009, Cutshall, Wentworth et al. 2011). Another traditional self-guided method that is known to induce relaxation is deep breathing. A number of approaches exist to practice deep breathing (e.g., Pranayama, Kapalabhati, Bhastrika) (Pal and Velkumary 2004, Jerath, Edry et al. 2006). Deep breathing addresses the autonomic imbalance that arises from exposure to a stressor by recruiting the parasympathetic nervous system and inhibiting the sympathetic action leading to a calmer state (Camm, Malik et al. 1996). While these interventions have been shown to be effective in

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[7] Telomeres are DNA–protein complexes that lead to chromosomal stability and provide a way for explaining human longevity (Epel, Blackburn et al. 2004).

mitigating stress, they suffer from a number of shortcomings. Self-guided interventions, including meditation and yoga, suffer from high dropout rates (Rose, Buckey et al. 2013) due to the unengaging nature of the exercises and lack of motivation (Davis and Addis 1999). In addition, these techniques teach self-regulation in quiet, controlled settings, which may not generalize to stressful, real world scenarios (Driskell and Johnston 1998).

2.3 Technology based methods

As one of the main factors causing stress is the increasing usage of mobile technologies, this dissertation explores whether these technologies can be used to combat the negative effects of stress. In fact, in recent years a number of technology-based interventions have been developed for stress self-regulation. Examples of these interventions include virtual reality (VR) based methods (Wood, Webb-Murphy et al. 2009, Stetz, Kaloi-Chen et al. 2011), meditation apps (Clinic 2009), and biofeedback. A number of commercial devices have also appeared, including StressEraser[8], Heartmath[9], Resperate[10], and Spire[11].

VR methods allow individuals to become active participants within an artificially-generated scene and provide an immersive training. These methods have been used to provide exposure therapy to treat combat related stress and PTSD (Wood, Webb-Murphy et al. 2009). While engaging, VR based methods are still restricted to

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[8] www.stresseraser.com

[9] www.heartmath.com

[10] http://www.resperate.com/

[11] https://spire.io/

specialized settings due to the cost involved in the both the hardware and software (generating artificial environments/scenes).

Biofeedback systems monitor various physiological signals (e.g., blood pressure, heart rate, breathing rate, EEG) and then present them to the user, generally on a visual display (Stein 2001). This allows the users to visualize the effects of stressors on their physiology and help them self-regulate their stress response. A number of biofeedback tools have been developed to influence user's physiology (Schein, Gavish et al. 2001), lower blood pressure (Grossman, Grossman et al. 2001), reduce anxiety after exposure to stressor (Reiner 2008), increase HRV (Zucker, Samuelson et al. 2009) and reduce the symptoms of stress (Richardson and Rothstein 2008). While effective, some of the biofeedback visualizations tend to be non-intuitive for users (especially those of skin conductance, electroencephalogram) (Pallavicini, Algeri et al. 2009). Furthermore, biofeedback methods also suffer from attrition due to the monotonic nature of the exercises.

To summarize, while technology based methods have been shown effective for stress self-regulation, these methods suffer from high attrition rate due to unengaging exercises (especially for traditional biofeedback and relaxation apps) resulting in decreasing motivation level with time. In addition, some of these methods (e.g., VR) can be cost prohibitive[12] for most. Finally, most of these methods again share a common element that they train users to self-regulate their stress responses in a quiet relaxed

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[12] However, this may change in the near future with the recent advancements in graphics processing on smartphones and VR technology.

environment and not in the presence of stressors. Therefore, these may not lead to skill transfer in high paced and stressful settings where they are really needed. These drawbacks of the existing methods indicate the need for an intervention that is engaging and promotes self-regulation skill in high arousal conditions.

2.3.1 Videogames for stress recovery and health and wellness applications

Videogames appear to be ideally suited to address the issues in both traditional and technology based methods. Videogames are inherently engaging and extremely popular: 53% of adults in the United States play video games, both men and women (Williams, Martins et al. 2009). Furthermore, games are designed to increase the arousal level of the player (Buckley and Anderson 2006, Bailey, West et al. 2011). Therefore, games can be used to teach participants to self-regulate their stress response and stay calm while performing a task that is designed to increase arousal, a form of stress inoculation that may promote skill transfer to real-world scenarios.

Videogames have been used in the past to improve mood and stress recovery and reduce the effects of stress. Russoniello, O’Brien et al. (2009) studied the effects of casual videogames on mood and stress. They found that playing videogames led to improvement in positive mood (as measured by electroencephalogram) and reduction in stress (measured by heart rate variability). Collins and Cox (2014) studied the usage of digital games in stress recovery. In a survey of 491 people, they found that the total duration spent on playing games per week was positively correlated with overall recovery. They attributed this effect to the psychological detachment experienced by the players. Reinecke (2009) demonstrated that videogames have a significant potential for stress recovery. The author found that participants playing games showed improvements in all four facets of recovery- psychological detachment, relaxation, mastery, and control.

Along with stress recovery, videogames have also been used for a number of health and wellness applications. Video games have been used to facilitate treatment for a variety of medical conditions, from diabetes to asthma (Read and Shortell 2011), and to promote physical fitness in the general population (Fujiki, Kazakos et al. 2008). Commercial video games have also been used as distractors to focus the patient away from the side effects of treatments or to reduce anxiety prior to medical procedures (Patel, Schieble et al. 2006, Fish 2011). The appeal of these games stems from their ability to increase the user’s motivation and engagement, which is particularly beneficial when the treatment involves painful procedures (e.g., chemotherapy) or is intrinsically boring and repetitive (e.g., physical therapy) (Ceranoglu 2010, Kato 2010).

The repetitive nature of videogame play makes it well suited to promote skill learning and practice (Rosas, Nussbaum et al. 2003). As an example, Brown, Lieberman et al. (1997) developed a video game for children with diabetes; the objective of the game was to keep the avatar’s glucose levels within healthy range by managing insulin and food intake. Similar “instructional” games have been developed for children with asthma (Lieberman 1997), adolescents with cancer (Kato, Cole et al. 2008), bladder and bowel dysfunction (Herndon, Decambre et al. 2001). Researchers have also explored using videogames with children with impulsive and attention deficit disorders (Pope and Palsson 2001).

2.3.2 Biofeedback games for stress self-regulation

Physiological sensors have garnered a great deal of attention in the gaming research community (Vilozni, Barker et al. 2001, Rani, Sarkar et al. 2005, Nacke, Kalyn et al. 2011). Physiological variables such as heart rate, skin conductivity, Electroencephalography (EEG) etc. are under autonomic control (i.e., involuntary), and therefore can provide objective measures of the player's affective state. As noted by Hettinger, Branco et al. (2003), physiological sensors "*open an additional channel of communication from the user to the computer, albeit a largely unconscious one*". Thus, physiological sensors enable new forms of gameplay and new applications beyond entertainment and develop game-like health interventions including stress training. As an example, Vilozni, Barker et al. (2001) developed a video game that taught breathing skills to children; in the game, the player controlled an animated critter with their breathing, measured with a spirometer. In related work, Herndon, Decambre et al. (2001) developed a biofeedback-based game to help children with voiding dysfunction learn to control their pelvic floor muscles. By contracting or relaxing their muscles, the patients could control aspects of the game, such as shooting accuracy in basketball or distance travelled in a golf game.

Tennent, Rowland et al. (2011) explored the use of breath control as an interaction modality for videogames. The aim of their study was to evaluate the viability of breathing both as a control mechanism and as a means to enhance the user immersion and overall gaming experience. The authors modified five videogames to include breathing parameters as a control input. To measure breathing, they used a gas mask which provides them with breathing rate, inhale-exhale duration, and flow rate. In their study, they observed that instead of being a one dimensional or a binary signal, breathing parameters provide additional dimensions of control allowing for enhanced interactivity. While they obtained positive reviews from the participants regarding breathing as a control mechanism, the usage of a face mask makes the system cumbersome for every day usage and unsuitable for ambulatory settings.

A few authors have also explored biofeedback games to help patients regulate the impact of stress. Leahy, Clayman et al. (1998) developed a game to teach deep relaxation to patients with irritable bowel syndrome, a condition to which stress is a major contributor. The game required patients to achieve increasing levels of relaxation (measured with EDA) in order to progress through a visualization of the digestive tract. Their results show that most patients learned to reach a relaxed state after four 30-min biofeedback sessions and reported a reduction in bowel symptom scores. Note, however, that the game was equivalent to biofeedback techniques because stress levels were only used for visualization purposes (i.e., to show progress through the digestive tract). Several commercial systems employ similar “game-like” strategies to make biofeedback more intuitive. In these systems, sensor signals are transformed into visually-pleasing graphics and animations; see e.g., Wild Divine[13]. While such elaborate biofeedback displays may be more appealing than visualizing raw sensor signals, much more could be gained if biofeedback was fully integrated into a dynamic game (Pope and Palsson 2001). As an example, Sharry, McDermott et al. (2003) developed *Relax to Win*, a biofeedback game to treat children with anxiety disorders. In the game, two players enter a race in which the speed of each player's avatar (a dragon) increases with the player's ability to relax, as measured with electrodermal activity; however, only anecdotal evidence was provided to support the effectiveness of the game. In recent years, researchers have explored the possibility of using biofeedback games to help patients regulate the impact of anxiety and stress.

In related work, Bhandari, Parnandi et al. (2015) presented a music based respiratory biofeedback system to teach deep breathing skills while performing visually demanding tasks (i.e. playing an immersive videogame). The intervention, termed *sResp* comprised of monitoring user's breathing rate and adapting the quality (e.g. signal to noise ratio) of the music to encourage slow and deep breathing while listening to their favorite music. The authors compared their intervention against auditory biofeedback and soothing music in its ability to reduce arousal levels. They found that *sResp* leads to reduced electrodermal activity (an indicator of low arousal) than the other methods.

In recent years, researchers have explored the possibility of using biofeedback games to help patients regulate the impact of anxiety and stress. Sonne and Jensen (2016) presented ChillFish, a breath-controlled biofeedback game to help children with

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[13] http://www.wilddivine.com/

ADHD relax in situations of acute stress. ChillFish is designed to retain child's attention by combining a breathing exercise with a videogame to calm children down in situations of acute stress or emotion outburst. During gameplay, children control the size of a pufferfish with their respiration; slower breathing increased the size of the fish, which allowed them to collect more rewards. The authors reported significant increases in average HRV values of the ChillFish group compared to other activities (talking and playing Pacman). However, they did not find significant differences in the HRV values of the ChillFish group compared with relaxation exercise where the participants were asked to relax.

More recently, Dillon, Kelly et al. (2016) studied the effectiveness of mobile games ("The Loom" and "Relax and race") combined with a commercially available biofeedback device (Personal Input Pod, Galvanic Ltd., Ireland) to reduce stress. The authors measured the player's electrodermal activity during gameplay and used it to determine progress: the more relaxed the player, the greater the progress in the game. Their results showed that thirty minutes of training with the biofeedback game led to a significant reduction in heart rate and self-rated stress measures, compared to a control group.

2.3.3 Biofeedback games and relaxation skill transfer

A handful of studies have explored whether relaxation skills learned with biofeedback transfer to new scenarios, where biofeedback is not present (Larkin, Zayfert et al. 1992, Goodie and Larkin 2006, Bouchard, Bernier et al. 2012).

In an early study on relaxation skill transfer, Larkin, Zayfert et al. (1992) examined the role of heart rate (HR) feedback and contingent reinforcement in reducing cardiovascular responses to stress; in contingency reinforcement, the game score was jointly determined by the participants' game performance *and* their ability to keep a low HR. As a second objective, the study also sought to determine whether reduced HR reactivity learned during training would generalize to a second task not employed during training. For this purpose, the authors divided participants into four groups depending on whether or not they received biofeedback while playing the game (groups 1-2) and based on combined reinforcement score contingency (group 3) or solely by performance (group 4). They found that participants who received combined score and HR feedback showed a significant reduction in HR reactions in post-assessment tasks, which included the game without feedback and a novel mental arithmetic challenge not used during training. These results lead the authors to conclude that HR feedback during training facilitates the simultaneous learning of two tasks: improved game performance and reduced HR reactivity. In a later study, Goodie and Larkin (2006) trained participants to lower their HR while performing three tasks (video game, mental arithmetic, handgrip) with HR feedback, then asked participants to repeat the three tasks and a new task (spontaneous speech) without HR feedback. However, the study showed that HR reductions with biofeedback transfer when the same tasks are performed without biofeedback immediately after training, but do not transfer to a new task or when the three tasks are conducted after a short delay (1-2 days). The authors concluded that limitations in skill transfer may be due to topographic differences between the training task and the novel task, and suggest that successful skill transfer may require training using a variety of stressors that mimic real-world scenarios.

In a more recent study, Bouchard, Bernier et al. (2012) assessed the effectiveness of auditory and visual biofeedback in an immersive video game that aimed to teach tactical breathing (a stress management skill) to soldiers. In particular, the authors sought to determine whether relaxation practice in the presence of a stressor is more effective than conventional classroom training (i.e., formal description of techniques followed by brief practice). Study participants were soldiers with prior basic stress management training; they were divided into two groups: a treatment group and a control group. The treatment group participated in three sessions (one 30-min session per day) of immersive first-person shooter game followed by a stressful medical simulation for testing. Audio-visual biofeedback was provided during gameplay but not during testing. In turn, the control group received a 15-min briefing on stress management training on the first day, followed by testing on the fifth day. The authors found the biofeedback gaming method to be more effective in reducing stress during testing than the control group, as measured through salivary cortisol and heart rate. They also reported that the treatment group had significantly better task performance (identifying the appropriate treatment to a severe chest wound) than the control group during testing.

To summarize, this chapter discussed the effects of stress on human body, health, mental health, and performance. The chapter then presented an overview of traditional interventions (therapy and self-guided methods) and technology based methods (including biofeedback tools and games) for health and wellness application and stress recovery. Finally, a review of existing biofeedback games for teaching relaxation skills and promoting skill transfer was presented.

3. DESIGN AND VALIDATION OF THE GAME BIOFEEDBACK APPROACH[14]

This chapter presents an overview of the proposed game biofeedback (GBF) approach including its core components and the implementation details. Briefly, the GBF approach combines biofeedback with adaptive videogames to assist the user in building self-regulation skills. The chapter begins by providing a detailed description of the game, game adaptation mechanism, physiological correlates of arousal and the associated signal processing methods for real time arousal estimation on a smartphone. Finally, an evaluation of the proposed system with a pilot study is presented to validate its efficacy in reducing arousal during gameplay and facilitating skill transfer.

3.1 System overview

The GBF framework comprises of four main modules; see Figure 3(a). The front-end comprises of the videogame and the wearable sensor while the arousal estimation and game adaptation modules are on the backend. During a GBF session, a user plays the videogame while their physiological information is captured using wearable sensors. These signals are transmitted to a smartphone where the arousal estimation module computes user's current stress/arousal level. The estimated arousal level is then used for

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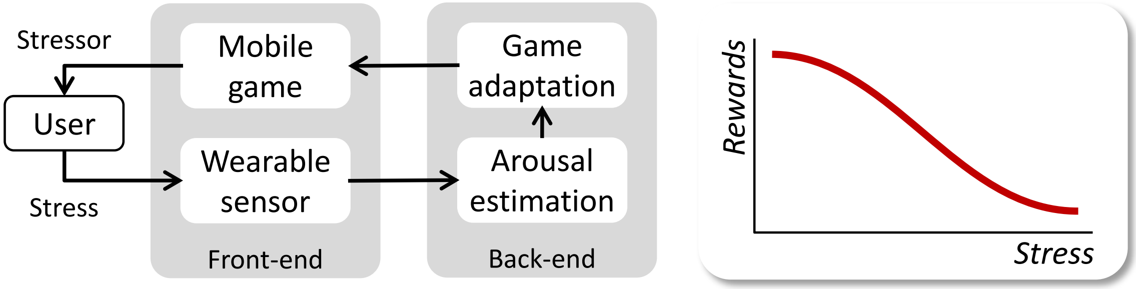
[14] The description of the method and the experimental results are reprinted with permission from "Chill-Out: Relaxation Training through Respiratory Biofeedback in a Mobile Casual Game" by Parnandi, Ahmed, Shipp, and Gutierrez-Osuna, 2013. *In International Conference on Mobile Computing, Applications, and Services, pp. 252-260, 2013*, ©2013 Springer

both visual display of physiology and game manipulation (e.g. change difficulty, randomness of the game) by the game adaptation module.



(a) (b)

Figure 3 (a) System overview with its four main building blocks: mobile game, wearable sensor, stress estimation, and game adaptation. (b) Rewarding states of relaxation through gameplay.

The game adaptation module takes the user's current arousal level and current game state (difficulty level) as inputs and provides modified game parameters as outputs and update the game state accordingly. This happens according to a transfer function that maps arousal level with game difficulty; see Section 3.3. The game parameters are modified in a positive feedback loop, such that high levels of arousal lead to increasingly more difficult gameplay, whereas lower levels of arousal result in more fluid gameplay. Unlike conventional biofeedback training, where feedback is explicit, GBF provides an implicit form of feedback through subtle changes in gameplay. For example, increases in heart rate variability (an indication of relaxation) could be used to improve certain characteristics of the game, e.g., better road conditions/visibility in a car racing game.

This allows users to focus on the gameplay experience rather than on monitoring their physiological signals, which makes the training more engaging.

As illustrated in Figure 3(b), the key element in the intervention is for the game to be adapted in a way that rewards states of relaxation and penalizes stress. This is an unconventional strategy since it can lead to system instability (i.e., if the player's stress increases the game becomes more difficult, which in turn creates additional stress for the player); it also runs counter to techniques for dynamic difficulty adjustment (DDA) (Liu, Agrawal et al. 2009), where one seeks to keep the player engaged regardless of their skill levels (i.e., by adjusting game difficulty based on the player's skills or performance). Notice, however, that the objective of the intervention is not to entertain but to help patients learn to self-regulate their stress response: was the game to be adapted in the opposite direction (i.e., by reducing difficulty with increased stress) it would not challenge patients to maintain control of their stress response.

Fogg (2003) argued that there are three reasons that restrain individuals from performing a target behavior: 1) lack of motivation; 2) lack of ability; and 3) lack of a well-timed trigger to perform the behavior. The GBF approach is consistent with the three conditions: first, with the game being a central component, GBF is inherently engaging, thus providing motivations to the players to play and learn self-regulation. Second, the GBF treatment framework provides instructions and training to the users on appropriate breathing behavior for inducing relaxation. Third, GBF continuously monitors user's arousal during a gameplay session and provides triggers in the form of game penalty, thus urging players to lower their arousal.

3.2 Biofeedback game

Selection of game: Selection of a suitable game genre is critical because the game is the activity through which players learn to regulate their breathing rate. There is empirical evidence to indicate that games can be effective in improving learning (Cordova and Lepper 1996). They do so by enhancing student motivation, which leads to greater attention to training and higher retention (Ricci, Salas et al. 1996). Garris, Ahlers et al. (2002) reviewed prior literature on games for learning and identified key features of a game that are conducive for learning. These include interactivity, dynamic visual, rules, goals/goal directed action, challenge, and learner’s control. Based on these features there are a number of game genres that seem suitable for biofeedback training, including first person shooter, strategy, role playing, simulation, sports; see Figure 4.

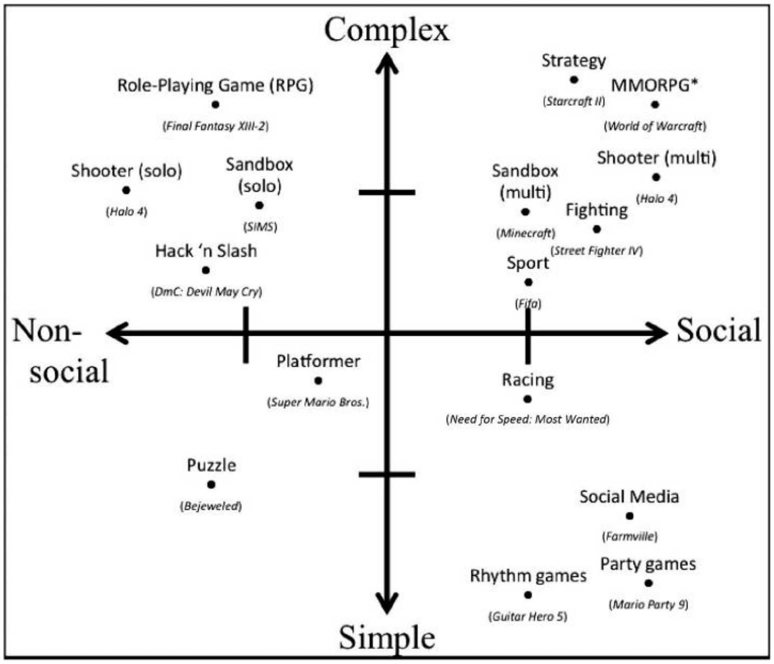


Figure 4 Categorization of games (Granic, Lobel et al. 2014) (reprinted with permission)

A few genres (e.g., first-person shooter) are unsuited due to their violent content and their possible connection with aggressive behavior (Anderson and Bushman 2001, Kato 2010). A few other genres require long time commitment (e.g. role playing, strategy), which makes them best suited for a specialized segment of the population, such as expert players (Gackenbach and Bown 2011). A few of the remaining genres (e.g., quiz, board games) also lack the dynamic content that would be required to develop adaptive gameplay. The ideal game for physiological training belongs to what have been described as casual games: "*games developed for the general public,… appeal to people of all ages, gender and nationalities, … are fun and easy to play, … and are* *usually played for a short period of time, from 5 to 20 minutes*"[15]. In fact, Russoniello, O'Brien et al. (2009) studied the effects of casual videogames on mood and stress. They found that playing casual videogames led to improvement in positive mood and reduction in stress. Based on these considerations, the GBF approach was implemented using Frozen Bubble[16], a popular casual puzzle type game that is available through a GNU General Public License. Figure 5 shows screenshots of the game; the player is presented with an arena containing a spatial arrangement of colored bubbles. The objective of the game is to eliminate all the hanging bubbles before the ceiling collapses. For this purpose, the player controls the orientation and firing of a small cannon that shoots bubbles of random colors. Placing a new bubble next to two or more of the same color makes them disappear; otherwise they pile up until the arena fills up, at which point the game ends. The ceiling of the arena drops one notch every eight moves, which reduces the play area over time and adds an element of time pressure. Different initial arrangements of bubbles can be used to make the game arbitrarily easy or hard, thus allowing the experimenter to increase the challenge level as the player progresses from one screen to the next. The game was developed on a Google Nexus 5 running Android 5.0.

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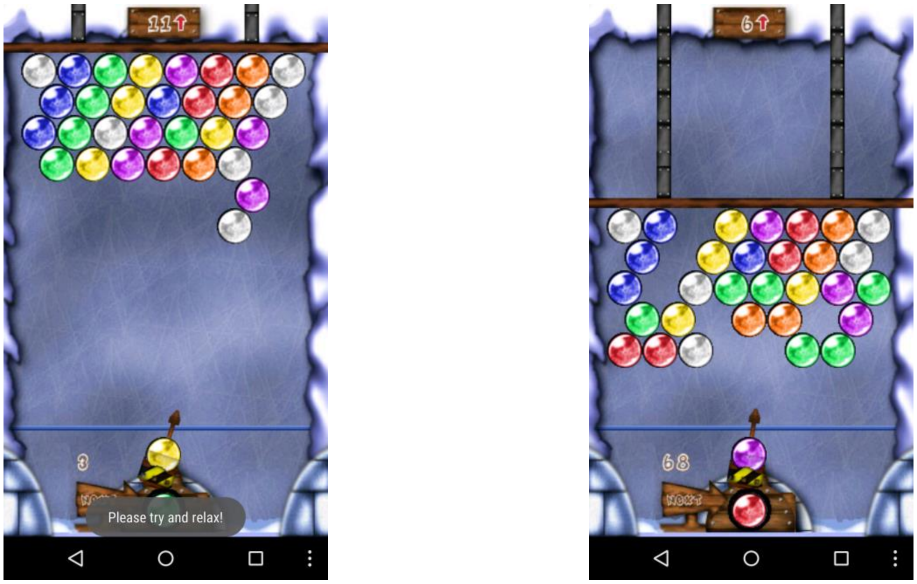
[15] www.casualgamesassociation.org

[16] https://github.com/robinst/frozen-bubble-android



Please try and relax!

Figure 5 Screenshots of the modified Frozen Bubble game showing breathing rate and trend.

3.3 Game biofeedback and instrumental conditioning

The central mechanism in teaching relaxation skills with game biofeedback is instrumental conditioning. Instrumental conditioning is the process of presenting rewards or penalties to the user based on their response. This is also known as the reinforcement and can be used to modify a behavior (Skinner 1953, Pope, Stephens et al. 2014). The reinforcement can be categorized as appetitive when the outcome is pleasant and aversive when the outcome is unpleasant. Whether the conditioning procedure increases or decreases a behavior depends on both the nature of the outcome (i.e., aversive or appetitive) and whether the behavior produces or removes the outcome. Based on these criteria, instrumental conditioning procedure can be classified into the following four categories; see chapter 5 in (Domjan 2014).

- *Positive reinforcement*: The target behavior produces an appetitive outcome. This leads to a reinforcement of the behavior.
- *Punishment*: The target behavior produces an aversive stimulus and this leads to a reduction in this behavior.
- *Negative reinforcement*: The target behavior eliminates the occurrence of an aversive stimulus. This leads to a reinforcement of the behavior.
- *Omission training*: The target behavior eliminates the occurrence of an appetitive stimulus and this reduces the behavior.

The GBF approach has been developed using the concept of negative reinforcement instrumental conditioning (NR-IC). Under a NR-IC setup, the users must lower their arousal level (i.e. the instrumental response) to reduce game penalty (the aversive outcome) and progress in the game. In other words, there is a negative contingency between the instrumental response and aversive outcome. This is a form of stress training that has been used in prior work for teaching stress self-regulation skills in military and other settings (Cannon-Bowers 1998). Therefore, by adapting the game in a way that encourages relaxing behavior, the user is prompted to modify their response to stressors and learn to self-regulate. Furthermore, NR-IC increases the likelihood that the instrumental behavior will be repeated in the future (Domjan 2014) indicating skill transfer.

3.3.1 Game adaptation

During gameplay, the game-adaptation controller modulates the game difficulty based on the deviation between the current arousal level and the desired value. Under a negative-reinforcement instrumental-conditioning paradigm elevated levels of arousal lead to increasing game difficulty, whereas lower levels of arousal reduce the difficulty. The controller compares the current arousal level (proportional term) and its rate of change (derivative term) with the baseline arousal level of the participant to determine the penalty in the game. Penalty is applied when it is detected that user's arousal level is higher than the reference and is increasing. The controller also uses the slope of arousal to detect participant's efforts to relax (indicated by negative slope). If it is observed that participant's arousal level is higher than reference but it is reducing, no penalty is applied.

Frozen Bubble provides a few parameters that are amenable to adaptation, such as auto-shooting rate, how fast the ceiling drops, or angular rate and lag of the cannon. Out of these, the auto-shooting frequency as the game difficulty was chosen for game adaptation, as it demands immediate action from the player. As the arousal crosses the threshold, the auto-shooting frequency increases making it harder to play the game. Hence to make progress on the game, the user must maintain a low arousal level.

Table 2 summarizes the effect of arousal level and its rate of change on game adaptation. Table 3 presents the pseudo code explaining the game adaptation procedure including comparison of stress with the reference level, computation of shooting interval based on the piecewise linear relationship between the arousal level and random firing in

Figure 6. When the arousal is below the reference level r_0 (relaxed state), there is no penalty in the game; as the arousal increases beyond the reference value the game difficulty also increases in a piecewise linear fashion. In this work, the control law penalizes states of non-relaxation by increasing the game difficulty. These states are defined as those with breathing rates higher than 6 breaths per minute (bpm) and increasing ($BR > 6 \wedge \Delta BR > 0$); breathing rates lower than 6 bpm are not penalized.

Table 2 Mapping between arousal level (r), its rate of change ($\frac{dr}{dt}$), and penalty during the game. Reference arousal (r_0) is measured during an initial paced breathing session.

	$r \leq r_0$	$r > r_0$
$\frac{dr}{dt}$>= 0	No penalty	No penalty
$\frac{dr}{dt}$< 0	No penalty	Penalty

The controller uses a proportional derivative (PD) control law to adapt the game; see Equations (1) and (2).

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

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

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

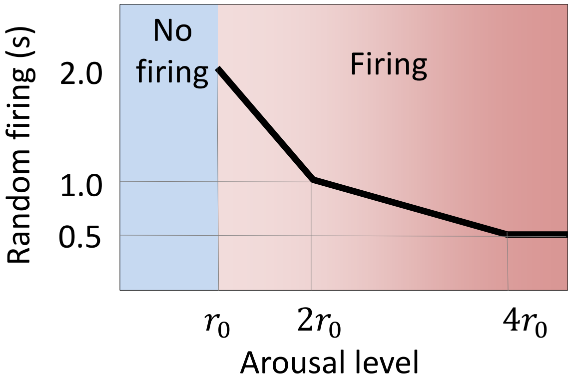


Figure 6 Relationship between user's arousal and automatic shooting frequency in the game when conditions for penalty ($r > r_0$ $and \frac{dr}{dt} \geq 0$) are satisfied; $r_0 = baseline$.

Table 3 Pseudo code for game adaptation

```
    procedure GameAdapt ($sensor, r_0, \alpha, \alpha_{min}, \alpha_{max}$)

    $[\alpha_{norm}, \alpha_{min}, \alpha_{max}]$ ← minmax($\alpha, \alpha_{min}, \alpha_{max}$)
    if ($sensor = HRV$)
        $\alpha_{norm}$ ← 1 - $\alpha_{norm}$
    endif
    if ($\Delta\alpha_{norm} > 0$ AND $\alpha_{norm} > r_0$)
        $ShootingRate$ ← CalculateShootingRate ($\alpha_{norm}, r_0$)
    else
        $ShootingRate$ ← $null$
    endif
        return $ShootingRate$
    endwhile

    subroutine $ShootingRate$ = CalculateShootingRate ($\alpha_{norm}, r_0$)
        if ($2r_0 \geq \alpha_{norm} > r_0$)
            $ShootingRate \leftarrow 3 - \alpha_{norm}/r_0$
  elseif ($4r_0 \geq \alpha_{norm} > 2r_0$)
            $ShootingRate \leftarrow 1.5 - Arousal_{norm_i}/4r_0$
  elseif ($\alpha_{norm} > 4r_0$)
            $ShootingRate \leftarrow 0.5$
  endif
    end subroutine
```

3.4 Arousal estimation

Stress disrupts the balance between sympathetic and the parasympathetic branches of the autonomic nervous system (ANS) with the sympathetic nervous system (SNS) being dominant (fight-or flight response). This leads to changes in the physiological conditions such as increased muscle tension, heart rate, pupil dilation, adrenaline production, secretion of hormones such as cortisol, and difficulty in breathing. Physiological manifestation of the stress response can therefore be studied by monitoring variables including electrodermal activity (EDA) (Boucsein 2011), electroencephalography (EEG) (Pope, Bogart et al. 1995), heart rate (HR), heart rate variability (HRV) (Camm, Malik et al. 1996), pupillary fluctuations (Goldwater 1972, Laeng, Sirois et al. 2012), breathing rate (BR) (Jerath, Edry et al. 2006), blood pressure (BP) (Kulkarni, O'Farrell et al. 1998) as well as biomarkers such as cortisol and alpha-amylase (Dickerson and Kemeny 2004).

In order to gain acceptance, the stress monitoring system must be minimally cumbersome to allow users to carry out activities of daily living without hindrance. While EEG devices have garnered recent attention as an input modality for gaming (Nijholt, Bos et al. 2009, Anguera, Boccanfuso et al. 2013), they are still fairly cumbersome for everyday use as they require head-mounted electrodes. Similarly, measurement of blood pressure requires an arm inflation cuff and an air pump. This restricts the movement of the user and is not suitable for ambulatory settings. Cortisol and alpha-amylase must be measured analytically and the measures are discrete in time, whereas pupillary measures are invasive and susceptible to ambient illumination. While

HR, which is modulated by the ANS seems like a viable option, cardiac fluctuations are modulated by a number of variables including circadian rhythm, temperature regulation, respiration, and the two autonomic nervous system (ANS) branches (Strauss Blasche, Moser et al. 2000). In addition, HR is also affected by other variables including activity, posture, and respiration making HR alone an unreliable indicator of arousal. Taking usability and other concerns into consideration, EDA, HRV, and BR appear better suited for GBF since they can be measured inconspicuously with wearable sensors (a critical consideration in ambulatory settings), can produce a continuous measure of stress (also critical for gameplay adaptation), and are relatively robust to environmental disturbances.

3.4.1 Electrodermal activity

Electrodermal activity (EDA) reflects changes in conductance at the skin surface due to activation of the sweat glands. As shown in Figure 7(a-c), the raw EDA response consists of two characteristic components, (i) a slowly changing offset known as the skin conductance level (SCL) which is highly subject dependent Figure 7(c), and (ii) a tonic response observed as a series of transient peaks known as skin conductance responses (SCR) (Figure 7(b)) that occur in reaction to startle events, cognitive activity, emotion arousal and also spontaneously in which case they are referred to as non-specific (NS.SCR) (Boucsein 2011).

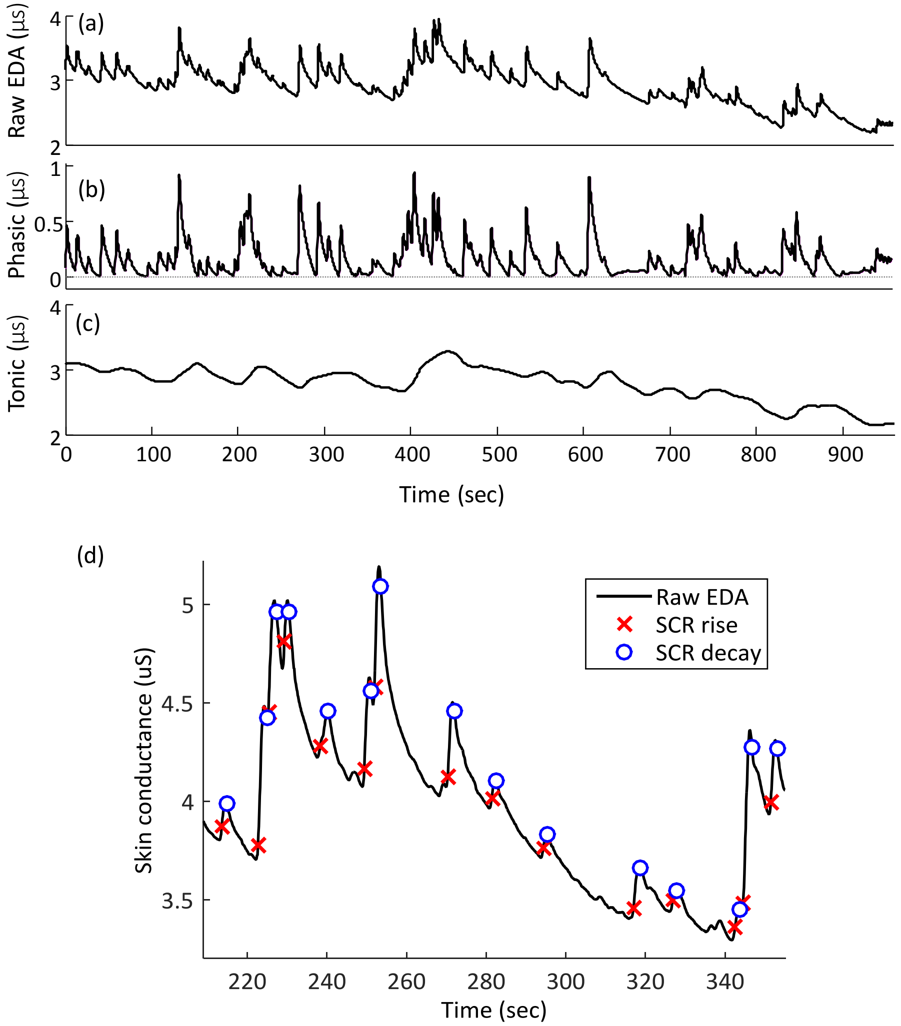


Figure 7 (a) Raw skin conductance (SC) response decomposed into (b) phasic (c) tonic components using LedaLab (Benedek and Kaernbach 2010). (d) Sample EDA signal and detected SCR events following the algorithm in Table 4.

The proposed GBF system uses the tonic response as a measure of stress, namely the number of SCRs over a fix time window of 30 seconds. Offline computation of SCRs was performed using LedaLab[17] EDA analysis tool. It detects SCRs by performing iterative non-negative deconvolution between a standard SCR template and raw EDA

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[17] http://www.ledalab.de/

signal. The SCR is characterized by a steep increase in skin conductance followed by a slow recovery (Boucsein 2011). In their implementation, Benedek and Kaernbach (2010) used a biexponential function to describe the shape of an SCR; see Equation 3.

$$f(t) = g * (e^{-\frac{1}{\tau_1}} - e^{-\frac{1}{\tau_2}}) \tag{3}$$

Deconvolution of the skin conductance signal: The sudomotor nerve activity can be considered as a driver signal, comprising of nerve impulses. By convolving it with an impulse response function (IRF) results in the observed phasic skin conductance signal; see Equation 4. IRF is a transfer function and represents the basic SCR shape that would result from a unit impulse as input.

$$SC_{phasic} = Driver_{phasic} * IRF \tag{4}$$

The skin conductance signal comprises of the phasic skin conductance activity combined with the underlying tonic component; see Equation 5.

$$SC = SC_{tonic} + SC_{phasic} = SC_{tonic} + Driver_{phasic} * IRF \tag{5}$$

Similar to the phasic skin conductance signal, the tonic component can also be represented as a convolution sum of the tonic driver with the IRF; see Equations (6) and (7).

$$SC_{tonic} = Driver_{tonic} * IRF \tag{6}$$

$$SC = \left(Driver_{tonic} + Driver_{phasic}\right) * IRF \tag{7}$$

Finally, by de-convolving the skin conductance signal with the IRF, the driver function can be extracted. This driver function comprises of both the tonic and phasic components; see Equation (8). Since tonic EDA is observed in the absence of any phasic activity (Boucsein 2011), the intervals between phasic activities can be classified as the tonic component. This provides the phasic driver implicitly.

$$\frac{SC}{IRF} = Driver_{tonic} + Driver_{phasic} \tag{8}$$

Finally, the tonic component in the driver is estimated using nonnegative deconvolution. Deconvolution results in discrete compact responses (derived using the impulse driver) that correspond to SCRs. Even though Ledalab provides a comprehensive analysis of the EDA signal, it is computationally expensive $O(n^4)$ due to multiple optimization, and curve fitting and approximation steps making it unsuitable for real time applications. For real-time computation of SCRs on a mobile phone during gameplay, a computationally-efficient method was developed; see Table 4. Briefly, SCRs are detected by identifying a rise in EDA above a certain threshold. Specifically, an increase in EDA is considered an SCR if the slope (δ) of the signal is greater than δ_{min} = 0.01 $\mu S/s$ while the minimum amplitude ($Amp_{\min}$) criterion is set to $0.05\ \mu S$. Illustrative results of the proposed SCR detection algorithm with the onset/offset of individual SCRs are shown in Figure 7(d). EDA was monitored using disposable AgCl electrodes placed at the palmar and hypothenar eminences of the player's non-dominant hand. This recording site was chosen because it has highest density (200-600 per cm^2) of eccrine sweat glands and has been shown to provide accurate recordings of EDA (Benedek and Kaernbach 2010).

Table 4 Pseudo-code of the SCR detection algorithm

```
procedure fscr ($SC, \delta_{min}, Amp_{min}$)
Initialization:
  $Rise \leftarrow false$
  $scrCount \leftarrow 0$
for $i = 1\ to\ Length(SC)$
    $\delta \leftarrow SC(i) - SC(i-1)$
    if ($Rise = false$ AND $\delta > \delta_{min}$)
        $Rise \leftarrow true$
        $StartEDA \leftarrow SC(i)$
    elseif ($Rise = true$ AND $\delta < 0$)
           $Rise \leftarrow False$
           if ($SC(i) - StartEDA \geq Amp_{min}$)
              $scrCount \leftarrow scrCount + 1$
           endif
    endif
endfor
Return $scrCount$
```

3.4.2 Heart rate variability

In contrast with sweat glands, the heart is innervated by both autonomic branches (parasympathetic and sympathetic), which generally act antagonistically to regulate the length of time between consecutive heart beats: increased sympathetic activity leads to higher heart rate, whereas increase parasympathetic activity slows down the heart. The end result, heart-rate-variability (HRV), can be used as a measure of stress, albeit a less selective one than EDA given that it results from the continuous interplay between both branches. Moreover, fluctuations in beat-to-beat period are driven by the respiratory cycle: heart rate increases during inhalation and decreases during exhalation –a phenomenon known as respiratory sinus arrhythmia (RSA), and these fluctuations have been shown to reach a maximum at a breathing rate of approximately 6 breaths per min or 0.1 Hz (Vaschillo, Vaschillo et al. 2006). Thus, given that respiration can influence HRV, the latter can be viewed as being under partial voluntary control.

A number of HRV indices have been proposed, which can be grouped into time-domain and frequency-domain measures (Camm, Malik et al. 1996) The proposed implementation uses two time-domain measure known as the square root of the mean squared differences of successive R-R intervals (RMSSD)— see Equation (9) and $pNN50$. These measures were chosen since they are computationally efficient ($O(n)$), which is important for a real time adaptive system. In contrast, the frequency domain measures are more expensive, primarily due to the interpolation[18] required to resample the R-R interval series to obtain a uniformly sampled signal before computing the spectrum: $O(n^2)$ for polynomial interpolation followed by FFT($O(n\ Log\ n)$).

$$RMSSD_i = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N-1}[(RR)_{i+1} - (RR)_i]^2} \tag{9}$$

where $(RR)_i$ and $(RR)_{i+1}$ are the i^{th} and $(i+1)^{th}$ R-R intervals and N is size of the window (30 sec). Along with RMSSD, $pNN50$ was also used; $pNN50$ is computed by dividing the number of successive RR intervals greater than 50 ms by the total number of RR intervals, i.e. the fraction of consecutive RR intervals greater than 50 ms. HRV was extracted from Bioharness BT chest strap sensor (Zephyr Tech.) which also provided the respiratory signal. Figure 8 shows an ECG signal (along with the R-R peak

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

intervals in ms), the tachogram (R-R interval time series) and the HRV (RMSSD) while performing deep breathing (at 6 bpm) and a cognitively demanding task.

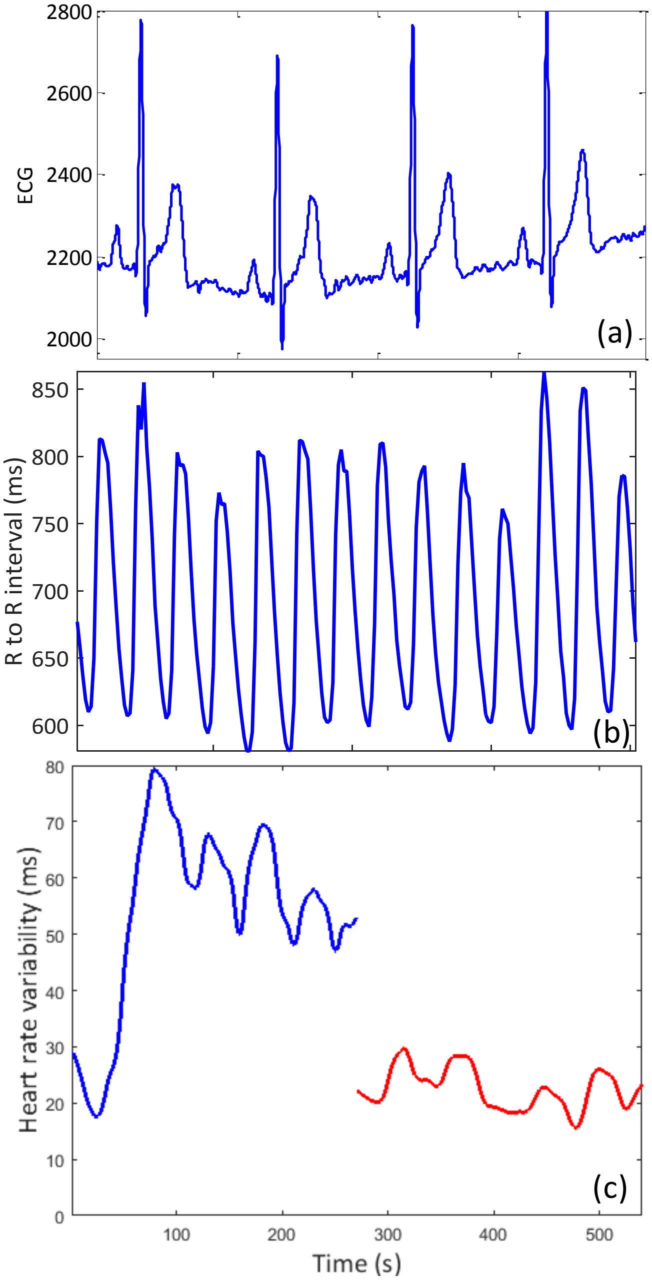

Figure 8 (a) Electrocardiogram (b) R-R interval time series (c) Heart rate variability (HRV) during deep breathing (blue) and during a cognitively demanding task (red).

3.4.3 Respiration

Respiration refers to the rhythmic process of interchange of oxygen and carbon dioxide between the environment and the human body. It comprises of breathing (ventilation), diffusion of gases in the alveoli, movement of O_2 and CO_2 by the circulatory system, and exchange of gases between tissues and capillary blood; see Chapter 2 in Batzel, Kappel et al. (2007).

In contrast with EDA and HRV, respiration is under both autonomic and behavioral (voluntary) control. Autonomic control occurs in the respiratory center in the brain (located in the medulla oblongata) and is involuntary. The control center modulates the depth and frequency of breathing to maintain homeostatic levels of O_2 and CO_2 in arterial blood (Wientjes 1992). In contrast, behavioral control is voluntary and requires a certain amount of focus. Voluntary control of breathing happens to accommodate changes resulting from e.g., stress, emotional stimuli, or physical activity, and is provided by the cerebral cortex. Due to this voluntary aspect, controlled breathing – specifically deep breathing, is regularly recommended as a technique for relaxation. Deep breathing addresses the autonomic imbalance that arises from exposure to a stressor. It does so by recruiting the parasympathetic branch of the nervous system and inhibiting the sympathetic action leading to a calmer state (Jerath, Edry et al. 2006). Figure 9 shows BR of a participant while performing paced breathing exercise for the first half, followed by a cognitively demanding task in the second half. The contrast in the two phases is evident in the figure with a high BR during the cognitive task performance.

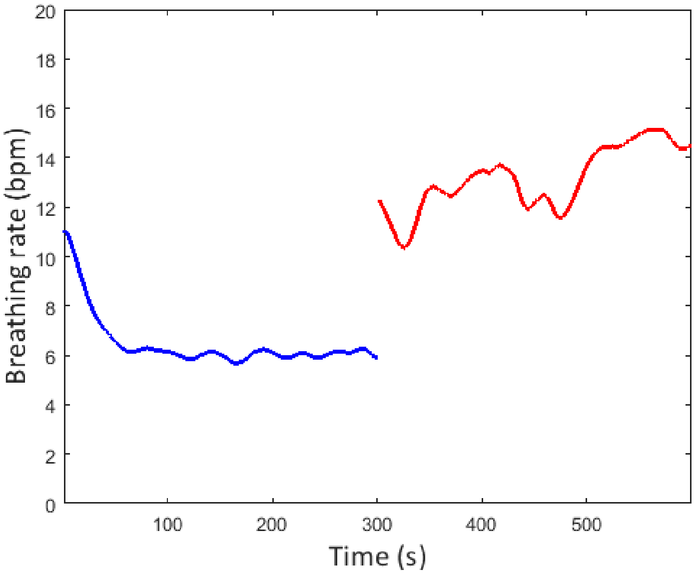

Figure 9 Breathing rate during Deep breathing at 6 bpm (blue) and during cognitively demanding task (red)

3.4.4 Sensor calibration

Raw physiological measures, particularly those from EDA and HRV, tend to fluctuate quite significantly not only across speakers (e.g., due to age, health and fitness levels) but also within speaker across sessions (e.g., time of day, rest and diet). Thus, these measures must be normalized before they can be used for game adaptation. A two-step calibration procedure was followed to remove inter- and intra-subject variability. In a first step (off-line), the participants are asked to perform a relaxation exercise that consists of following an audiovisual pacing signal of 6 breaths per minute, a respiration rate that has been shown to maximize HRV (Vaschillo, Vaschillo et al. 2006) and lead to a calm, relaxed state (Jerath, Edry et al. 2006). Average EDA and HRV values over the last minute of the relaxation are then taken as baseline or reference levels (r_0) for the user[19]. In a second step (on-line), the range of each signal is normalized by tracking the minimum (α_{min}) and maximum (α_{max}) values observed during gameplay. The initial minimum and maximum values for normalization are obtained from the paced breathing relaxation exercise. During the experiment, every time a new value arrives, it is compared with the current min/max value. If the new value is greater (or less) than the current maximum (minimum), the old value is replaced with the new maxima (minimum). This normalization step brings the three signals on the same scale and maintains uniformity in game adaptation.

3.5 Software architecture

The biofeedback game was developed on Google Nexus 5 running Android 5.0. The Android software architecture can be divided into four layers: application, application framework, android libraries and the Linux kernel; see Figure 10. The videogame and the arousal estimation code runs on the top-most layer (Application) along with the sensor specific Bluetooth libraries. The application interacts with Android application framework that manages the basic function of the device including activity and resource management. It also provides access to the Bluetooth through the Android Bluetooth APIs. Using these APIs, an application can scan for other Bluetooth devices, query for paired devices and establish connections with other devices. Android core libraries and Android runtime constitute the third layer and have several components

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[19] A value of 6 breaths/minute is taken as the respiratory baseline for each user.

including surface manager, media framework, SQLite, OpenGL, Webkit etc. Finally, there is the Linux kernel running on top of the hardware.

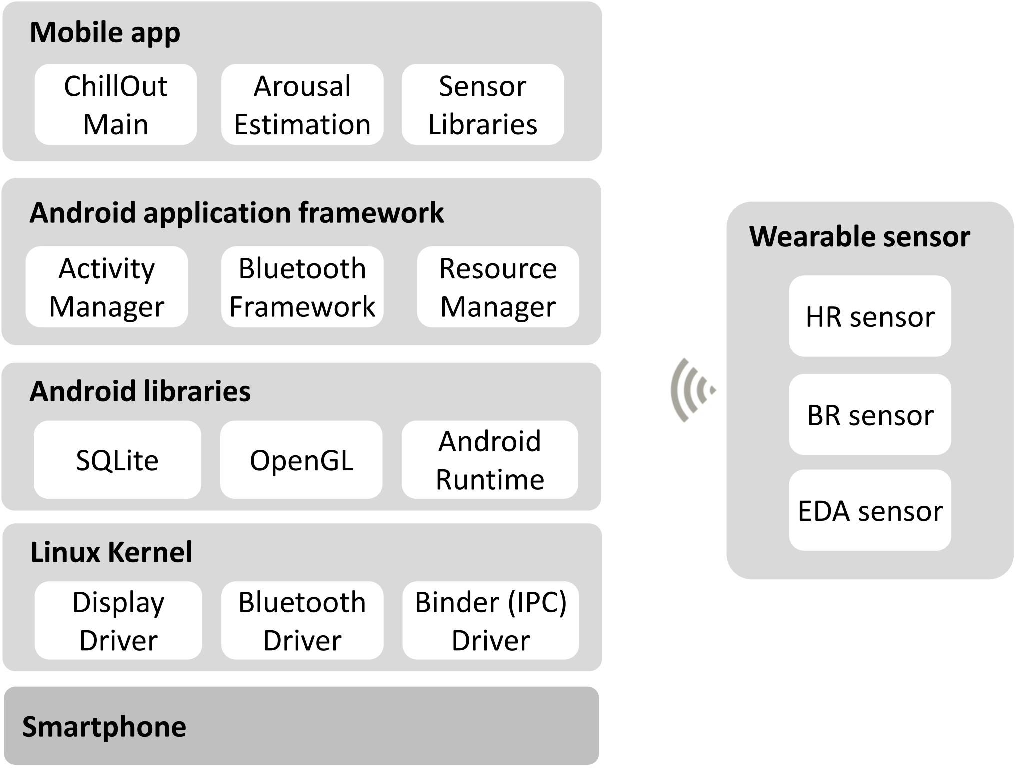


Figure 10 Android architecture and game biofeedback application running on Android. The GBF app consists of the Main routine, arousal estimtion module and sensor libraries for interfacing with the wearable physiological sensors over bluetooth

Specific to the game are the ChillOut and the arousal estimation modules; see Figure 11. ChillOut module connects to the Bioharness and shimmer sensor via Bluetooth and queries for physiological data. This is then used by the arousal estimation module for computing the arousal and corresponding penalty in the game for game adaptation (Figure 6).

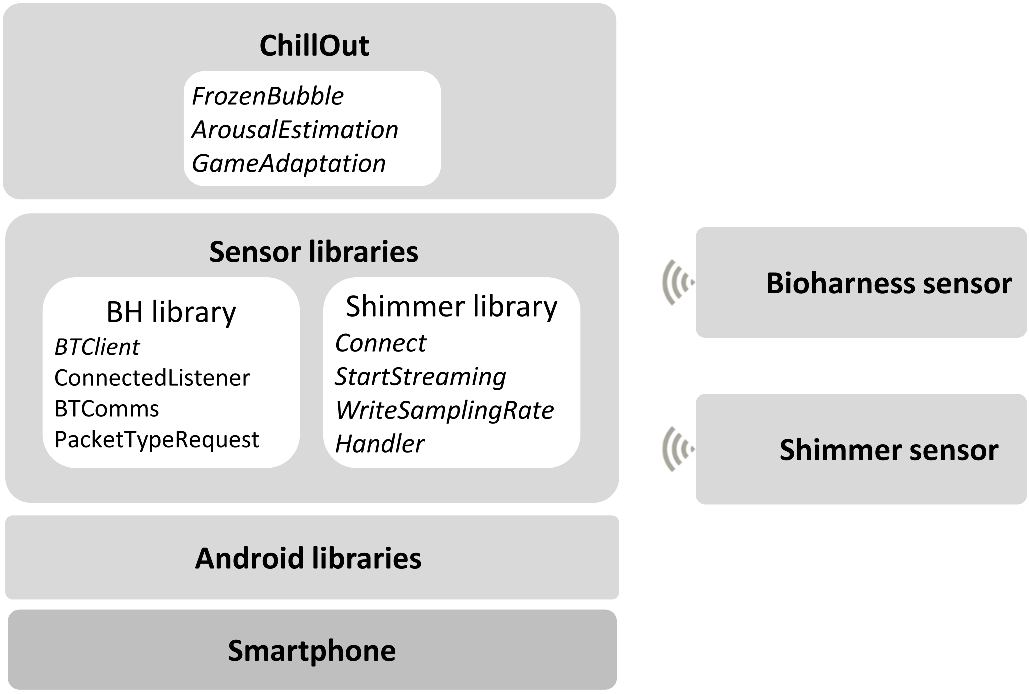
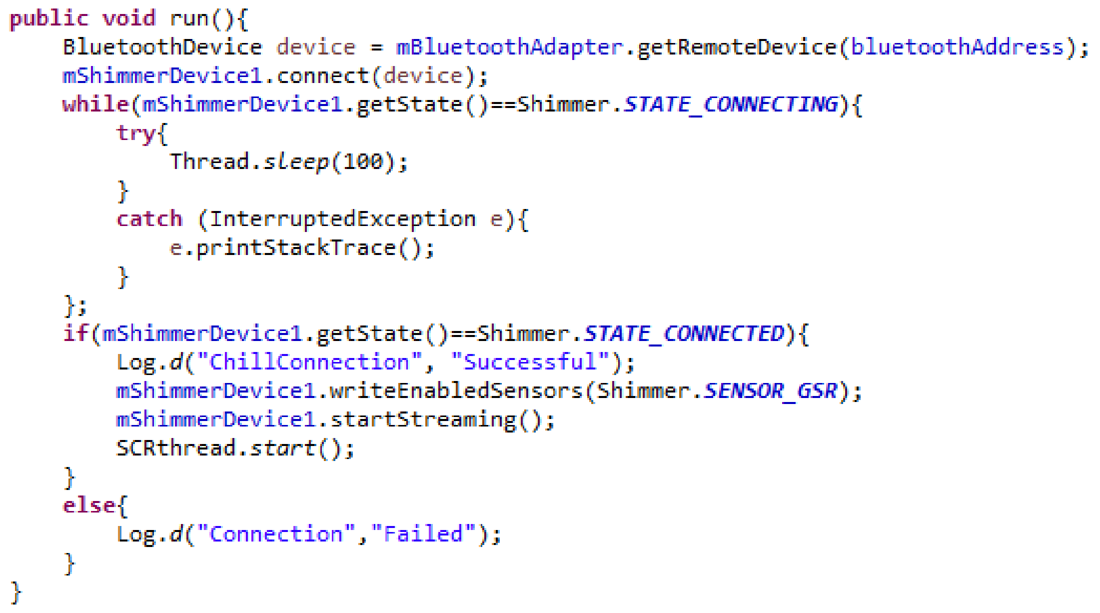


Figure 11 Architecture of the game biofeedback app running on Android system

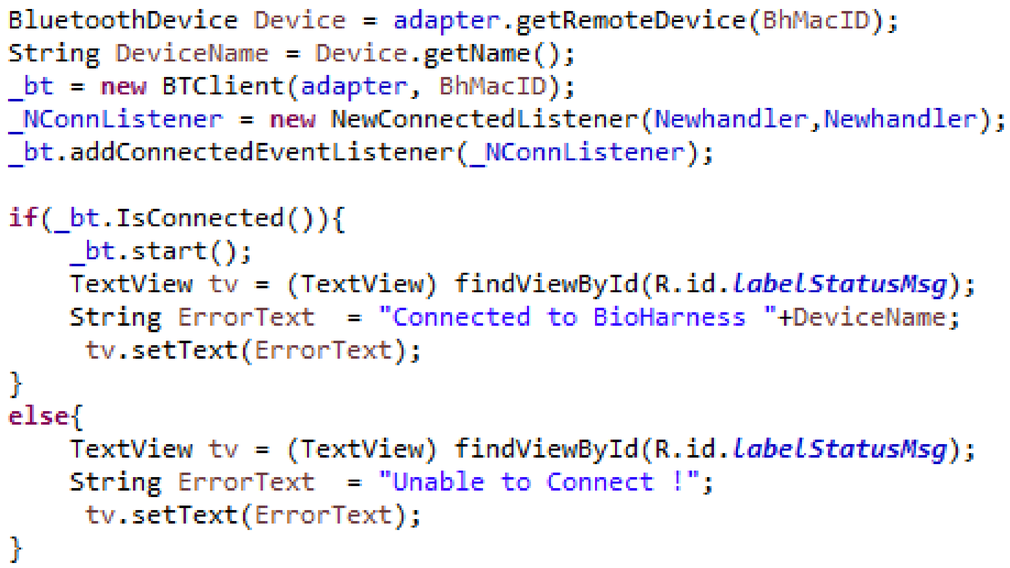
Figure 11 presents the architecture of the game biofeedback app running on Android. The sensor libraries comprise of various classes to connect with the specific sensor, configure them, and stream physiological data. In the ChillOut application, each Shimmer device is represented by an object which is an instance of the Shimmer class; see Figure 12. The Shimmer class relies on the Bluetooth stack provided by Android to connect to sensor via the serial port profile (SPP). SPP emulates a serial link over Bluetooth. Shimmer class presents a number of functions to control and interact with the device including *Connect*: to connect Android device with Shimmer device; *StartStreatming* and *StopStreaming* to start and stop the streaming of data; *Inquiry*: to learn the current setup/configuration of the Shimmer device; *WriteSamplingRate*: to configure the sampling rate etc. Sensor data, commands, and status messages are passed between the Android application and shimmer class using the *Handler* Class (provided by the Shimmer Android library). While the Handler class is collecting the data, a parallel thread computes SCR peaks from the raw EDA data using the algorithm described in Section 3.4.1.



```
public void run(){
    BluetoothDevice device = mBluetoothAdapter.getRemoteDevice(bluetoothAddress);
    mShimmerDevice1.connect(device);
    while(mShimmerDevice1.getState()==Shimmer.STATE_CONNECTING){
        try{
            Thread.sleep(100);
        }
        catch (InterruptedException e){
            e.printStackTrace();
        }
    };
    if(mShimmerDevice1.getState()==Shimmer.STATE_CONNECTED){
        Log.d("ChillConnection", "Successful");
        mShimmerDevice1.writeEnabledSensors(Shimmer.SENSOR_GSR);
        mShimmerDevice1.startStreaming();
        SCRthread.start();
    }
    else{
        Log.d("Connection","Failed");
    }
}
```

Figure 12 Code snippet explaining shimmer connect functionality

The Bioharness Android library provides several classes for interfacing with the sensor and achieving various functions; see Figure 13. Connection between the Android device and Bioharness sensor is established using the *BTClient* class which manages the overall Bluetooth connectivity. *NewConnectedListener* class creates an interface for interacting with the device while the *ConnectedListenerlmpl* class is used to handle the processing of the input packet from Bioharness and is responsible for parsing the input stream and display the data on the Android device. *BTComms* class is used to read from input stream and write to output stream. *PacketTypeRequest* class contains methods to enable/disable the different packet types and allows for choosing the data required for the application (e.g. BR, ECG, R-R, accelerometer etc.). Finally, the *ZephyrPacket* class performs a sanity check on the incoming data i.e. Packet length, CRC etc.



```
BluetoothDevice Device = adapter.getRemoteDevice(BhMacID);
String DeviceName = Device.getName();
_bt = new BTClient(adapter, BhMacID);
_NConnListener = new NewConnectedListener(Newhandler,Newhandler);
_bt.addConnectedEventListener(_NConnListener);

if(_bt.IsConnected()){
    _bt.start();
    TextView tv = (TextView) findViewById(R.id.labelStatusMsg);
    String ErrorText  = "Connected to BioHarness "+DeviceName;
     tv.setText(ErrorText);
}
else{
    TextView tv = (TextView) findViewById(R.id.labelStatusMsg);
    String ErrorText  = "Unable to Connect !";
     tv.setText(ErrorText);
}
```

Figure 13 Code snippet explaining bioharness connect functionality

3.6 Pilot study

The rest of this chapter evaluates the effectiveness of ChillOut in building self-regulation skills in an individual and facilitating skill transfer through a pilot study. This study is designed to examine the effect of a short-term GBF treatment in influencing breathing behavior (i.e. teach deep breathing) without using a pacing signal. For this initial assessment breathing rate is used as the biofeedback signal. This choice was motivated by the fact that breathing modifications, especially deep breathing (DB), is regularly recommended as a way to address autonomic imbalance arising from exposure to a stressor (Jerath, Edry et al. 2006); see Section 3.4.3. In addition, humans can regulate their respiration rates in a relatively short time period (Ley 1999) making it suitable for short term experiments.

To validate its effectiveness, ChillOut is compared against a standard treatment[20] of deep breathing (DB) and a non-adaptive, non-biofeedback game that serves as the control group. The three methods are compared based on three criteria (1) transfer of DB skills, (2) reduction in physiological arousal, and (3) task performance measured during a subsequent stress-inducing task.

3.6.1 Experimental

The experimental protocol comprises of four phases, as shown in Figure 14. Prior to the experiments the participants were asked to relax for 5 minutes. In the first phase, all participants followed an auditory pacing signal and performed deep breathing for 2 minutes at 6 breaths per min[21] (bpm). This phase allowed the user to practice deep breathing and also provided their baseline arousal levels. During the second phase (pre-training assessment task or pre-test), participants performed a modified Stroop color

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[20] Standard treatment refers to intervention that is traditionally used for stress management. It is the treatment that is normally provided (as prescribed by a physician) to patients with a given condition and is also known as active control.

[21] More specifically, the pacing signal instructed participants to inspire for 4 seconds and exhale for 6 seconds, an experimental choice motivated by prior work showing that a respiratory cycle with a short inspiration followed by a long expiration period leads to higher RSA than a respiratory cycle with a long inspiration and a short expiration (Strauss Blasche, Moser et al. 2000).

word test (CWT) for 4 minutes; see section 3.6.2. During the third phase (treatment), participants were randomly assigned into one of three groups, a group that played the biofeedback game (GBF), a baseline group that performed deep breathing (DB), and a control group that played the original Frozen Bubble game without adaptation or respiratory feedback (game only - GO). Participants in the DB condition were asked to follow an audio pacing signal that guided them to breathe at a rate of 6 bpm. The game difficulty level in the GO condition was the lowest level (i.e., easiest) in the GBF condition, which GBF participants could only achieve under slow and sustained breathing. Following prior work (Parnandi, Son et al. 2013), the duration of the treatment was 8 minutes for the three groups. During the final phase (post-test), participants repeated the CWT for an additional 4 minutes.

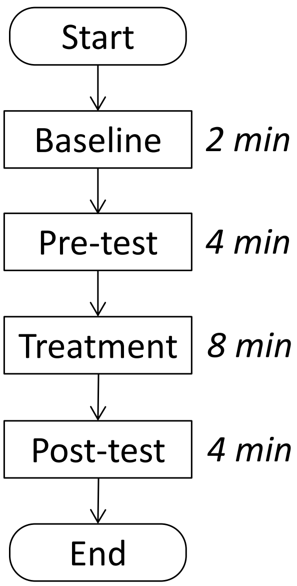

Figure 14 Experimental protocol. Baseline: paced breathing; pre-test and post-test: color word test; Treatment: GBF, GO, or paced breathing

The experiment trials were conducted as part of an independent study with each participant completing a randomly assigned protocol. This between-subjects experimental design was adopted to avoid order effect such as learning or fatigue. 9 participants, (7 male, 2 female) participated in the study. The age of the participants ranged from 22 to 33 years. Subjects reported that they were in good health; none reported excessive drinking or smoking habits. Approval from the Institutional Review Board (IRB[22]) was received prior to the study and signed consent from individual participant was received before the experiment session; see Appendix C.

3.6.2 Assessment task: Stroop color word test

To compare the three groups in their ability to retain relaxation skills, the Stroop Color word test (CWT) is used as an assessment task (Stroop 1935). CWT is widely used to induce cognitive workload and arousal. In the conventional CWT, the participant is shown one of four words (red, blue, green, and yellow) displayed in different ink color. They are then asked to either choose the displayed word or ink-color of the displayed word; see Figure 15. In addition, the current implementation also switched between two modes (congruent and incongruent) every 30s. In congruent mode, the word and the ink color were the same while in incongruent mode these were different. Further, the location of the answer buttons is also randomized with each presentation. Every correct answer increases the score by one while wrong answer imposes a penalty

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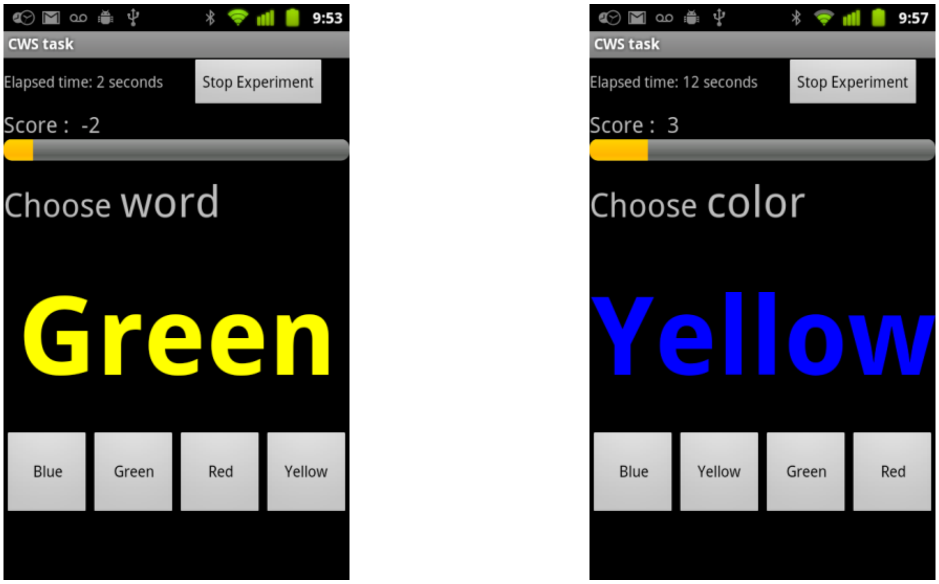
[22] Texas A&M Institutional Review Board (IRB) protocol number IRB2009-0420F.

of negative one. During the assessment, the stimulus is displayed for 1s, and the participant had 3s to respond.



(a) (b)

Figure 15 Screenshot of Stroop color word test used in the pre- and post-tests

3.6.3 Results: Acquisition of relaxation skill and skill transfer

The three methods (GBF, GO, and DB) were first evaluated by their effectiveness in reducing breathing rate (BR). Figure 16 shows the BR of the participants over the duration of the experiment. Subjects in the GBF condition lower their breathing rate during the treatment phase from its initial high value at pre-test and, more importantly, maintain that slow breathing rate during post-test, an indication that the deep breathing skill transferred successfully. Subjects in the DB condition also lower their breathing rate while performing the treatment but, unlike GBF subjects, revert during post-test to the high breathing rate shown at pre-test; this is particularly noticeable for subject #4. Also, it is worth noticing how subject #5 maintained a low respiratory rate during the entire experimental session, which suggests that none of the treatments could have been of much direct benefit. Finally, the breathing rate for subjects in the GO condition does not change significantly over the duration of the experiment, and never reaches the deep breathing zone.

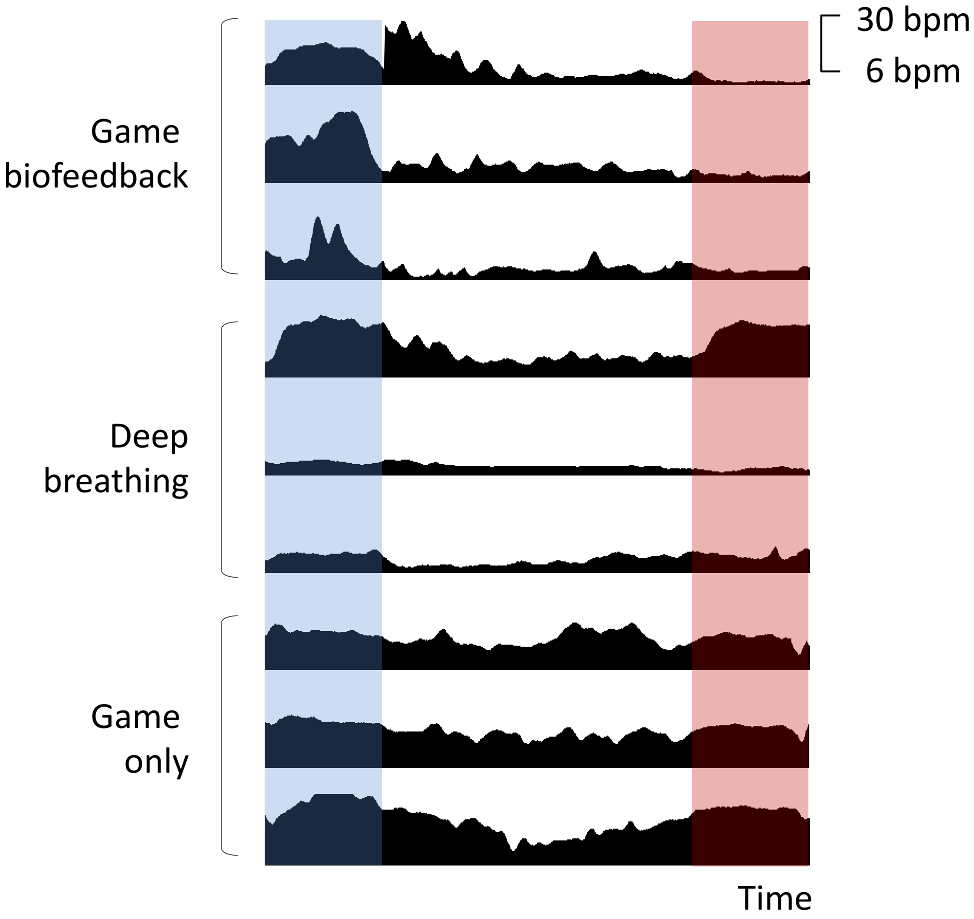


Figure 16 Evolution of the breathing rate during the experimental session for all the participants. Shaded area in blue represents the pre-test, white: treatment, and red: post-test.

The three treatments were also compared by their ability to transfer the relaxation skill to a subsequent task. For this purpose, the respiratory signal during pre- and post-tests were compared. Figure 17 shows the average BR during the pre-test, treatment and post-test for the three groups. For subjects in the GBF condition, there is a marked difference in the respiratory rate before and after game play: the pre-task BR being high, whereas the post-task BR is centered on 6 bpm (i.e., the BR rewarded during gameplay). In contrast, the respiratory trend for subjects in the DB does not show a significant difference before and after treatment. However, participants in the DB group did show a low BR during the treatment. This suggests that the slow breathing skills did not transfer. Finally, subjects in the GO condition displayed a high breathing rate pre- and post-test, showing that playing a casual game alone does not encourage a relaxing respiratory behavior.

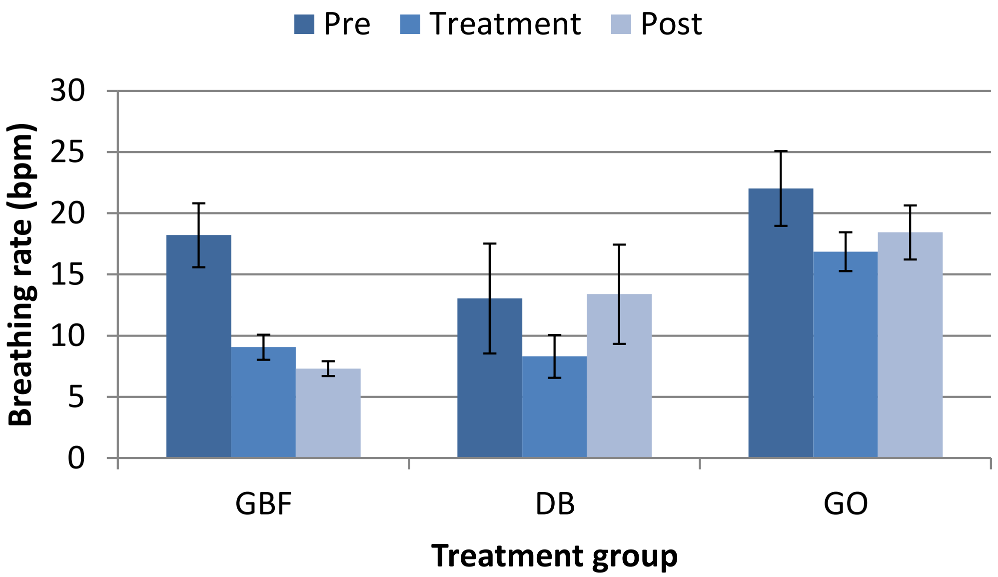


Figure 17 Average breathing rate and standard error for participants in three groups (GBF, DB, and GO) during the three phrases (pre-test, treatment, and post-test)

A 1-wav ANOVA comparing the three groups showed a statistically significant difference: $F(2,6) = 19.12,\ p < 0.003$. Pairwise post-hoc tests were performed to analyze the differences between the pairs of groups and results are presented in Table 5. Post-hoc tests indicated statistically significant differences in GBF vs. DB and GBF vs GO groups and a marginally significant difference between GO vs DB groups. This implies that the effectiveness of the GBF group in promoting skill transfer to an immediate post-task.

Table 5 Statistical difference (F-ratio) between the three groups in terms of BR change (post-pre). **p<0.05; *p<0.1). Degrees of freedom: df_1 (between groups) = 1and df_2 (within groups) = 4

	GBF	DB	GO
GBF	-	29.04**	11.19**
DB		-	14.21*
GO			-

The physiological arousal of the participants was also analyzed through EDA and HRV measures. It is important to note that these indirect measures were collected for monitoring purposes and were not used for biofeedback in this study. EDA results for all subjects in the experiments are shown in Figure 18. For subjects in the GBF condition, there is sharp decrease in EDA when going from pre-test to treatment and this lower EDA level is maintained during post-test, which indicates that playing the biofeedback game led to a significant reduction in arousal at post-test. Subjects in the DB and GO conditions showed a decrease in EDA during (however the reduction was smaller compared to the GBF group). In contrast with the GBF groups, the other two groups showed an increase in EDA during post-test.

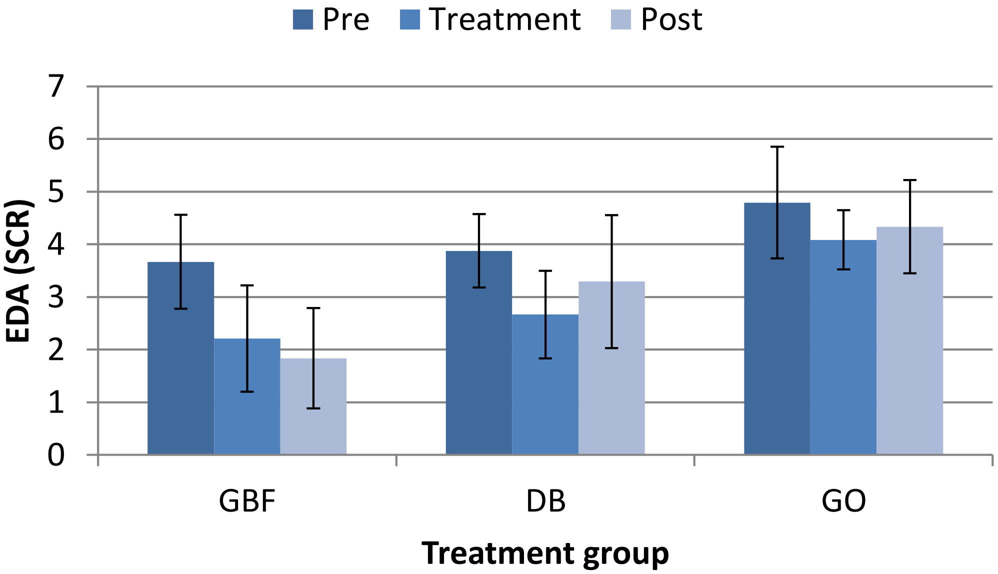


Figure 18 Average electrodermal activity (skin conductance response) and standard error for participants in three groups (GBF, DB, and GO) during the three phrases (pre-test, treatment, and post-test)

A 1-way ANOVA of the difference in EDA between pre-test and post-test with treatment (GBF, GO, and DB) as the factor shows statistically significant differences among the three protocols $F(2,6) = 7.4$, $p < 0.03$. Post-hoc analysis is presented in Table 6. The results indicated marginally significant differences in GBF vs. DB and GBF vs GO groups in terms of the EDA before and after the treatment. There was statistically insignificant difference between the GO vs DB groups.

Table 6 Statistical difference (F-ratio) between the three groups in terms of EDA change (post-pre). **p<0.05; *p<0.1). Degrees of freedom: df_1 (between groups) = 1and df_2 (within groups) = 4

	GBF	DB	GO
GBF	-	10.84*	19.45*
DB		-	0.07
GO			-

Figure 19 shows the average HRV computed over the duration of the pre-test, treatment, and post-test segments. HRV increased significantly for subjects in the GBF condition, corroborating results from EDA that indicate lower arousal after completion of the biofeedback game. The HRV continued to increase during the post-test indicating the participants could maintain a low arousal level following the treatment. In contrast, no specific trends were observed in the DB and GO groups and their HRV remained largely unaltered.

A 1-way ANOVA on the HRV difference between pre-test and post-test with the three treatments as factors also shows a statistically significant difference $F(2,6) = 10.73,\ p < 0.02$. Post-hoc tests indicated statistically significant difference in GBF vs. GO and marginally significant difference between GBF vs DB groups in terms of the HRV before and after the treatment; see Table 7. There was an insignificant difference between the GO vs DB groups. These results corroborate with the breathing rate results and reflect the effectiveness of the GBF approach in reducing physiological arousal in the post-test.

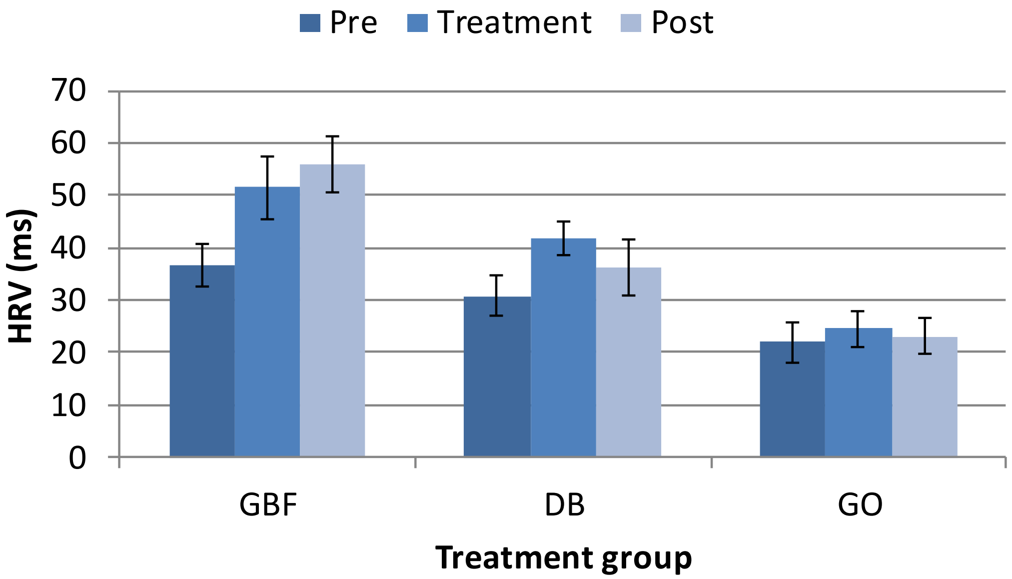


Figure 19 Average heart rate variability (RMSSD) and standard error for the three groups (GBF, DB, and GO) during the three phrases (pre-test, treatment, and post-test)

Table 7 Statistical difference (F-ratio) between the three groups in terms of HRV change (post-pre). **p<0.05; *p<0.1). Degrees of freedom: df_1 (between groups) = 1and df_2 (within groups) = 4

	GBF	DB	GO
GBF	-	9.22*	29.39**
DB		-	0.99
GO			-

3.6.4 Results: Task performance

Finally, the effect of the treatment on performance was analyzed by comparing the CWT scores during pre-test and post-test. Results are shown in Figure 20 for 8 subjects[23]. Subjects in the GBF and DB conditions had higher CWT scores in the post task, whereas subjects in the GO condition had mixed results. The high standard deviation for the post-test in the DB group is due to one participant scoring a low score of 50 in the CWT. In this case, a 1-way ANOVA shows that the differences among treatments were not statistically significant ($p < 0.41$).

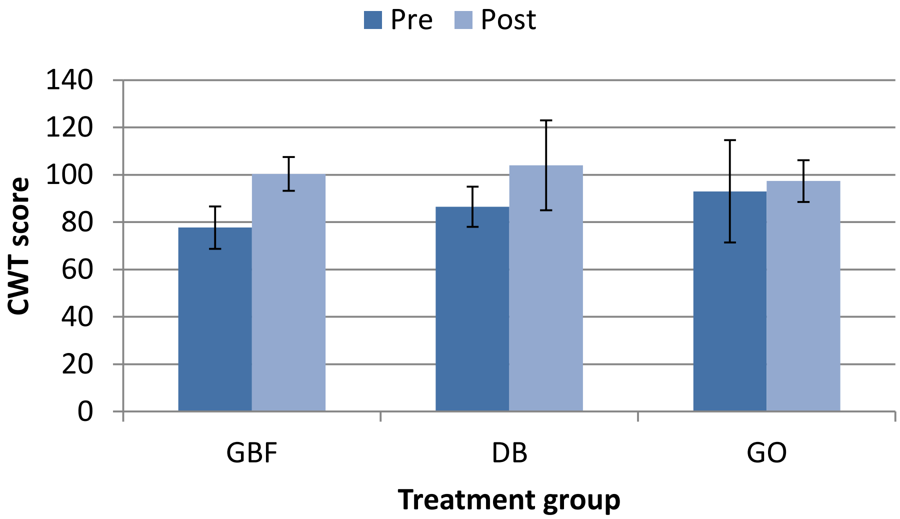


Figure 20 Average CWT scores for the three groups

3.6.5 Discussion

This chapter presented the GBF framework and discussed the various constituent modules including the game adaptation process and physiological signal processing. Through a pilot study, the feasibility of this approach in reducing arousal and promoting skill transfer was also tested. In the pilot study the proposed GBF approach was compared against a traditional method of deep breathing method (paced breathing) and a

---

[23] Task performance data for one participant was not recorded properly and had to be discarded.

non-adaptive, non-biofeedback version of the game. Results show that GBF is as effective as paced breathing in teaching deep breathing and is more effective than either alternative in transferring these skills to a subsequent stress-inducing task, and it also leads to significantly lower arousal, as measured by electrodermal activity and heart rate variability. Integrating physiological signals in a game for stress training leads to several interesting questions including the physiological signal to be used, presentation of biofeedback information, and the effectiveness of GBF to maximize skill retention. The next chapter will investigate various physiological signals for biofeedback and their effectiveness in facilitating acquisition of stress self-regulation skills with GBF and promoting skill retention.

4. PHYSIOLOGICAL MODALITIES FOR RELAXATION SKILL TRANSFER IN BIOFEEDBACK GAMES[24]

The previous chapter presented the GBF framework and validated its effectiveness in teaching deep breathing skills via a pilot study. Integrating bio-sensors with games for stress training poses many research questions. One such question pertains to the physiological signal that should be used for biofeedback to best teach relaxation skills. The choice of signal is important for two reasons, having to do with the degree of voluntary control over physiological signals and the degree of selectivity in measuring arousal. For example, electrodermal activity (EDA) is highly selective of stress –eccrine (sweat) glands are exclusively innervated by the sympathetic branch of the autonomic nervous system, but is under poor voluntary control. In contrast, breathing rate (BR) is not directly indicative of stress—though states of high stress are known to cause hyperventilation, but can be under complete voluntary control. Halfway across, heart rate variability (HRV) is partially selective since it is under the influence of both autonomic branches: sympathetic and parasympathetic, and is also under partial voluntary control (through respiratory sinus arrhythmia). As such, these three physiological modalities can be measured noninvasively with commercial wearable sensors and allow for examining the tradeoffs in the selectivity vs. voluntary-control

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[24] The description of the method and the experimental results are reprinted with permission from "Physiological Modalities for Relaxation Skill Transfer in Biofeedback Games" by Parnandi and Gutierrez-Osuna, 2017. *IEEE Journal of Biomedical and Health Informatics, vol. 21, no. 2, pp. 361-371, March 2017*, ©2017 IEEE

space. This chapter evaluates these physiological indices of stress for biofeedback in a game and evaluate their effectiveness in teaching stress self-regulation skills during gameplay and promote skill transfer.

In this chapter, Section 4.1 reviews the relevant literature comparing various physiological signals for biofeedback in games and other applications for stress management. Section 4.2 presents the physiological signals used for biofeedback during gameplay. Following this the experimental protocol and experimental details are discussed in Section 4.3. Section 0 presents the results from the experimental trials followed by a discussion explaining the theoretical underpinning of this work in Section 0.

4.1 Related work

In the past, only a handful of studies have studied the influence of physiological modalities in biofeedback games. Dekker and Champion (2007) investigated HRV and galvanic skin response (GSR) signals as biofeedback to enhance gameplay experience in a first-person shooter game (Half Life 2). The data from the physiological sensors was used to dynamically modify game features such as speed of avatar, AI difficulty, weapon damage and other screen effects to increase augmented horror affordances. They compared the biofeedback group with a control group (with no biofeedback) and found that that the physiological data led to an increase in the situated feeling of horror. Based on their survey results they also found while that biofeedback in the game increased the level of engagement.

In related work, Nacke, Kalyn et al. (2011) investigated sensor mappings for two types of physiological signals: voluntary (direct) and involuntary (indirect) to augment traditional game controls. They used eye gaze and muscle activation as direct inputs and used heart rate and skin conductance as indirect inputs to a side-scrolling game. The authors sought to determine the response of the players when physiological signals are used to augment traditional controllers. They concluded that participants did enjoy using physiological inputs especially the direct physiological controls. They also suggested that direct input should be mapped intuitively into actions, whereas indirect input should be used to affect environmental variables of the game for novel experiences.

More recently, Raaijmakers, Steel et al. (2013) studied the effect of EDA and HRV biofeedback based games on the affective state. The aim of the experiment was to determine whether HRV and SCL biofeedback led to increase in HRV and reduction in SCL (both indicative of relaxation). In their study, the authors compared changes in various physiological, affective and cognitive variables after administering a biofeedback treatment to participants. Here a “fake” biofeedback group served as control. During the treatment, the participants were not informed about the biofeedback modality (i.e. EDA or HRV) controlling the game or whether they belonged to the “genuine” or “fake” biofeedback group. The authors did not observe strong correlations between HRV and any of the physiological, cognitive, or affective variables that were measured. They, however, did observe a correlation between SCL and the error percentage in a cognitive task. Based on these prior studies, it can be seen that only a handful of researchers have looked at various physiological signals for biofeedback games. Furthermore, there has been minimal work in studying the efficacy of various physiological signals in teaching relaxation skills and promoting skill transfer, which is the purpose of this study.

4.2 Physiological modalities for biofeedback

A number of physiological correlates of stress have been identified, including electrodermal activity (EDA), electroencephalography (EEG), heart rate variability (HRV), pupillary fluctuations, breathing rate (BR), and biomarkers such as cortisol and alpha-amylase; see Section 0 for more details. Among these, EDA, HRV, and BR appear ideally suited for this purpose as they can be measured inconspicuously with wearable sensors, can produce a continuous measure of stress for real time game adaptation, and are relatively robust to environmental disturbances. Besides being influenced by the ANS, these three measures also allow for an examination of the tradeoffs in their selectivity towards stress and degree of voluntary control as explained next.

4.2.1 Electrodermal activity

EDA reflects changes in conductance at the skin surface due to activation of the sweat glands. Unlike most other organs, sweat glands are innervated exclusively by the sympathetic nervous system (SNS). As such, EDA is a relatively selective measure of arousal (Poh, McDuff et al. 2011). EDA is affected by a number of brain centers including hypothalamus for thermoregulatory sweating, amygdala for affective processing, prefrontal cortex for attention, and premotor cortex during motor control

(Dawson, Schell et al. 2007). It is also known to be affected by skeletal responses such as breathing and muscular movement, however, it is considered to be independent of voluntary/cognitive control. Though individuals are generally unable to voluntarily influence EDA (Leiner, Fahr et al. 2012), classical and instrumental conditioning techniques can be used to gain some degree of control over the EDA response; see Section 3.1.2 in Boucsein (2011). Therefore, in a plot with the selectivity in measuring arousal and the degree of control space as the two dimensions, EDA can be placed in the top-left; see Figure 21.

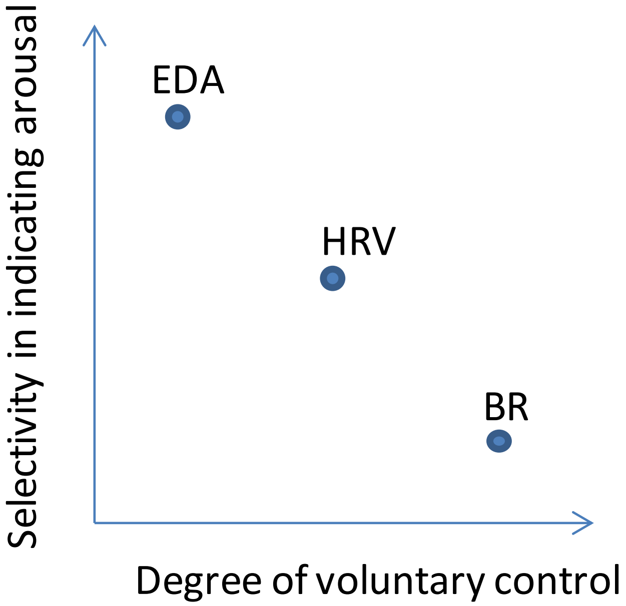

Figure 21 Characteristics of the three physiological signals in the selectivity in measuring arousal and degree of control space

Arousal was measured as the number of skin conductance responses (SCR) per minute. SCR was computed from the raw EDA signal using the online SCR detection algorithm presented in Section 3.4.1. Finally, the SCR time series was normalized following the approach described in Section 3.4.4.

4.2.2 Heart rate variability

In contrast with sweat glands, the heart is innervated by both autonomic branches (parasympathetic and sympathetic), which generally act antagonistically to regulate the period between consecutive heart beats[25]: increased sympathetic activity leads to higher heart rate, whereas increase parasympathetic activity slows down the heart; see Section 3.4.2 for more details. The end result, heart-rate-variability (HRV), can be used as a measure of stress, albeit a less selective one than EDA given that it results from the continuous interplay between both branches. Moreover, fluctuations in beat-to-beat period are driven by the respiratory cycle: heart rate increases during inhalation and decreases during exhalation—a phenomenon known as respiratory sinus arrhythmia (RSA), and these fluctuations have been shown to reach a maximum at a breathing rate of approximately 6 breaths per min or 0.1 Hz (Vaschillo, Vaschillo et al. 2006). Thus, given that respiration can influence HRV, the latter can be viewed as being under partial voluntary control. Given these characteristics, HRV can be placed in the selectivity in measuring arousal vs voluntary control space as shown in Figure 21. The root mean square of successive differences of the R-R interval (RMSSD) (described in section

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[25] HR was not used for biofeedback since along with ANS it is also affected by other variables including activity, posture, and respiration, making it an unreliable indicator of arousal.

3.4.2) was used as a measured of HRV. Normalization on the signal was performed following the approach in Section 3.4.4.

4.2.3 Respiration

In contrast with EDA and HRV, respiration is under both autonomic and behavioral (voluntary) control. Autonomic control occurs in the respiratory center in the brain (located in the medulla oblongata) and is involuntary. The control center modulates the depth and frequency of breathing to maintain homeostatic levels of O_2 and CO_2 in arterial blood (Wientjes 1992). In contrast, behavioral control is voluntary and requires a certain amount of focus. Voluntary control of breathing happens to accommodate changes resulting from e.g., stress, emotional stimuli, or physical activity, and is provided by the cerebral cortex. Given the nature of the BR signal, it can be placed on the selectivity vs voluntary control space towards the left bottom, as shown in Figure 21.

Studies on the effect of stress on respiration patterns have shown that hyperventilation occurs during periods of intense mental effort and stress (Suess, Alexander et al. 1980). However, breathing rate alone is an insufficient measure of stress response to psychological stimuli, and additional variables such as tidal volume, end-tidal CO_2 should be used. However, measuring tidal volume and end-tidal CO_2 requires face masks or capnography, which are obtrusive and restrict the primary activity (gameplay). Thus, BR is not a particularly selective measure of stress/arousal.

4.3 Experimental

4.3.1 Protocol

A user study was conducted to evaluate the effectiveness of the three physiological signals (HRV, EDA, and BR) as biofeedback in inducing relaxation and promoting skill transfer. Please refer to Section 3.2 for a description of the biofeedback game. Along with the three biofeedback groups, a non-biofeedback version of the game was used as a control group and deep breathing (a traditional relaxation method) as the standard treatment[26]. Experimental trials were conducted as part of an independent study with each participant being randomly assigned to one of the three biofeedback groups, the control group, or the standard treatment. 25 participants (15 male, 10 female; 19-33 years) participated in the study, 5 participants per group. BR, EDA, and HRV readings from all participants were collected during the entire experiment session for monitoring purposes and game adaptation in the respective biofeedback groups. Signed consent[27] was received from each participant before the experimental session. The experimental protocol is shown in Figure 22 and consisted of four phases (I-IV).

- **Phase I (baseline)**: participants were asked to follow an audio pacing signal that guided them to breathe at a rate of 6 breaths per minute (bpm) for 2 minutes. More specifically, the pacing signal instructed participants to inspire for 4 seconds and exhale for 6 seconds, an experimental choice motivated by prior

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[26] Standard treatment in this context refers to intervention that is traditionally used for stress management. It is the treatment that is normally provided (as prescribed by a physician) to patients with a given condition and is also known as active control.

[27] Texas A&M Institutional Review Board (IRB) protocol number IRB2009-0420F.

work showing that a respiratory cycle with a short inspiration followed by a long expiration period leads to higher RSA than a respiratory cycle with a long inspiration and a short expiration (Strauss Blasche, Moser et al. 2000). Data from this phase provided a baseline for the three physiological signals.

- **Phase II (pre-test)**: participants performed a modified Stroop color word test (CWT) (Stroop 1935) for 4 minutes –see section 3.6.2, which served as a pre-test condition to assess their physiological response to stress prior to treatment. Instructions on how to perform the CWT were provided prior to the beginning of the task. The CWT is widely used in psychology studies to induce mental workload and arousal.
- **Phase III (treatment)**: participants were assigned to one of five groups: BR-GBF (breathing rate game biofeedback), HRV-GBF (heart rate variability game biofeedback), EDA-GBF (electrodermal activity game biofeedback), DB (deep breathing) and GO (game only). The duration of the treatment was 8 minutes for all groups, with the following procedure during the treatment session:
    - *GBF (experimental treatment)*: Participants played one of the three biofeedback games (BR-GBF, HRV-GBF, or EDA-GBF). They were instructed to (1) do the best they could in the game and score maximum points, and (2) stay calm during the gameplay and try and breathe slowly i.e. in the same way they had practiced during the baseline phase. All participants were given the same instructions regardless of treatment type.

- *GO (control)*: Participants played the non-biofeedback game. They were given the same instructions as those in the GBF conditions.
- *DB (standard treatment)*: Participants in this group did not play a game. Instead, they were instructed to stay calm and try and breathe slowly by following an audio pacing signal that guided them to breathe at a rate of 6 breaths/min (inhale for 4s and exhale for 6s).

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

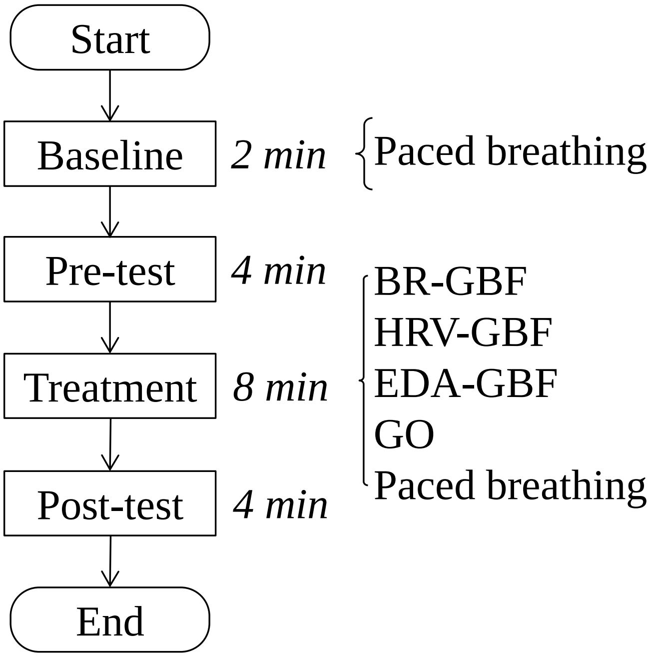

Figure 22 Experimental protocol showing the four phases and their respective durations. A color word test was used during the pre- and post-test.

4.4 Experimental results

4.4.1 Average physiological response per treatment

To compare the efficacy of the five methods in teaching relaxation skills, the participants' BR, EDA and HRV during the pre-test, treatment, and post-test were analyzed. Figure 23(a-b) show the average BR and changes in BR relative to pre-test. During treatment, the BR-GBF and DB groups had lower BRs than during pre-test, whereas the other two biofeedback groups (EDA-GBF and HRV-GBF) only had a moderate reduction in BR and the GO group had a moderate increase. During post-test, participants in the BR-GBF and DB groups continued to have lower BRs than during pre-test, a result that indicates the deep-breathing skill was transferred; note, however, that the reduction in BR at post-test is more pronounced in the BR-GBF group than in the DB group. The remaining groups did not have a reduction BR during the post-test, which suggests the deep-breathing skills did not transfer.

The statistical significance of these results was assessed by performing a 1-way ANOVA on the difference between pre- and post-test BRs. This analysis showed a marginally significant difference between the five groups: $F(4,20) = 2.83, p = 0.052$. Pairwise post-hoc tests were performed to analyze differences between pairs of groups; results are presented in Table 8.

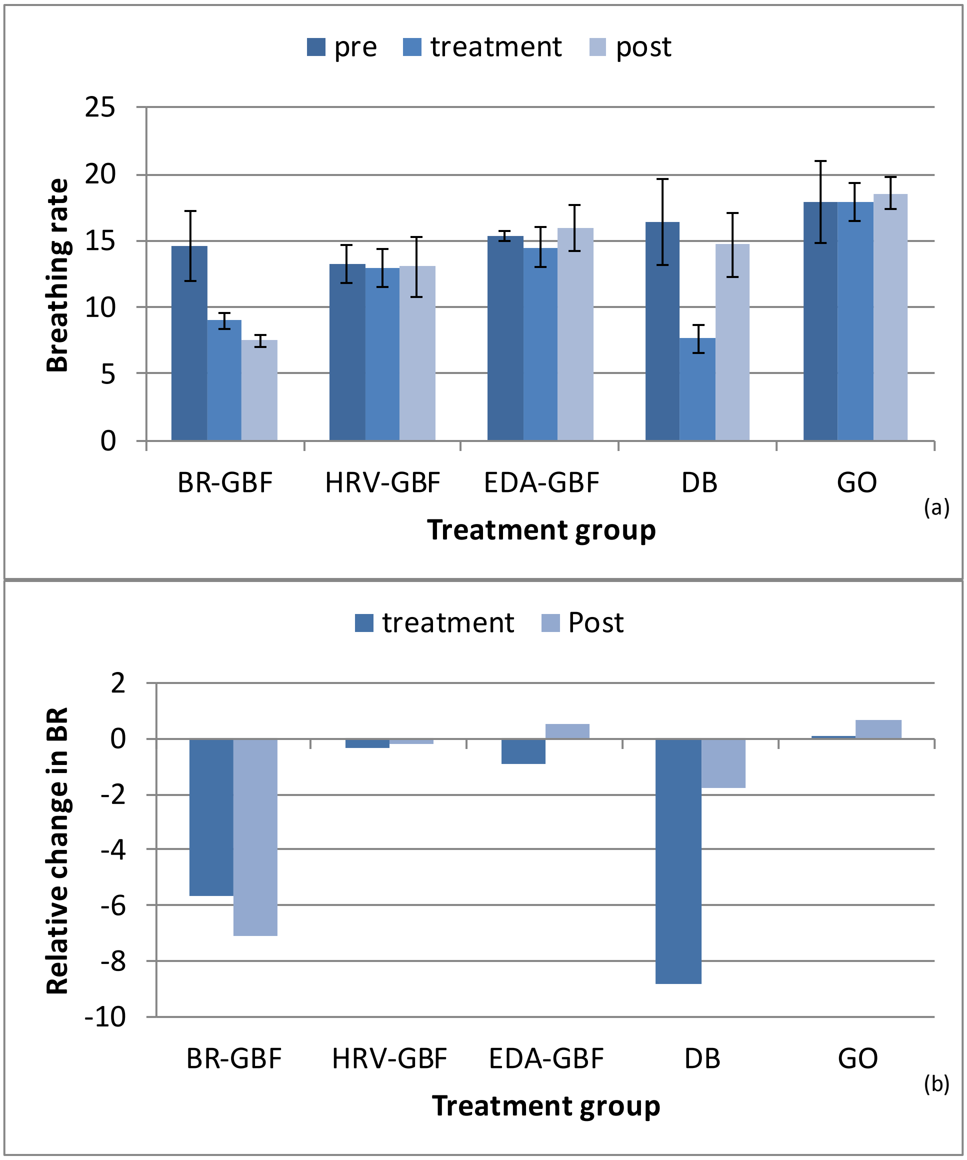

Figure 23 (a) Average BR values during the pre-test, treatment, and post-test for the five groups. (b) Relative change in BR during the treatment and post-test with respect to the pre-test

Table 8 Statistical difference (F-ratio) between the five groups in terms of breathing rate change (post – pre). (**p<0.05; *p<0.1). Degree of freedom: df_1 (between groups) = 1 and df_2 (within groups) = 8

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

Statistically-significant differences were observed in BR-GBF vs. HRV-GBF and in BR-GBF vs. EDA-GBF groups, and marginally-significant differences in BR-GBF vs. DB and BR-GBF vs. GO groups, which indicates the effectiveness of BR-GBF in promoting skill transfer. No statistically-significant differences were found in any other pairs. To study the contribution of individual factors, a 2-way ANOVA was performed with degree of voluntary control and selectivity in measuring arousal as the factors with the hypothesis that the gain in breathing rate between pre- and post-test is same across all groups. This analysis showed a marginally significant main effect for degree of control $F(1,16) = 4, p < 0.06$ and an insignificant main effect for selectivity in arousal $F(1,16) = 3.45, p < 0.082$. No interaction was observed between the two factors $F(1,16) = 2.74, p < 0.12$. This analysis indicates that degree of control played a higher role in lowering arousal compared to selectivity in arousal.

Figure 24 shows the average HRV during treatment, pre- and post-tests, and the relative changes. During treatment, HRV increased noticeably for participants in the BR-GBF and DB groups, compared to only modest increases for the HRV-GBF and EDA-GBF groups and a reduction for the GO group. During post-test, the BR-GBF group had a further increase in HRV (relative to treatment), compared to a reduction for the DB, HRV-GBF and EDA-GBF groups (also relative to treatment). In summary, these results indicate that EDA-GBF and HRV-GBF were less effective than BR-GBF (or DB) in reducing arousal levels during the treatment and led to negligible transfer of relaxation skills during post-test.

A 1-way ANOVA on the delta values shows a statistically-significant difference between the five groups: $F(4,20) = 2.9, p < 0.05$. Pairwise post-hoc analysis show a statistically-significant difference in BR-GBF vs. EDA-GBF groups, in BR-GBF vs. DB groups, and in BR-GBF vs. GO groups, and marginally significant differences in BR-GBF vs. HRV-GBF groups, and in DB vs. GO groups; see Table 9. No statistically significant differences were found in any other pairs.

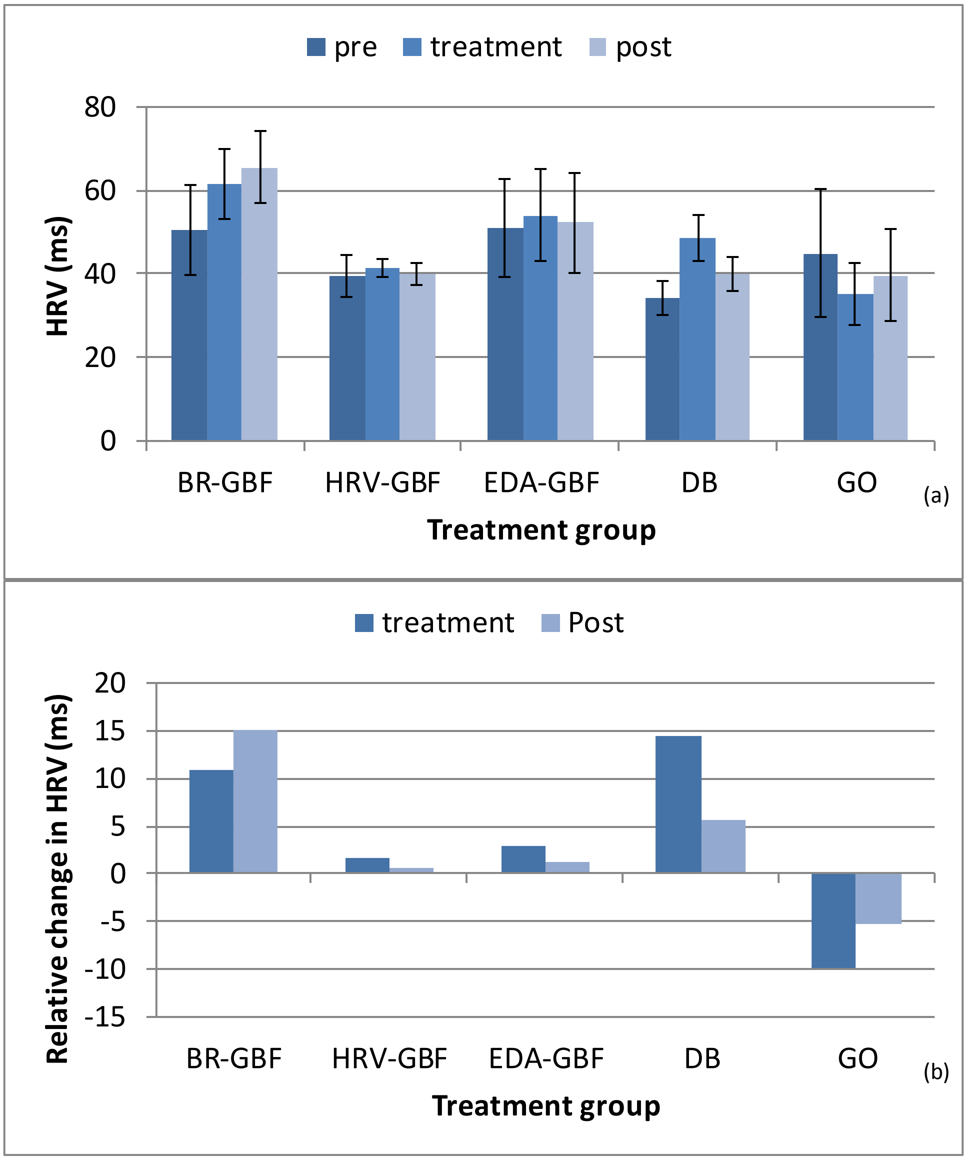

Figure 24 (a) Average HRV values during the pre-test, treatment, and post-test for the five groups. (b) Relative change in HRV during the treatment and post-test with respect to the pre-test

Table 9 Statistical difference (F-ratio) between the five groups in terms of heart rate variability change (post – pre) (**p<0.05; *p<0.1). $df_1 = 1$ and $df_2 = 8$

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

Lastly, Figure 25 summarizes EDA results in terms of the number of SCRs per 30-sec ($SCR_{\#}$). Participants in the BR-GBF group had a monotonic decrease in EDA from pre-test to treatment to post-test, indicating that the treatment led to reduction in arousal. Likewise, participants in the DB group had lower EDA during treatment and post-test (relative to pre-test), though EDA increased at post-test relative to during treatment. No particular trend was seen in the HRV-GBF group during treatment or post-test, while the EDA-GBF group had a minor decrease in EDA during treatment followed by an increase during post-test. Finally, there was an increase in EDA during the treatment and post-test for the GO group. A 1-way ANOVA comparing the five groups did not show a significant difference: $F(4,20) = 1.98, p < 0.14$. However, pairwise post-hoc analysis revealed a statistically-significant difference in BR-GBF vs. GO groups, and marginally-significant differences in BR-GBF vs. HRV-GBF groups, in BR-GBF vs. EDA-GBF groups, and in GO vs. DB groups; see Table 10.

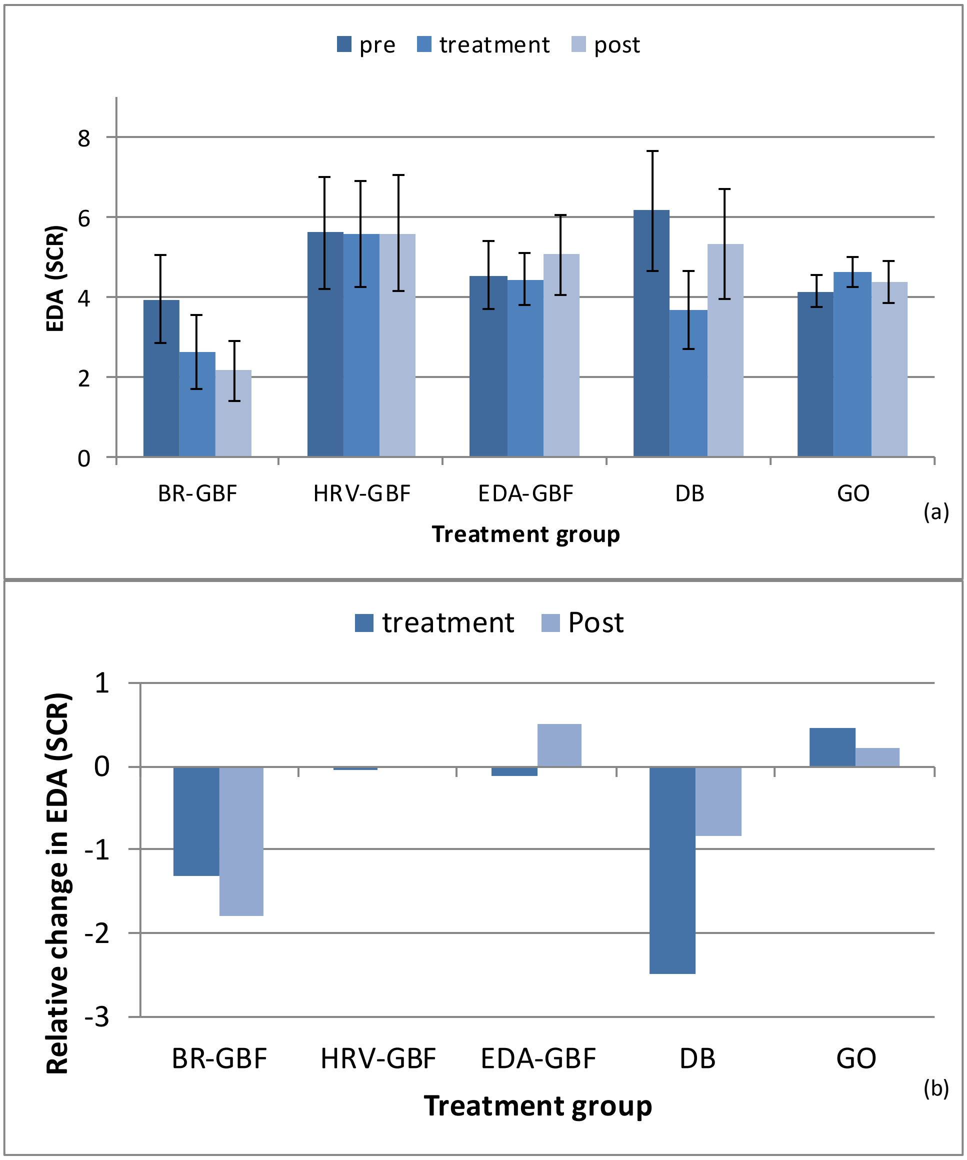

Figure 25 (a) Average EDA (SCR) values during the pre-test, treatment, and post-test for the five groups. (b) Relative change in EDA during the treatment and post-test with respect to the pre-test

Table 10 Statistical difference (F-ratio) between the five groups in terms of electrodermal activity change (post-pre) (**$p<0.05$; *$p<0.1$). $df_1 = 1$ and $df_2 = 8$

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

In summary, the preceding analyses reveal a significant difference between subjects who underwent treatment in the BR-GBF group (lower BR, lower EDA and higher HRV, all indicative of reduced arousal) during post-training compared to the other four groups. While the DB group showed a lowering of arousal during treatment, this was followed by an increase during post-test, which indicates minimal transfer of relaxation skills. In addition, participants in the HRV-GBF and EDA-GBF groups did not show much difference between the three sessions, whereas participants in the GO group had higher arousal during both treatment and post-test –an expected result since games are known to increase arousal.

4.4.2 Performance

To analyze whether the different treatments had an effect on task performance, the differences in CWT scores at pre- and at post-test were analyzed. Results are presented in Figure 26. Task performance improved for all groups, which suggests some learning effects took place. A 1-way ANOVA on the delta values showed a marginally-significant difference ($F(4,20) = 2.41, p < 0.08$) across groups. Post-hoc assessment also showed marginally-significant differences in BR-GBF vs. EDA-GBF ($F(1,8) = 5.12$; $p < 0.06$), in BR-GBF vs. GO ($F(1,8) = 4.04$; $p < 0.07$), in EDA-GBF vs. HRV-GBF ($F(1,8) = 3.78$; $p < 0.09$), and in HRV-GBF vs. GO ($F(1,8) = 3.89$; $p < 0.08$). No significant group differences were observed between other pairs.

In a final step, the effect of arousal on performance for participants in the five groups was studied and the results are presented in Table 11. Differences in the CWT scores (post-pre) show no correlation with changes in each of the three physiological signals (BR, HRV, EDA). The improvement in performance seen in all the groups may therefore be attributed to learning effects in the CWT.

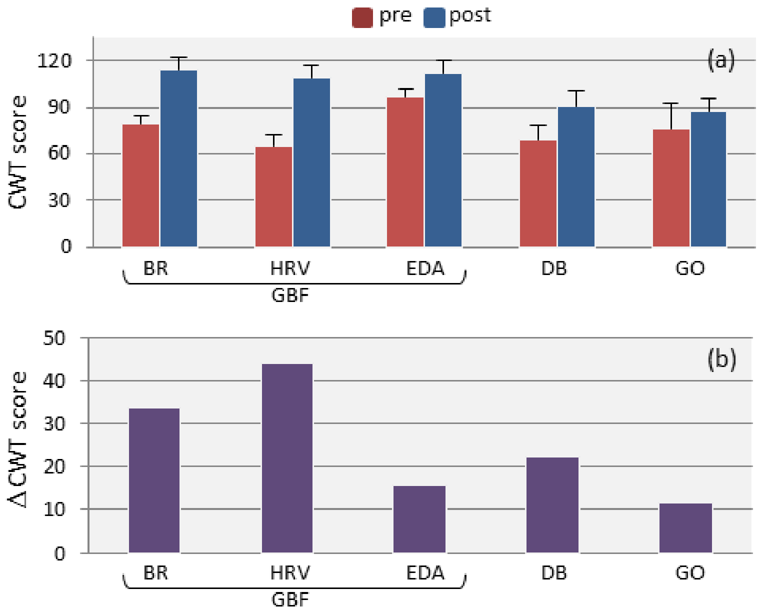

Figure 26 (a) Pre- and post-test task performance (CWT score) for the five groups (b) Change in CWT score

Table 11 Pearson correlation coefficient ρ (p-value) between changes (post-pre) in CWT scores and changes in physiological response for all participants

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

4.5 Discussion

This chapter compared three biofeedback modalities for game adaptation (EDA, HRV, and BR) against a control group (game only) and a standard treatment (deep breathing) by their ability to teach relaxation skills. The results show that breathing-based game biofeedback (BR-GBF) is more effective than the other groups in terms of lowering arousal during the treatment *and* transferring relaxation skills to a subsequent acute stressor.

The advantage of BR-GBF over GO and DB in lowering arousal during treatment and the subsequent acute stressor may be the result of *contextualized learning*. BR-GBF combines virtual objects (e.g. video game) and real-world tasks (e.g. deep breathing), in this way allowing players to internalize and reinforce the relaxation process while performing a task that is designed to increase arousal. This may lead to a better transfer of skills to other real world tasks (Dalgleish 2004). Furthermore, existence of such schemas prepares the mind for new (stressful) events by providing a pre-existing representational structure against new experiences. The superior performance of BR-GBF may also be attributed to *instrumental conditioning* i.e. rewarding relaxing behaviors and penalizing others.

A plausible explanation for differences among the three game biofeedback groups is the degree to which the individual has voluntary control of the physiological signal modulating the game (e.g. BR, EDA, or HRV). Breathing is normally controlled by the autonomic nervous system, but can be overridden voluntarily and therefore can be considered to be under full voluntary control. In contrast, HRV is not under direct voluntary control but is the result of autonomic processes that regulate blood pressure and respiratory efficiency (Lehrer 2007). However, HRV can be altered with proper breathing technique, so it can be viewed as being under partial voluntary control. Finally, controlling EDA (reducing it, in particular) is more difficult than HRV or respiration, so EDA can be considered to be under low voluntary control. According to this argument, having a higher degree of control of the physiological signal, participants in the BR-GBF group could self-initiate the lowering of breathing rate during gameplay, which in turn led to a lowering of their arousal. This is an interesting finding because, though EDA is the most specific indicator of arousal among the three modalities, EDA-GBF did not assist participants in lowering their arousal. This indicates that, for biofeedback gameplay, physiological variables that can be directly manipulated by the participants may facilitate learning of stress self-regulation skills.

A second factor underlying the observed results may be the instructions given to participants during the experiment. Prior to treatment, participants in the three GBF groups were asked to '*stay calm during the gameplay and try and breathe slowly, i.e., in the same way they practiced during the* baseline phase' (see Section 4.3.1). No specific instructions in reference to maintaining high HRV or low EDA levels were provided.

Thus, even though slow breathing is shown to lower the arousal levels, the lack of specific instructions and/or training may have led to the poorer performance in the EDA-GBF and HRV-GBF groups. In an early study, Blanchard, Scott et al. (1974) showed that subjects who were provided HR biofeedback and were told that they were being trained to change HR did better than those who were not; this group in turn did better than those told being trained to change skin conductance, indicating the importance of providing specific instructions during training. More recently, Raaijmakers, Steel et al. (2013) studied the effect of EDA and HRV biofeedback-based games on affective state. In this study, participants were not informed about the biofeedback modality (i.e. EDA or HRV) controlling the game and were not given any instructions on how to control their EDA and HRV; instead, they were told to '*find out themselves how to achieve control*'. Their results showed no effect of biofeedback on the user's affective state. Based on these results, it may be tempting to conclude that HRV-driven or EDA-driven game biofeedback are not effective in reducing stress reactivity; however, further work with longer training duration is required to validate this claim.

Results presented in this chapter are consistent with prior work (Larkin, Zayfert et al. 1992, Goodie and Larkin 2006, Bouchard, Bernier et al. 2012) in showing that biofeedback video games can be an effective technique to teach relaxation skills; due to the repetitive nature of video games, these skills are reinforced and can potentially be applied to subsequent tasks without biofeedback. This leads to an important question: how does learning and reinforcement of relaxation skills occur? A plausible mechanism proposed by Pope, Stephens et al. (2014) is that of a two-step process of instrumental learning and classic conditioning. While most biofeedback systems, including GBF, are designed from the ground-up using concepts of instrumental conditioning, classical conditioning also assists in learning. Briefly, classical conditioning, which is also known as Pavlovian learning, involves the pairing of a neutral stimulus (e.g. bell sound) with an unconditioned stimulus- UCS (e.g., food) (Grant 1964). The UCS triggers a natural response of salivation, which is the unconditioned response (UCR). With repeated exposure, the neutral stimulus leads to the same response and is now called a conditioned response. Researchers have observed that both classical and instrumental conditioning help form associations between the biofeedback information and physiological states facilitating learning (Pope, Stephens et al. 2014, Strehl 2014). In fact, classical conditioning is always happening during instrumental conditioning based learning, so it is difficult to separate the two. Strehl (2014) noted that, in a neurofeedback setting, classical conditioning helps form an association between the target behavior and the conditioned stimuli Furthermore, Pope, Stephens et al. (2014) argued that during gameplay with player's effort and motivation to excel in a game and through repeated associations, the learned changes can be generalized to other tasks.

The underlying principle that explains the reinforcement process is known as Premack prepotent principle, according to which "*a high probability behavior will reinforce a low probability behavior*" (Premack 1965). In the context of GBF, a high probability behavior is the activity that the user performs more frequently (i.e. playing a game in this case), whereas the low probability behavior is the elicitation of desired physiological response, i.e., staying calm.

By working with GBF, a user is able to form an association between the biofeedback outcome (i.e., game penalty) and the target behavior. This process of forming associations of a behavior with outcome in a biofeedback setting is that of learned discrimination (Brener 1986). Learned discrimination refers to the user's ability to identify and discriminate outcome in response to their behavior. Through practice the user develops internal procedures to perform the task (Sun, Merrill et al. 2001, Sun, Slusarz et al. 2005) and gradually become more proficient in perceiving visceral states, eliciting the target behavior (Anderson 1982) and reaching a state of automaticity.

A study by Koepp, Gunn et al. (1998) on the effect of video games on the brain showed that playing a video game led to substantial dopamine release compared to baseline. Dopamine release is an indicator of memory storage events, learning, reinforcement of behavior and attention, and helps learn stimuli or actions that predict rewarding or aversive outcomes. In their study, players showed a steady increase in the level of dopamine during a gameplay session, which stayed at levels higher than baseline after the gaming session ended. These results provide a link between behavioral manipulation and dopamine release, and suggest that biofeedback video games can chemically prepare the brain for learning and can be used to detect stress triggers, and learn/reinforce relaxation skills.

Another variable that plays an important role in developing self-regulation skills and facilitating recovery is the sense of control while performing a task (Hobfoll and Shirom 1993). As noted by Reinecke (2009) and Bandura (1994), the control over a task further enhances mastery and self-efficacy, both of which are important for skill acquisition (Bandura 1997, Sonnentag and Fritz 2007). The results in this chapter showed that BR, which is under complete voluntary control, is more effective in reducing arousal than either HRV or EDA. In contrast with non-interactive medium, such as traditional methods of relaxation, videogames allow players to control the progression of events (Grodal 2000, Klimmt and Hartmann 2006, Reinecke 2009). In a game, players can control and manipulate game elements and experience the consequences of their action in the game, which serves as reinforcement and can be used to modify behavior. Since biofeedback games provide the control of the game to the players over two channels- game controls and physiology, while providing feedback and reinforcement, they appear to be an ideally suited medium for stress self-regulation.

Finally, there are a few additional factors that are important in facilitating skill learning including motivation and confidence (Bandura 1994)), challenge level in the task (Locke and Latham 2002), past experiences, short and long term memory, and other factors (beliefs, motivation, personal and social factors) (Buckley and Anderson 2006). These have been covered in depth in prior work (Bandura 1994, Locke and Latham 2002, Buckley and Anderson 2006, Reinecke 2009, Pope, Stephens et al. 2014)

4.6 Conclusion

The objective of this study was to evaluate various physiological modalities for biofeedback during an engaging intervention to allow individuals practice stress management. In this context, the work presented in this chapter further validated the game biofeedback approach for acquisition and retention of stress self-regulation skills. More importantly, the results showed how various physiological signals (BR, EDA, and

HRV), which differ in the degree of selectivity in measuring arousal and voluntary control may be used in game biofeedback. Finally, the findings were analyzed in the light of psychological theories of learning and reinforcement and neuroscience. The next chapter will study the link going from the game to the user and evaluate different ways in which the biofeedback information is presented to the user during gameplay and their influences on skill acquisition and retention.

5. VISUAL BIOFEEDBACK AND GAME ADAPTATION IN RELAXATION SKILL TRANSFER

Several design choices can affect the effectiveness of a game based stress interventions: the characteristics of game (e.g., immersive vs. casual, action vs. puzzles), the physiological signal used to monitor the patient's state (e.g., cardiovascular, central nervous system), the type of channel used to deliver biofeedback (e.g., auditory, visual, haptic) and the way in which the biofeedback and the game are integrated. The previous study (Chapter 4) examined one such design choice: the type of physiological variable used as input to the game and its effectiveness in relaxation skill acquisition and retention. In the proposed design, the user received two types of biofeedback simultaneously: directly, through a peripheral visual display, and indirectly, through changes in the game mechanics. As such, the prior study was unable to determine whether one or the other form of biofeedback is more effective. Answering this question is the objective of this chapter.

This chapter compares three types of biofeedback in the game by their ability to teach relaxation skills and promote skill transfer. The first method, *visual* biofeedback, presents physiological information directly to the user (e.g., via a visual display) but otherwise does not affect gameplay. The second method, *game* biofeedback, presents the physiological information indirectly through subtle changes in gameplay, e.g. by changing game difficulty in proportion to the player's stress levels. The third method, *combined* biofeedback, delivers visual biofeedback and game biofeedback simultaneously. The three methods are assessed based on two criteria: 1) ability to reduce arousal during game play; and 2) improve relaxation skill transfer to subsequent cognitively demanding tasks when biofeedback is not present. This study also evaluates the contribution of individual biofeedback channels in promoting relaxation, and the learning curve for each form of biofeedback.

The rest of this chapter is organized as follows. Section 5.1 reviews prior work on game-based interventions for health and wellness, paying attention to games and biofeedback games for stress management. Section 5.2 describes the biofeedback game and the three biofeedback modalities. Section 5.3 presents the experimental protocol as well as the physiological and subjective measures used to compare the three forms of biofeedback. Section 0 analyses experimental results from the study. The chapter concludes with a discussion of these results in Section 5.5.

5.1 Related work

A number of studies in the past have studied biofeedback presentation in games for various applications. Rani, Sarkar et al. (2005) compared two types of feedback to adjust game difficulty levels. The first approach (anxiety feedback) consisted of modulating game difficulty based on the physiological state of the player in a negative feedback loop; high levels of anxiety (as measured through physiological indicators) caused the difficulty level to drop, and vice versa. The second approach (performance feedback) consisted of varying the level of difficulty according to the player's performance in a positive feedback loop: better performance led to an increase in difficulty level state, and vice versa. In both cases, the game could switch among three difficulty levels states (easy, moderately difficult, and very difficult) using a finite state machine. The authors found that anxiety-based feedback was more effective than performance-based feedback in challenging players, improved their performance, and lowered their anxiety.

Baranowski, Lieberman et al. (2013) organized a panel and reviewed various game mechanics in videogames for health. They noted that some mechanics provide fun or enjoyment, others excitement, suspense, while some are designed to promote behavior change. In their assessment, the found that many game mechanics that succeed in off-the-shelf entertainment games, may not be well suited for games for health. One of the panelists, Debra Lieberman, noted that to teach skills for healthy lifestyle and to change health-related behaviors, simulation and scenario based games are especially effective. Another panelist, Wei Peng, noted that mechanics that helped the players maintain a sense of autonomy and competence led to greater game enjoyment and satisfaction. A third panelist, Brenda Wiederhold found that presenting real time physiological information during therapy sessions helped increase both short and long-term effectiveness and lowered relapse rates. They also noted that the choice of both the game genre and game mechanics should depend on the subject population and health condition being targeted.

In related work, Kuikkaniemi, Laitinen et al. (2010) explored the influence of implicit and explicit biofeedback game in the context of a first-person shooter (FPS) game. Implicit feedback occurs when the game player is not aware that the game is manipulated according to their physiological state; the player may sense the feedback mechanism but only at a subconscious level. In contrast, explicit biofeedback occurs when the player has conscious control over specific game dynamic. The authors used a within-subjects design and discovered significant increases of immersion only in the explicit biofeedback condition. In a recent study, Nacke, Kalyn et al. (2011) investigated sensor mappings for two types of physiological signals: voluntary (direct) and involuntary (indirect). An example of direct (voluntary) control would be to use muscle activation or eye gaze, whereas an example of indirect (involuntary) control would be to use heart rate or skin conductivity. The authors concluded that direct input should be mapped intuitively into actions, whereas indirect input should be used to affect environmental variables of the game.

In prior work (Parnandi and Gutierrez-Osuna 2014), a biofeedback car racing game was presented with an aim to maintain a player's arousal at an optimum level. This was achieved by manipulating game difficulty in response to the player's physiological state (measured via electrodermal activity). The approach modeled the player-biofeedback game relationship as a control problem. The study used three game mechanics- car speed, visibility, and steering jitter as three adaptive game mechanics that were manipulated based on user's arousal level in a negative feedback loop. It also compared two control laws- proportional and proportional-integral-derivative for game adaptation. The experimental trials showed statistically significant differences among the three game mechanics and also between the two control laws in their ability to manipulate user's arousal level. Briefly, the study showed that manipulating car speed provides a high control on arousal than the other two mechanics and that the PID controller reduces oscillations in closed loop response.

More recently, Wang, Parnandi et al. (2016) presented an approach to use commercial videogames for biofeedback games for stress self-regulation. The approach consisted of capturing physiological signals and modifying the game controls accordingly so as to drive the user towards relaxation. The authors used a car racing game and compared two different biofeedback mechanisms in the game, namely car speed and visual overlay. Experimental results showed that compared to a control group, both the biofeedback groups were able to promote deep breathing in participants during treatment and also facilitate skill transfer during subsequent driving simulations.

5.2 Biofeedback game

To compare the biofeedback modalities in a game, three forms of biofeedback (based on peripheral visual cues, based on game adaptation, and a combination of the two) were implemented using the open-source game of Frozen Bubble (see Section 3.2). Following the results from Chapter 4, breathing rate was used as the physiological variable for biofeedback in the game.

- *Biofeedback through peripheral visual display*: Visual biofeedback was presented by means of two visual cues: a numeric indicator of the player's breathing rate (BR) at the top of the game screen, and an icon indicating whether their BR is increasing (red up-arrow) or decreasing (green down-arrow). Both cues were displayed continuously throughout the game. In addition, a text prompt *'Please try and relax!'* was displayed at the bottom of the screen whenever the player's BR was increasing. Both types of displays are illustrated in Figure 5.

- *Biofeedback through game adaptation*: Game biofeedback was implemented by manipulating the game based on the player's BR. Under this biofeedback mechanism, the cannon fired bubbles automatically without user input, the auto-shooting interval being defined as a piece-wise linear function of the player's BR– see Figure 6 and Table 2. For more details, please refer to Section 3.3.1. No visual indication of user's BR i.e., the numeric indicator, up/down arrows, and text prompts were displayed.

Combined game biofeedback: Combined game biofeedback was implemented by integrating visual biofeedback and game adaptation. Thus, in this condition users are presented physiological information via both biofeedback mechanisms during gameplay. This group allows was also used in the previous study and allowed for a study of the interaction effects between the two factors.

5.3 Experimental

Experimental trials were conducted as part of an independent study with each participant playing a single randomly assigned treatment (visual, game biofeedback, combined) or a control condition (game only). This between-subject design was adopted to avoid ordering effects from learning or fatigue**.**

- Visual biofeedback (*visual*): The player's BR is displayed numerically along with the up/down arrows and text prompts, but the game does not adapt.

- Game biofeedback (*GBF*): The game adapts based on the player's BR, but the numeric indicator, up/down arrows and text prompts are not displayed.
- Visual and game biofeedback (*combined*): The game adapts based on BR, and also displays the numeric indicator, up/down arrows and text prompts.
- Game only (*GO*): Participants play a game without biofeedback or displays of physiological information. This serves as the control group.

Game difficulty level for the *visual* and control groups was set to the lowest (i.e., easiest) level, whereas participants in the *game biofeedback* and *combined* could only play at this level under slow and sustained breathing. 24 participants (6 participants per group) were recruited for this study: 9 females and 15 males, all in the age range of 19-31 years. Signed consent form (see Appendix C) was received from each participant before the experimental session.

5.3.1 Protocol

The experimental session consisted of five phases: baseline, pre-test, training, treatment, and post-test; see Figure 27.

Baseline: During this phase, participants followed an auditory pacing signal, which guided them to breathe at 6 bpm; inhaling for 4 sec and exhaling for 6 sec. This choice was motivated by prior work (Strauss Blasche, Moser et al. 2000) showing that a respiratory pattern with a short inspiration followed by long expiration leads to a higher respiratory sinus arrhythmia (RSA)28. The baseline phase had a duration of 5 minutes.

Pre-treatment assessment (Pre-test): Participants performed a modified Stroop Color Word Test for 3 minutes; see section 5.3.5 for details. This phase provided an initial measure of the player's arousal when presented with a mild stressor.

Training: Participants played the game (without biofeedback or game adaptation) for 3 minutes to familiarize themselves with the game prior to the treatment.

Treatment: Participants are assigned to one of the four groups (*visual*, *GBF*, *combined*, or *control*). They play the corresponding version of the game for 6 sessions, each session lasting 5 minutes (30 minutes total) with a 1 minute break between sessions. During this break, participants are given their game score and relaxation score (see section 5.3.4), and are asked to improve both.

Post-treatment assessment (Post-test): Following treatment, participants complete the CWT a second time, and a previously-unseen mental arithmetic task (King of Math) for 3 minutes each; see section 5.3.5 for details. The order of the two tasks was counterbalanced to remove any ordering effects.

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

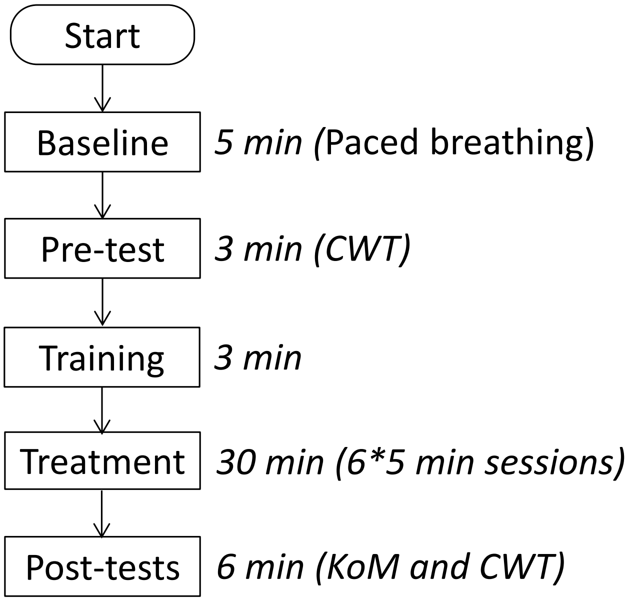

Figure 27 Experimental protocol. CWT: color word test, KOM: King of Math (mental arithmetic task)

5.3.2 Instructions

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

- Common to the four groups
  - Before treatment. “Relax, Try and breathe slowly, maintaining your BR around 6 bpm. Try and do the best in the game to score maximum points”
  - Before post-test. “Stay calm by using the skills you learned during the treatment session. Try and do the best in both assessment tasks”
- Common to the three biofeedback groups

  - Scoring scheme. “Your score will depend on both your game performance and how relaxed you are while playing the game. At the end of each game session, we will give you two scores: your game score and your relaxation score. Try to improve on both”
- Specific to each group
  - *Visual*: “During gameplay you will be shown your BR and whether it is increasing or decreasing”
  - *GBF*: “The game will be affected by your BR; higher BR will make the game more difficult”
  - *Combined*: “The game will be affected by your BR; higher BR will make the game more difficult. In addition, during gameplay you will be shown your BR and whether it is increasing or decreasing”
  - *Control*: No relaxation scores were provided; participants were only asked to stay calm and do well in the game.

5.3.3 Physiological measures

Stress reactivity and skill transfer were measured by means of three physiological variables: breathing rate (BR)[29], heart rate variability (HRV), and electrodermal activity (EDA). Please refer to Section 0 for more details.

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[29] Breathing rate was used both assessment of arousal and for real-time game adaptation. For game adaptation, BR greater than 6 bpm and increasing was taken as the states of non-relaxation.

5.3.4 Computation of relaxation score

Following Larkin, Zayfert et al. (1992), participants in the three biofeedback groups (visual, GBF, combined) were verbally informed about their relaxation score after each 5-minute biofeedback gameplay session. The relaxation score captured the participant's ability to maintain a slow breathing pace during treatment. It was computed by analyzing BR data in 30-second windows (sliding by 1s) as follows:

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

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

5.3.5 Assessment tasks

Transfer of skills and performance were evaluated on two cognitive stressors: a modified version of the Stroop Color Word Test (CWT) and a mental arithmetic task. CWT has been described in the chapter 3; see Section 3.6.2 and Figure 28(a). For the mental arithmetic task, King of Math (KOM)[30] was used. KOM allows the player to practice various math exercises including basic arithmetic, geometry and fractions.

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[30] http://oddrobo.com/kingofmath2

During a KOM session, the participant solves math problems by choosing the correct answer from four options; see Figure 28(b). For this assessment, the mixed section of the app was used where the user is presented with an assortment of questions from the various categories. Each level consists of 10 questions, which have to be completed in a limited amount of time (100 seconds). Each level starts with an initial score of 100,000, which is reduced by 1,000 every second spent at that level. Thus, the faster the participant answers, the higher score they attain. In addition, every mistake leads to a 5,000-point penalty, and 3 mistakes within a single level prevent the participant from progressing to the next level.

(a) (b)

Figure 28 Screenshot of tasks used for assessment (a) Color word test (b) King of Math

5.4 Experimental results

The effectiveness of three game-biofeedback interventions in teaching relaxation skills and promoting skill transfer is evaluated by comparing the physiological variables (breathing rate, heart rate variability, and electrodermal activity) for participants in the four experimental groups. Pace of acquisition of deep-breathing skills is assessed by comparing participants' BR during the treatment phases, while task performance is compared using the scores achieved by the participants in the pre- and post-tests. Finally, a subjective evaluation of the proposed method including participant comments is presented.

5.4.1 Physiological arousal

Figure 29 shows the average BR for participants in the four groups during paced breathing, pre-test, treatment, and post-test. BRs for the four groups are equivalent during the first two phases: a low of approximately 6 bpm during the initial paced breathing session, which shows that participants successfully followed the pacing signal, and a maximum of approximately 17 bpm during pre-test, an expected result since the CWT acts as a mild stressor. Differences between the four groups emerge during treatment: participants in the control group maintain the high BR at pre-test, whereas those in the three biofeedback groups show a marked reduction in BR. Among the latter, combined biofeedback elicits the lowest BR during treatment, followed by game biofeedback. Differences among the three biofeedback groups become stark at post-test: the two game-adaptation groups (GBF and combined) lower their BRs beyond those achieved during treatment, making them comparable to those attained during paced breathing, whereas those in the visual group have the BRs attained during treatment but not lower. Participants in the control group do not show any reduction in BR compared to pre-test. These results provide strong evidence of skill transfer for the three biofeedback groups, with a clear advantage for game adaptation.

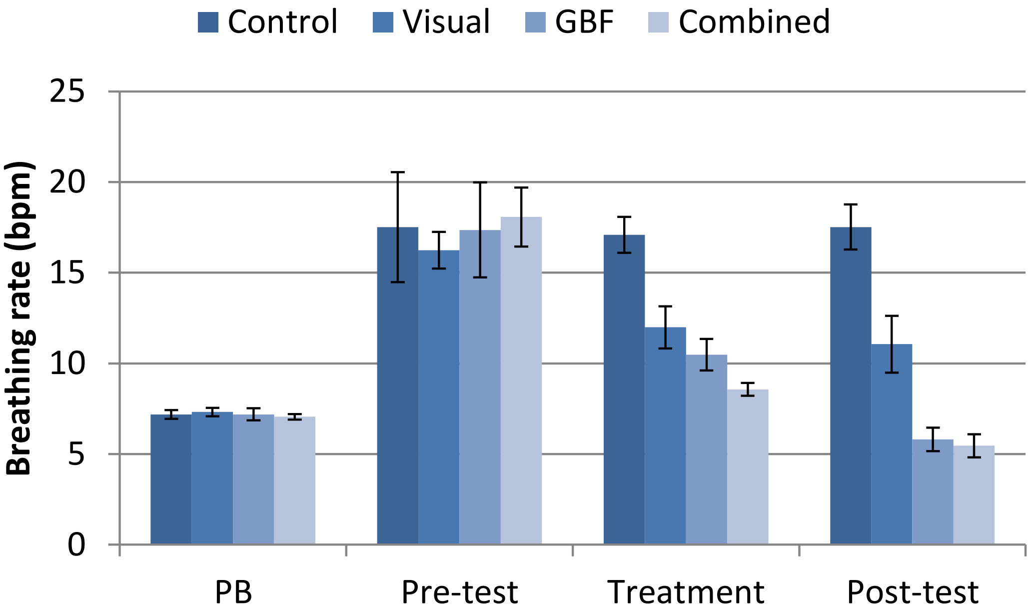

Figure 29 Average breathing (across participants) during paced breathing (PB), pre-test, treatment and post-test for all groups

To validate these results, a 1-way ANOVA on the gain values between pre- and post-test BRs was performed. This analysis showed a statistically significant difference between the four groups: $F(3,20) = 23.51, p < 0.05$. To evaluate the contribution of the different factors, a 2-way ANOVA with the two biofeedback mechanisms (visual and game adaptation) as the independent factors and BR gains as the dependent variable was performed. This analysis showed a marginally significant interaction between the two factors: $F(1,20) = 4.1, p < 0.06$ and statistically significant main effects for both factors (*visual*: $F(1,20) = 10.38, p < 0.05$; *GBF*: $F(1,20) = 56.04, p < 0.05$). This analysis indicates that both the two biofeedback mechanisms are involved in assisting the user lower their BR, albeit to different degrees. A comparison between the F-ratios for the factors indicates that game adaptation triggers a relaxation response and is more effective in reducing BRs, while visual biofeedback helps maintain the target BR. Finally, the time course of BRs during the experiment, with particular attention to the six treatment sessions (T1-T6) are examined. Results are shown in Figure 30.

The two game adaptation groups (*GBF* and *combined*) show a sharp decline in BRs as the treatment sessions progress, and reach the target BR in the last two sessions (T5, T6). In contrast, the *visual* group had a moderate decline as the treatment progresses, but the BR never reaches the target range. Also of note, BRs for participants who received one form of biofeedback (*visual* or game adaptation) also show a larger variance during treatment compared to participants who receive the two forms of biofeedback combined. The high variance observed in the *GBF* group (during the initial part of the treatment) may be attributed to the time it took for the participants to understand the nature of the biofeedback (i.e. game adaptation) and its effect on the game. Towards the end of the treatment session, the variance observed in the *GBF* group was similar to the *combined* group indicating they could follow the biofeedback and elicit the desired behavior. Finally, BRs for participants in the control group are flat-lined during the six treatment sessions, indicating that the game alone had no effect on breathing behavior.

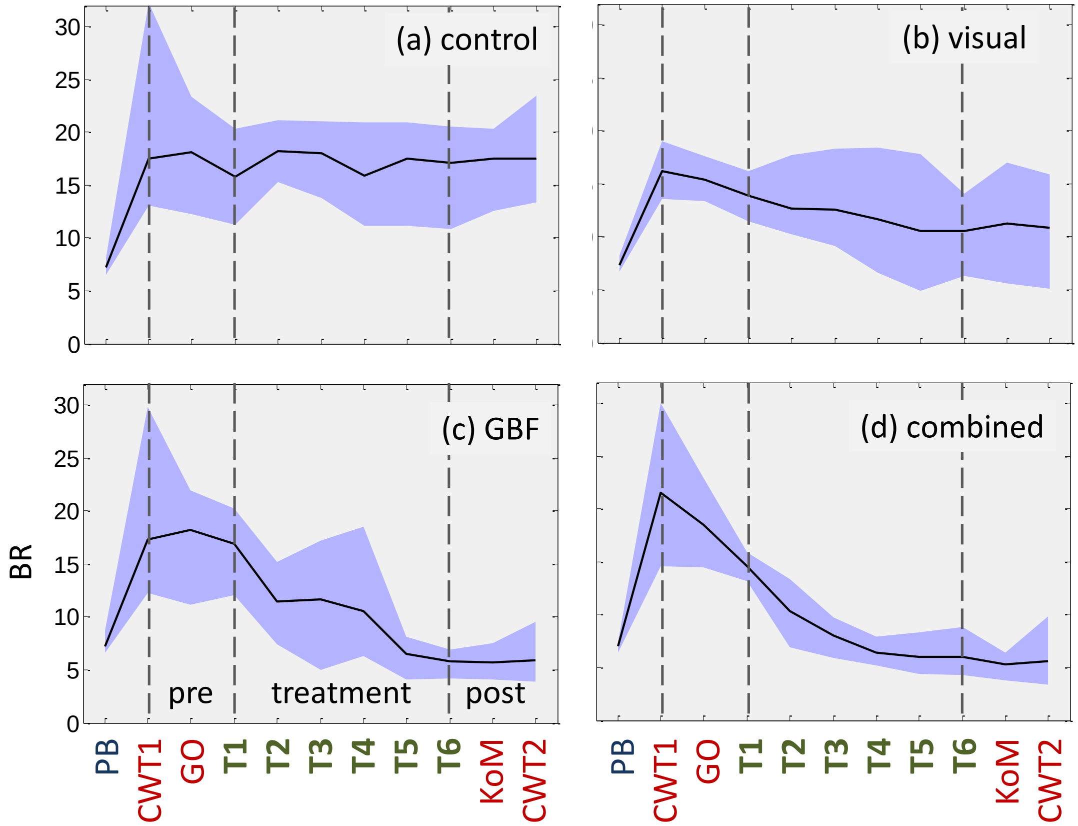

Figure 30 Average breathing rate during the course of the experiment (a) GBF (b) combined (c) visual (d) control. Shaded bands indicate one standard deviation. PB: paced breathing, CWT: color word test, control: game only, T1-T6: 6 treatment session, KOM: king of math. Vertical lines show onset of pre-test, treatment, and post-test.

In a next set of analyses, EDA statistics in terms of the number of skin conductance responses per min ($SCR_{\#}$) are compared. Results are shown in Figure 31. As with breathing rates, participants in the four groups had a low $SCR_{\#}$ during paced breathing (indicative of relaxation), followed by a notable increase during pre-test (consistent with the introduction of a stressor). $SCR_{\#}$ decline during treatment for all participants, including those in the control group, which suggests some degree of habituation to the game. However, only the *combined* group maintained a low $\mathrm{SCR}_{\#}$ at post-test, whereas the other three groups showed an increase relative to treatment. 1-way ANOVA on the increase in $\mathrm{SCR}_{\#}$ between pre- and post-tests indicates a statistically significant difference between the four groups: $F(3,20) = 3.65, p < 0.05$. A 2-way ANOVA with the two biofeedback mechanisms (visual vs. game adaptation) as factors indicated strong main effects (*visual*: $F(1,20) = 4.47, p < 0.05$; *GBF*: $F(1,20) = 6.48, p < 0.05$,), and no interaction effects ($F(1,20) = 0.01, p < 0.9$).

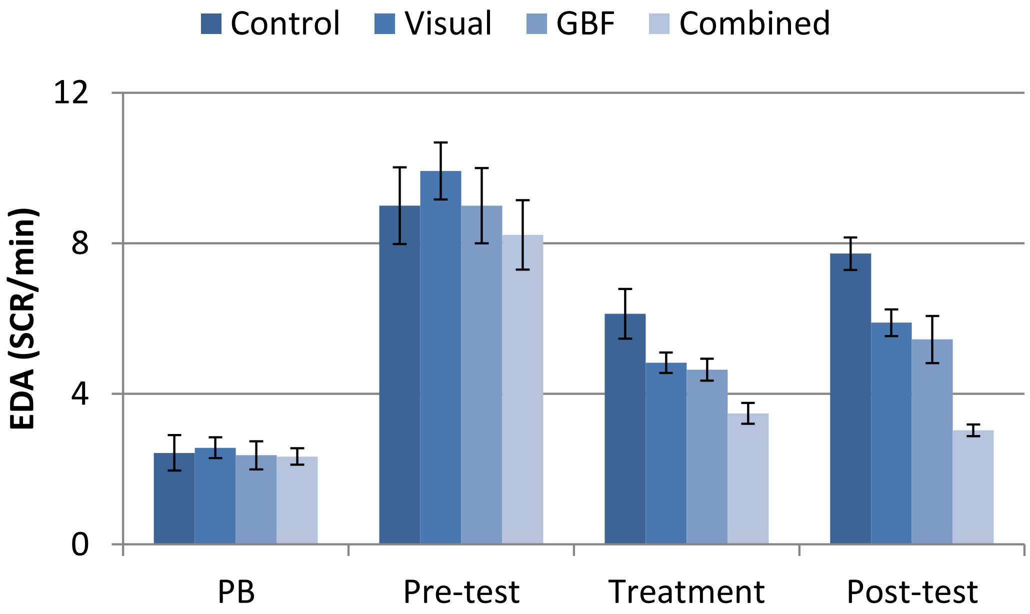

Figure 31 Average EDA (SCR/min) during paced breathing (PB), pre-test, treatment, and post-test for all groups

Figure 32 shows the time course of $\mathrm{SCR}_{\#}$ for each group during the experiment. As the treatment progresses (T1-T6), the *GBF* and *combined* groups show a gradual decrease in arousal following the higher values observed during pre-test. Participants in the *control* group also showed a decrease in $\mathrm{SCR}_{\#}$, though not as consistent as that on the

GBF or *combined* groups –see error bands. No particular trends were observed for *visual* biofeedback during treatment: participants in this group are able to lower their $SCR_{\#}$ within the first session (T1) and maintain it throughout the treatment. Two factors can explain this result. First, visual biofeedback is relatively intuitive, whereas game biofeedback is provided through changes in the game. As such, visual biofeedback is easy to grasp within a single treatment session. Second, visual biofeedback does not affect the game, whereas game biofeedback increases the game difficulty when breathing rates increase beyond the target rate. This introduces a learning curve for participants in the GBF and combined group. However, only the *combined* group had similar arousal levels at post-test than those obtained during the initial paced breathing session, which indicates stronger skill transfer than in the other three groups.

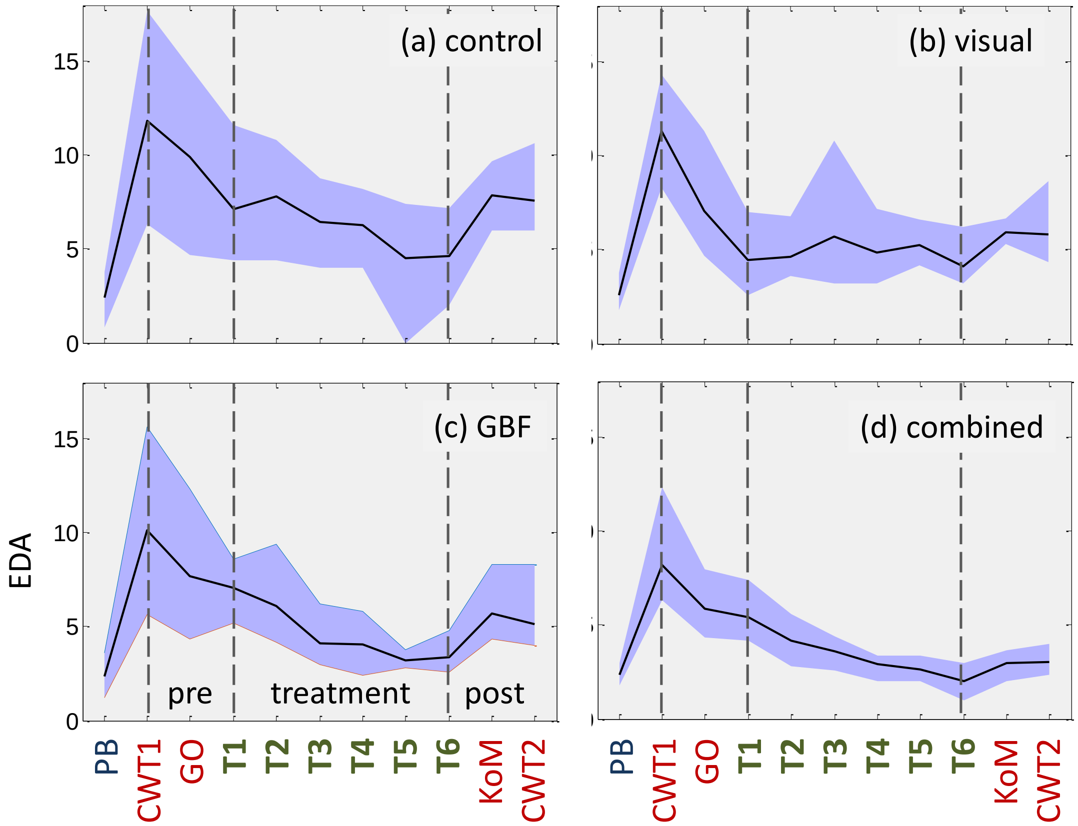

Figure 32 Average EDA (SCR#/min) during the experiment (a) GBF (b) combined (c) visual (d) control. Shaded bands indicate one standard deviation.

Finally, the HRV levels for participants in the four groups are compared. As shown in Figure 33 and Figure 34, the four groups display a high HRV during the initial paced breathing session followed by a reduction during pre-test; these results are consistent with those obtained on breathing rate and electrodermal activity. During treatment, participants in the three biofeedback groups (*visual*, *GBF*, and *combined*) experience a gradual rise in HRV as the sessions, whereas participants in the *control* group only show a marginal increase. Of note, the HRV for participants in the *combined* group continues to increase during post-test, reaching the baseline level attained during the initial paced breathing session. In contrast, participants in the *GBF* and *visual* groups show a drop in HRV during the post tasks relative to the values attained at the end of the treatment, the drop being more significant in the case of *visual* –see Figure 34(b, c).

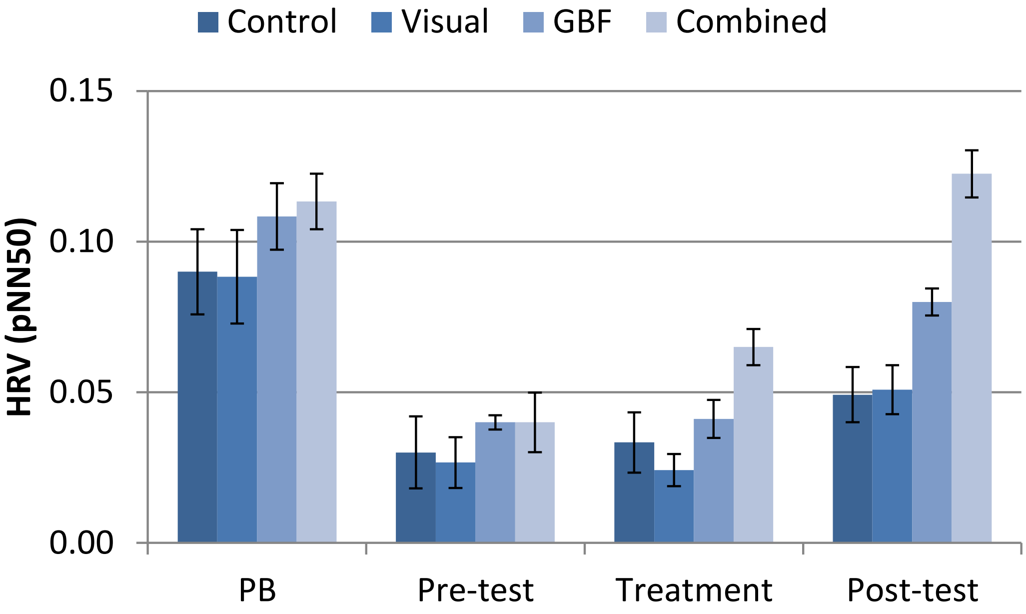

Figure 33 Average HRV (pNN50) during paced breathing (PB), pre-test, treatment, and post-test for all groups

A 1-way ANOVA of HRV differences between pre- and post-test shows no statistically significant differences among the four groups: $F(3,20) = 1.04, p < 0.39$. A 2-way ANOVA analysis fails to show any significant main effects (visual: $F(1,20) = 0.7, p < 0.41$; GBF: $F(1,20) = 0.16, p < 0.7$)) or interaction ($F(1,20) = 2.15, p < 0.15$) between the two biofeedback mechanisms (*visual* vs. *game biofeedback*).

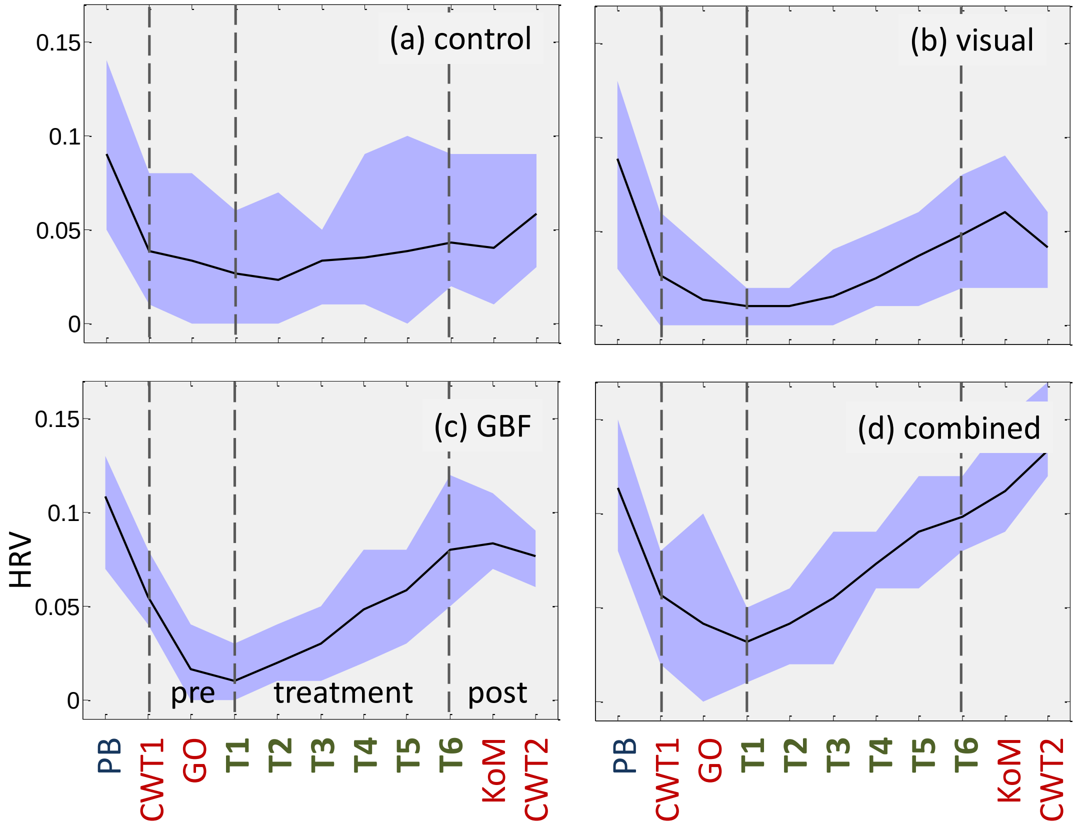

Figure 34 Average HRV (pNN50) during the course of the experiment (a) GBF (b) combined (c) visual (d) control. Shaded bands indicate one standard deviation.

5.4.2 Pace of learning

To examine the differences in pace of learning, measured as the amount of time participants needed to reach and maintain an average BR below 8 bpm for an entire (5 min) treatment session, participants' breathing trends were compared. Results are shown in Figure 35. All participants in the *GBF* and *combined* groups were able to bring their BR down to that level within the six treatment sessions (T1-T6), compared to only one participant in the v*isual* group and none in the *control* group. Direct comparison between the *combined* and *GBF* groups shows a faster acquisition of deep-breathing skills for *combined* (an average of 3.33 sessions) compared to *GBF* (4.16 sessions). Though most participants in the *visual* group could not reach the 8 bpm mark, as shown in Figure 35, they were able to lower their BR during treatment, albeit at a slower pace than *combined* and *GBF*. Perhaps, then, additional treatment sessions may have allowed *visual* participants to acquire the deep breathing skills.

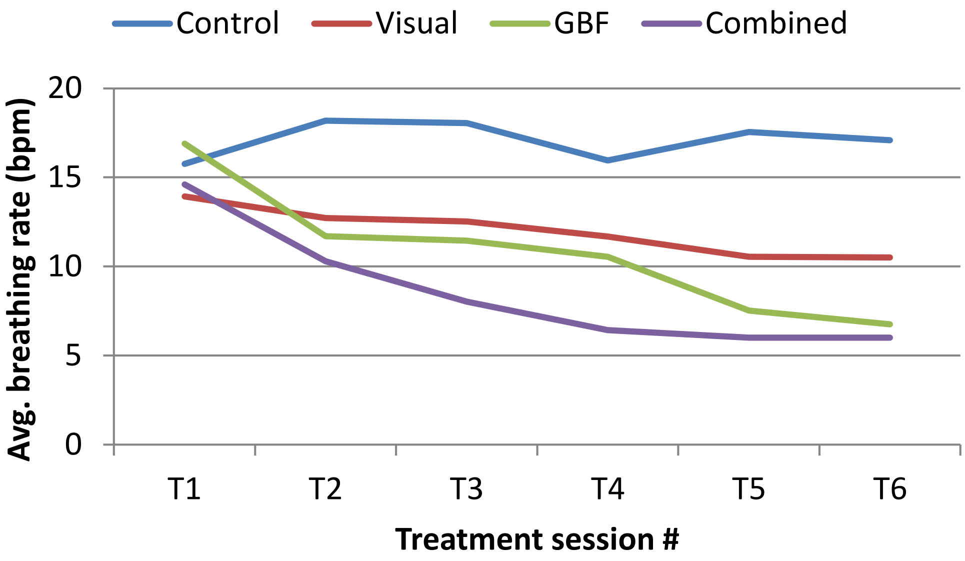

Figure 35 Pace of learning for the four groups during treatment

5.4.3 Performance results

Participant's performance was evaluated based on CWT (during pre- and post-test) and KOM scores (during post-test). As shown in Figure 36(a), all groups showed an increase in CWT score post treatment, a result that may be attributed to learning effects. The magnitude of increase was larger for the *visual* and *GO* groups (17.33 and 16.33 points) than for the *GBF* and *combined* groups (9.17 and 12.17 points), though 1-way

ANOVA did not result in a statistically significant difference between the four groups: $F(3,20) = 0.57, p < 0.64$. When analyzing performance in KOM, the participants' scores indicated that the *visual* and *GO* groups performed better than the *GBF* and *combined* groups; see Figure 36(b). This difference was however statistically insignificant: $F(3,20) = 0.83, p < 0.49$.

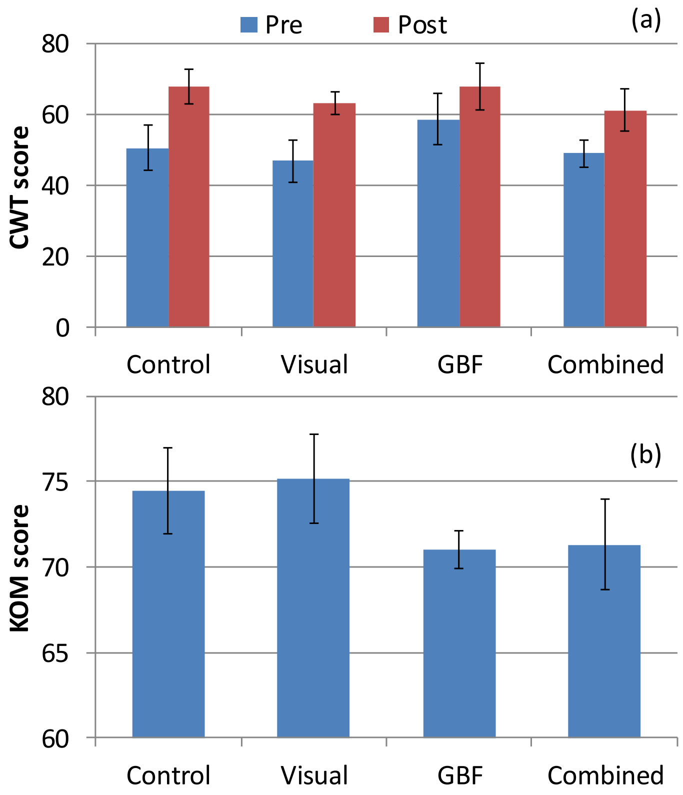

Figure 36 (a) Average CWT score during pre- and post-test (b) Average KOM score during post-test.

In summary, participants in the *control* and *visual* groups showed larger improvements in CWT and higher performance during KOM than the other two biofeedback groups. Considering that the *control* and *visual* groups had a higher level of arousal during post-task, it is possible that high arousal could have facilitated both tasks.

However, correlation analysis between performance scores and arousal at post-test reveals only a weak positive correlation; see Table 12. Another possibility is that because the control and visual treatments are less taxing, participants in these groups reach the post-test with lower mental fatigue than participants in the *GBF* or *combined* treatments, which require an intense focus on breathing rate to prevent the game from increasing in difficulty.

Table 12 Pearson correlation coefficient ρ between task performance in CWT and KOM and arousal

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

5.4.4 Subjective analysis

For a qualitative assessment of the results, the participants were also asked to complete a Game Biofeedback Questionnaire; see Appendix A. When asked *"were you able to concentrate on the game?"* all 24 participants responded positively. When asked "w*ould you find a video game like this a good diversion when you are feeling stressed?"* on a 3-point scale (1: no; 2: maybe; 3: yes), participants in the *Combined* group gave the highest average rating of 2.83 while the other groups all had a rating of 2.5; see Figure 37(a). When asked "*How enjoyable did you find playing the game?*" on a 5-point scale (1: very boring; 5: very enjoyable), *visual* group had the highest rating of 4.33, with *combined* group being the lowest with 3.83; see Figure 37(b). A 1-way ANOVA across groups did not indicate a statistically significant difference: Diversion: $F(3,20) = 0.36, p < 0.78$; Enjoyability: $F(3,20) = 0.62, p < 0.61$. Although differences between groups are not statistically significant, these results provide an interesting perspective: participants found *combined* group as the best distractor from stress but did not find the game as enjoyable as the other groups.

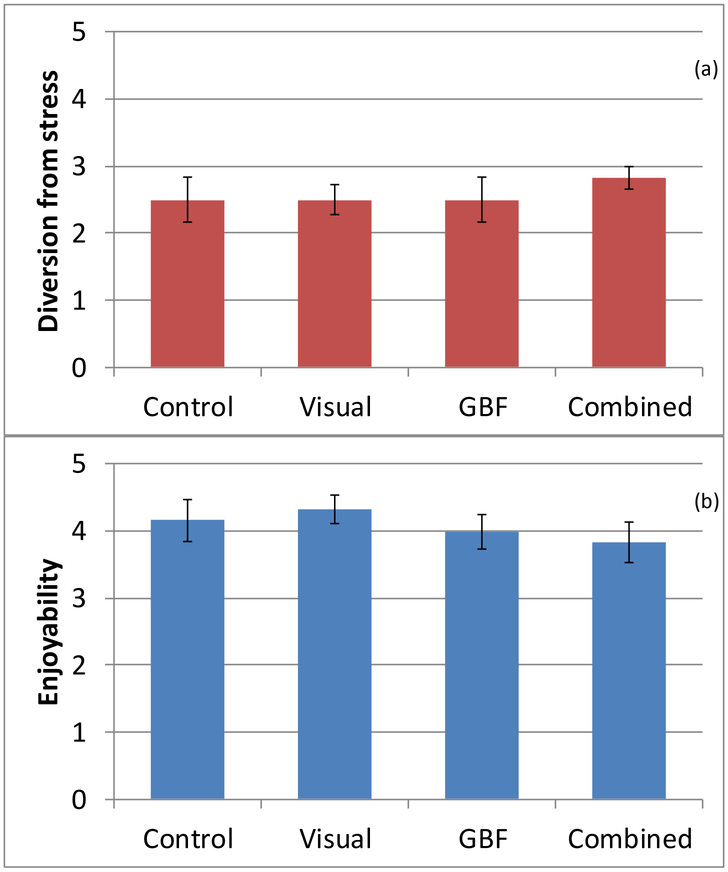

Figure 37 Subjective ratings. (a): Diversion from stress (b): Enjoyability.

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

5.5 Discussion

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

5.5.1 Skill acquisition and retention

The experiments in this chapter evaluated the three biofeedback mechanisms in the game (and a control group) by their effectiveness in teaching relaxation skills and transferring these skills to a subsequent stressor. Compared to the *visual* group the superior performance of the two groups receiving game adaptation based biofeedback (i.e. *GBF* and *combined*) in acquiring deep breathing skills can be explained in terms of the behavioral learning paradigm of instrumental or operant conditioning. Instrumental conditioning uses reinforcement/punishment to increase/decrease a behavior. GBF based relaxation training can be classified as passive avoidance operant conditioning (Grant 1964) in which a participant learns behaviors to prevent the occurrence of aversive stimulus (game penalty in this context). Therefore, during GBF training, game penalty acts as a deterrent against unhealthy breathing behavior.

Acquisition of relaxation skills and their control/execution can be explained via a two-step process: feedforward and feedback (Lacroix 1986). In a first step (feedforward step) the subject uses a previously learned behavior to accomplish a given task (e.g. relaxation) (Hayes-Roth, Pfleger et al. 1995). This generally happens during the initial phases of the treatment session where the participant can rely on previously learned skills (attained from initial DB sessions, instructions, and/or prior experience). This continues until user's actions no longer leads to the desired response (i.e. breathing performance reaches an asymptote) or they have tried all the actions in their repertoire. At this point, the emphasis switches to a more bottom-up approach of trial and error (feedback) to develop new actions or refine existing ones to accomplish the relaxation task. During this step, appropriate manipulation of the feedback mechanism helps the user abandon unhealthy breathing behaviors, reinforce relaxing ones assisting them to reach the target state. This also explains why *GBF* and *combined* methods, with their inherent bottom-up learning approach (i.e. rewards/penalties based on user’s arousal level), is more effective for relaxation skill training.

GBF based skill acquisition may be viewed as a combination of top-down and bottom-up learning; top-down because users learn declarative knowledge first in the form of instructions, and bottom-up because users modify their behavior based on the response from the game i.e., a stimulus-response driven process. While both top-down and bottom-up learning may be involved in teaching self-regulation skills with GBF, it is the latter that plays a more significant role as observed in these experiments. Results from the present study indicate that bottom-up learning with game adaptation is more effective in inducing relaxation than the top-down method of presenting explicit information with visual biofeedback. This observation is further strengthened by the results from the study presented in Chapter 4, where the game biofeedback approach is compared with deep breathing based self-regulation training. In this study, participants in the paced breathing group were provided with instructions and a pacing signal to practice deep breathing i.e. top-down learning. In contrast, the GBF group was presented biofeedback in the form of game adaptation i.e. bottom-up learning. The results showed the GBF based approach resulted in higher skill acquisition and retention during subsequent tasks.

Skill acquisition with game biofeedback and games in general can be explained from a neuronal perspective. Performing goal directed tasks i.e., playing a videogame, leads to dopamine[31] release in the striatum (Koepp, Gunn et al. 1998). Dopamine release is an indicator of memory storage events and attention (Achtman, Green et al. 2008), and is also involved in learning stimuli or actions that predict rewarding or aversive outcomes. In a study on the effects of videogame play on striatal dopamine releas,e Koepp, Gunn et al. (1998) showed a monotonic increase in dopamine levels during gameplay. They also found that the levels stayed higher (compared to baseline) after the gaming session ended. Since dopamine release is associated with memory storage, videogames may facilitate better learning of relaxation skills. It may further assist in detecting physiological stress triggers (i.e. improving perception of stress), and reinforcing relaxation behaviors.

The current study showed that the two game-adaptation treatments (*GBF*, *combined*) led to better transfer of relaxation skills during the subsequent stress-inducing tasks than visual biofeedback. This can be explained via *stimulus generalization* where a conditioned behavior (slow deep-breathing) learned in response to one stimulus (game penalty and high arousal) is elicited in response to another similar stimulus (stress inducing post task); see chapter 4 in Ormrod and Davis (2004). The skill transfer result is also consistent with previous studies on *contextualized learning*, a mechanism that couples learning with real-life experience and context (Dirkx, Amey et al. 1999). According to this view, combining virtual objects (e.g. videogames in this context) with real-world tasks (e.g. deep breathing during stressful situations) provides meaningfulness

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

to otherwise abstract physiological information (Herod 2002). This allows the player to internalize the relaxation process while performing a task, which leads to improved transfer of skills. To maximize retention of skills to subsequent tasks, first principle of transfer is also relevant. It states that “when stimuli and responses are similar in two situations, maximal positive transfer[32] occurs” (Osgood 1949, Ormrod and Davis 2004) . This suggests that training should be done under a number of different contexts to maximize transfer.

This study also showed that the *combined* treatment leads to fastest acquisition of deep breathing (see Figure 35), followed by *GBF*. All the participants in these two groups were able to reach the target BR within the 6 training sessions. In contrast, only 1/6 participants in the *visual* treatment and none in the *control* treatment could reach the target BR. Further analysis showed that that 4/6 participants in the *visual* group were able to lower their BR to 10 bpm and maintain it during treatment. This suggest the need for longer treatment sessions that continue until the participant acquires deep breathing skills –as opposed to the fixed length treatment session used in this study. This is similar to the training paradigm used by Goodie and Larkin (2006) where they set a dual stopping criterion for the training- participant reaching the target HR or 3-two hours sessions, whichever happened first. In contrast with the treatment groups, the *control* group did not acquire relaxation skills, an expected result since videogames are generally designed to increase the arousal levels rather than relax (Buckley and Anderson 2006).

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

5.5.2 Task performance and multi-tasking

The results in this chapter indicate that participants in the *visual* and *control* groups attained marginally higher scores during the post-tasks than those in the *GBF* and *combined* groups (though the differences were statistically insignificant); see Figure 36. Taken together with the physiological indicators, this may imply that higher arousal leads to higher task performance. However, correlation analysis showed only a weak positive correlation between arousal and performance; see Table 12. Compared the arousal levels during the two post-tasks showed that participants had higher arousal during KOM- a novel task, relative to CWT (used during both pre- and post-test). This is in agreement with Goodie and Larkin (2006), which showed that the participants' ability to lower their HR reactivity degraded during a novel task.

The proposed GBF intervention requires that participants perform two tasks concurrently: control their breathing and play the game. This can lead to task interference and negatively impact performance in both tasks. The multi-resource theory introduced by Wickens (2002) helps predict task interference and performance in various tasks (multi-task situations). Several studies (Pashler 2000, Dzubak 2008) have shown that multi-tasking results in lower performance on individual tasks, largely due to increased mental workload, increased working memory demands and task switching overhead. The results in this chapter show that the two game-adaptation treatments (*GBF* and *combined*) lead to improved performance on the deep breathing task while achieving only slightly lower (and statistically insignificant) performance on the post-tests than the *visual* and *control* groups. Multi-tasking performance can improve if one task provides additional information for completing the other task –as opposed to compete for resources (Solovey, Lalooses et al. 2011). Such seems to be the case in the GBF intervention, where BR information is dynamically integrated in the game. Such integration makes the cues indicating high breathing rate more salient allowing for more efficient task dual task performance and assists in subsequent tasks also. On similar lines, prior work (Wickens 2002) has shown that dual task performance improves if the two tasks utilize resources from separate dimensions (e.g. visual and auditory) as opposed to both competing for the same resource. This is consistent with comments from the participants regarding auditory feedback. Using both auditory and visual channels for biofeedback in the game would lead to lower task interference and better performance and skill transfer.

5.6 Conclusion

The effectiveness of biofeedback games depends on a number of variables, a few of which have been examined in past research. These include game genres (Russoniello, O'Brien et al. 2009), game difficulty (Chanel, Rebetez et al. 2011, Al Rihawi, Ahmed et al. 2014), score contingency (Larkin, Zayfert et al. 1992), sign of feedback (e.g., positive vs. negative) (Prinzel, Pope et al. 2002), type of feedback controller (Parnandi and Gutierrez-Osuna 2014), and physiological signal for biofeedback (e.g. HR, EDA, EEG) (Dekker and Champion 2007, Nacke, Kalyn et al. 2011). This chapter explored whether feedback in GBF should be delivered through a visual channel or through subtle changes in the game i.e. game adaptation. To answer this, the two forms of biofeedback were compared by their ability to facilitate acquisition of deep breathing skills and retention of these skills. The results indicate that biofeedback delivered through game adaptation is more effective than visual biofeedback, and that a combination of the two is more effective than either form of biofeedback in isolation. Furthermore, the *combined* biofeedback approach results in a faster acquisition of deep breathing skills.

In the previous two chapters, this dissertation has evaluated different physiological signals and biofeedback modalities in GBF and their influence on the skill acquisition process. Along with skill acquisition, the effectiveness of a stress self-regulation intervention is also determined by its ability to help users retain the skills once biofeedback is removed (i.e., extinction). The effectiveness of GBF in increasing resistance to extinction remains to be tested and the next chapter addresses this gap and evaluates the effect of reinforcement scheduling in GBF on skill retention.

6. PARTIAL REINFORCEMENT IN BIOFEEDBACK GAMES

Having validated the efficacy of the GBF approach in teaching relaxation skills, this chapter will focus on retention of learned skills, i.e., once the biofeedback is removed. As discussed in Section 3.3, GBF is based on the concept of instrumental conditioning[33]. In the past, instrumental conditioning methods have been successfully used for behavior change and teaching control of visceral functions (Miller 1978), including heart rate (McKinney, Geller et al. 1980) and electromyography (Cohen, Richardson et al. 2001). Researchers have also combined instrumental conditioning concepts with biofeedback games to develop interactive tools for stress training (Bouchard, Bernier et al. 2012, Sonne and Jensen 2016). While the effectiveness of biofeedback games in stress training has been studied in the past, there has been minimal work on investigating the effect of biofeedback games in improving resistance to extinction[34].

A factor that plays an important role in increasing resistance to extinction is the reinforcement schedule (Hatch 1980, McKinney, Geller et al. 1980, Cohen, Richardson et al. 2001, Voerman, Sandsjö et al. 2004). A reinforcement schedule determines the relationship between an instrumental response and its consequence[35] (Domjan 2014). These schedules can be classified into continuous reinforcement (CRF) and partial (or

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[33] Instrumental conditioning refers to the modification of behavior based on the consequences (rewards/penalties) of voluntary actions (Grant 1964, Furedy and Riley 1982).

[34] Resistance to extinction refers to the ability to maintain learned skills once biofeedback is removed.

[35] In other words, a reinforcement schedule determines which instances of the responses are reinforced or penalize and it influences how an instrumental response is learned and maintained.

intermittent) reinforcement (PRF). In a CRF schedule, reinforcement is presented after every elicitation of the target response. In contrast, in a PRF schedule, reinforcement is presented on a fraction of the elicited target responses; see section 6.2.2 for more details. Prior work on partial reinforcement scheduling has shown that the less often a behavior is reinforced during training the harder it is to extinguish. This is known as the as partial reinforcement extinction effect (PREE) (Wagner 1961, Domjan 2014). While reinforcement scheduling in biofeedback systems has been studied in the past, we are not aware of any investigations of its effects on adaptive biofeedback games for stress training. The goal of this study is to evaluate the effectiveness of PRF and CRF scheduling in GBF to maximize skill transfer to subsequent tasks. The working hypotheses are:

- *H1*: Partial reinforcement in GBF will lead to higher resistance to extinction of deep breathing skills after training due to PREE. In other words, participants who receive the PRF-GBF training will maintain slow breathing rate and a lower arousal longer in the post-training period than those who receive continuous GBF training.
- *H2*: Continuous reinforcement GBF will lead to a faster acquisition of deep breathing skills compared to a partial reinforcement schedule, due to a higher exposure to the reinforcement during gameplay.

6.1 Related work

Several studies have investigated the effects of partial reinforcement or intermittent feedback on skill acquisition and resistance to extinction (Ferster and Skinner 1957, Brener, Kleinman et al. 1969, Gatchel 1974, Morley 1979, Ely and Hart 1980, Gamble and Elder 1982, Gamble and Elder 1990, Cohen, Richardson et al. 2001, Voerman, Sandsjö et al. 2004). In early work, Gatchel (1974) compared a CRF schedule (100% reinforcement) against fixed ratio schedules of 20% (FR 5) and 10% (FR 10) in terms of modifying (increasing and decreasing) the user's heart rate (HR). In the fixed ratio schedule, every 5th (FR 5) or 10th (FR 10) response was reinforced by providing HR biofeedback to the user through a visual display. The author found that the CRF schedule led to the highest increase in HR compared to the FR 5 and FR 10 schedules. When comparing the deceleration of HR, the three feedback groups (CRF and two PRF) performed better than control groups. The author also conducted a replication study and again showed that the ability to control one's HR varies systematically with the frequency of feedback. No results on resistance to extinction of skills were presented. Gamble and Elder (1982) investigated the effects of auditory biofeedback along with verbal encouragement on modifying (increasing/decreasing) participant's diastolic blood pressure (BP). The authors compared a CRF schedule (i.e. 100%) with PRF scheduled according to a variable ratio of 50% and 25% reinforcement (i.e. feedback was presented to the user probabilistically on 50% or 25% of the desired responses) and a no feedback condition. They found that, compared to PRF and no feedback conditions, the CRF condition led to faster acquisition of skills in changing the BP. They also found that participants in the PRF groups showed a greater resistance to extinction. In a follow-up study, they investigated the effects of different response magnitude criteria and feedback schedules (0%, 50%, and 100%) on acquisition and extinction of diastolic BP change (Gamble and Elder 1990). They found that CRF schedules of positive reinforcement produced more rapid acquisition of bidirectional BP control than PRF and a control group. They also observed that partial feedback was superior to the control group in modifying BP. The authors reported that the PRF condition showed marginally greater resistance to extinction than the other groups. McKinney, Geller et al. (1980) studied the effects of contingently faded biofeedback on reduction of heart rate. The authors compared CRF schedule with faded PRF (75% reinforcement schedule followed by 50% and 25%) feedback that also included contingent rewards based on meeting certain performance criteria. Their results indicated that participants receiving the contingent faded PRF biofeedback had a significantly larger reduction in HR during the training session compared to the CRF group, and this effect was maintained during the extinction session. They also mentioned that, while HR reduction can be attained in a few sessions (3 sessions in their case), multiple training sessions may be necessary to develop resistance to extinction. Their results indicated that a combination of reinforcement fading (75% to 50% to 25%) and contingent reinforcement is an effective paradigm for teaching individuals to reduce their HR and retain these skills post training.

In more recent work, Cohen, Richardson et al. (2001) compared continuous and partial reinforcement schedules (variable ratio, variable interval, fixed ratio, fixed interval[36]) by their ability to increase forearm muscle tension. They trained participants with three sessions of biofeedback followed by one extinction session (no biofeedback). Their results indicated that CRF showed the highest EMG response followed by fixed ratio and variable interval PRF schedules. In extinction trials, the authors found considerable resistance to extinction in the EMG response across all groups. The VR and VI schedules were found to be most resistant to extinction, and CRF the least. In other words, the authors found the EMG response to be consistent with the PREE (Wagner 1961, Domjan 2014) i.e. higher resistance to extinction under PRF relative to CRF schedules. In a related study, Voerman, Sandsjö et al. (2004) studied the influence of partial schedules of myofeedback[37] training to teach users to relax the trapezius muscle. Feedback was provided in the form of an auditory tone based on a pre-determined relaxation level for the muscle. They chose an interval schedule for providing feedback with intervals of 5s, 10s or 20s; for example, in a 5s schedule, whether or not feedback should be provided was evaluated every five seconds. The authors found that a 10s-variable interval schedule resulted in the highest level of muscular relaxation. They also evaluated resistance to extinction of the trapezius muscle post the training. However, they did not find any of the three schedules to be resistant to extinction indicating minimal retention of learned skills. The authors explained that the training period may be too short to learn and retain the motor skills.

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[36] See section 6.5 for definitions.

[37] Myofeedback refers to detection of electromyographic signal from the muscles of interest (i.e., muscular activity) and presentation of this information to the user This form of feedback is generally used to reduce muscular tension.

To summarize, researchers in the past have evaluated the effects of continuous and partial reinforcement on modifying user's physiology (EMG, HR and BP) and behavior (Azrin, Rubin et al. 1968, Mackintosh 1974, Gamble and Elder 1990, Skinner 1990, Cohen, Richardson et al. 2001, Sangha, McComb et al. 2002). However, much of the prior work on skill acquisition and retention has been performed using traditional biofeedback systems. To date, no work exists on studying the effects of scheduling of biofeedback in games for stress training. The present study addresses this gap.

6.2 System overview

To evaluate the scheduling of reinforcement in GBF, the open-source casual game – Frozen Bubble – described in Chapter 3, was used. Based on the results in the previous studies in this dissertation (see Chapters 4 and 5), breathing rate (BR) was used as the physiological signal for biofeedback in the game and the *combined* method for biofeedback presentation i.e., the user is presented breathing information both through a visual display and game adaptation.

6.2.1 Continuous reinforcement with GBF

Under the continuous reinforcement (CRF) schedule, the game adaptation mechanism checks the user's breathing trend: if the user's $BR > 6 \; and \; \Delta BR \geq 0$ (i.e., high BR and increasing), a game penalty in the form of autoshooting of bubbles is applied for 3s. The auto-shooting frequency is governed by a piece-wise linear function of the player's BR –see Section 3.3. In addition, the user is also provided an auditory stimulus to the user in the form of an *Error* sound along with the game penalty. This was introduced following the user feedback from the prior study (Chapter 5). If the user's breathing trend is in the desired zone (i.e., $BR \leq 6\ or\ \Delta BR < 0$), no penalty is applied. Therefore, in CRF-GBF, all breathing responses that did not meet the target breathing criterion are penalized; see Table 13.

6.2.2 Partial reinforcement with GBF

To incorporate partial reinforcement (PRF) schedule in GBF, the proposed implementation considers the user's breathing response to consist of a series of individual breaths distributed over time (Hatch 1980). Namely, every breathing response can be probabilistically chosen to be reinforced using the game adaptation mechanism described in Section 3.3. In the partial reinforcement paradigm, the system evaluates the user's breathing rate and slope every second. If the conditions for game penalty are satisfied (i.e., $BR > 6\ and\ \Delta BR \geq 0$), autoshooting is applied for 3 seconds with a probability determined by the reinforcement schedule, i.e., 75%, 50%, or 25%. Figure 38 presents a flowchart explaining the game adaptation process under a partial reinforcement schedule of 50%. The game penalty in PRF-GBF is applied according to a variable-ratio (VR) schedule. Under this schedule, reinforcement is applied after an unpredictable (but on average constant) number of responses has been elicited. For example, with a 75% PRF, 3 out of 4 responses will be reinforced. Therefore, on average 1.33 (i.e. VR 1.33) breathing responses with $BR > 6\ and\ \Delta BR \geq 0$ will result in game penalty. In other words, the PRF-GBF mechanism only applies penalty to a certain percentage of responses provided the conditions for game penalty (i.e. high and increasing BR) are satisfied. In contrast, in CRF-GBF every time a high and increasing BR is observed, the game penalty is applied; see Table 13.

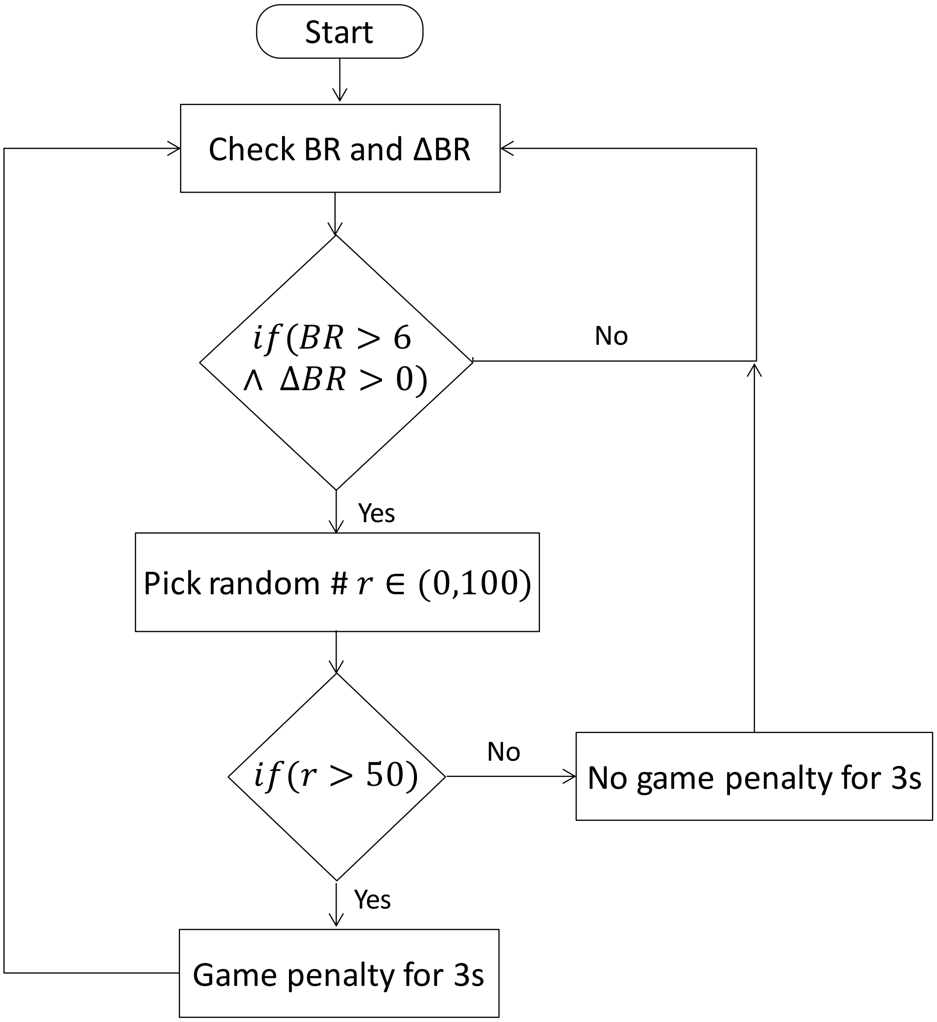

Figure 38 Game adaptation under a partial reinforcement schedule with 50% reinforcement. A continuous reinforcement schedule can be realized by setting $r > 0$ in the flow chart.

Table 13 Game adaptation under the continuous and partial reinforcement schedule

	$BR \leq 6 \text{ or } \Delta BR < 0$	$BR > 6 \text{ and } \Delta BR \geq 0$
$CRF - GBF$	No penalty	Game penalty
$PRF - GBF$	No penalty	Penalty based on reinforcement schedule

6.3 Experimental

Experimental trials were conducted as part of an independent study with each participant playing a single randomly assigned treatment (PRF-GBF or CRF-GBF) or a control condition (game only[38]). 15 participants (5 participants per group) were recruited for this study: 4 females and 11 males, age range of 19-28 years. Signed Institutional Review Board (IRB)[39]consent was received from each participant before the experimental session.

6.3.1 Protocol

The experimental protocol is summarized in Figure 39. It consisted of four phases: paced breathing, baseline, treatment, and extinction testing.

- Paced breathing: Participants follow an auditory pacing signal, which guides them to breathe at 6 bpm: inhaling for 4 sec and exhaling for 6 sec. This choice is motivated by prior work (Strauss Blasche, Moser et al. 2000) showing that a

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[38] In the control condition, participants play the Frozen Bubble game without biofeedback or displays of physiological information.

[39] Texas A&M Institutional Review Board (IRB) protocol number IRB2009-0420F.

respiratory pattern with a short inspiration followed by long expiration leads to a higher respiratory sinus arrhythmia (RSA). This phase lasts 5 min.

- Training: In the baseline phase, participants are asked to sit comfortably and play the Frozen Bubble game without any biofeedback or game adaptation. They are also asked to breathe at their normal pace. This phase provides the user practice with the videogame and helps compute user's baseline physiology without any pacing signal or biofeedback. The baseline phase lasts 5 min.
- Treatment: Participants are assigned to one of the three groups (*PRF-GBF*, *CRF-GBF* or *control)*. They play the corresponding version of the game for 3 sessions, each session lasting 5 min (15 min total) with a 1 min break between sessions. During this break, participants are given their relaxation score (see Section 5.3.4), and are asked to improve it. The relaxation score acts as a secondary reinforcer. During PRF-GBF treatment a faded feedback procedure was used. Under this protocol the reinforcement probability was gradually reduced in this order: 75%, 50%, and 25%, before the extinction testing (Hatch 1980, McKinney, Geller et al. 1980). The participants played the biofeedback game with the three reinforcement schedules for 5 min each.
- Extinction: The last session tests participants' ability to maintain a low breathing rate post-treatment, without any biofeedback reinforcement. This is again done in 3 sessions of 5 min each with a 1 min break in between. Participants are asked to maintain a low arousal state using the skills they acquired during the treatment sessions; however, no biofeedback or reinforcement is provided. In other words,

the participants, play a "vanilla" version of the Frozen Bubble game without biofeedback or displays of physiological information

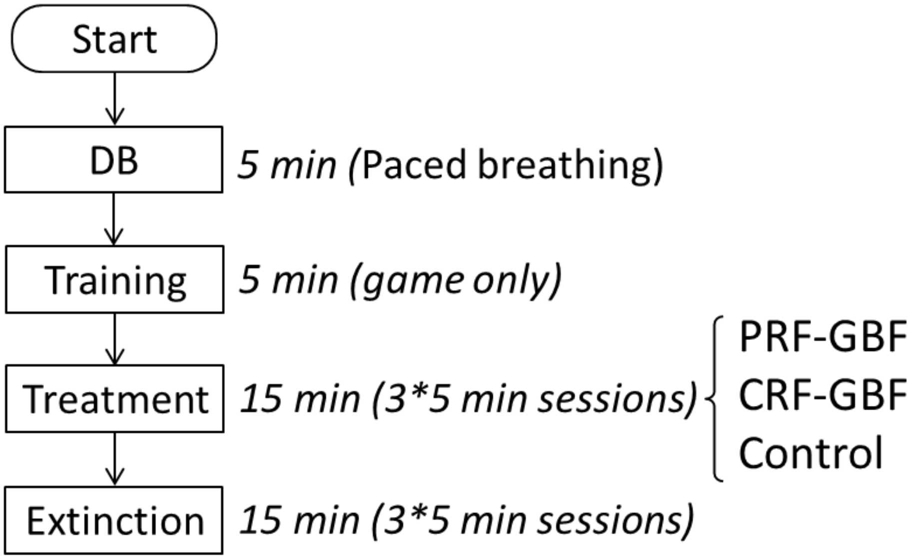

Figure 39 Experimental protocol with the four phases and their respective durations.

6.3.2 Instructions

Participants were given the following instructions at various points during the experiment.

- Common to the three groups
  - Before treatment. "*Relax, try to breathe slowly, maintaining your breathing rate around 6 bpm. Try to do the best in the game*"
  - Before extinction. "*Stay calm by using the skills you learned during the treatment session. Try to do the best in the game*"
- Common to the biofeedback groups

  - Scoring scheme. "*Your score will depend on both your game performance and how relaxed you are while playing the game. At the end of each game session, you will get two scores: your game score and relaxation score. Try to improve on both*"
- Specific to the biofeedback groups (before treatment)
  - CRF-GBF: "*The game will be affected by your breathing rate; higher BR will make the game more difficult. In addition, during gameplay you will be shown your BR and whether it is increasing or decreasing. You will also be presented with an auditory stimulus when your BR is high*"
  - PRF-GBF: "*The game may be affected by your BR; higher BR may make the game more difficult. In addition, during gameplay you will be shown your BR and whether it is increasing or decreasing. You may also hear an auditory stimulus when your BR is high*"

6.4 Experimental results

Figure 40 presents the average breathing rate of participants in the PRF-GBF, CRF-GBF, and control groups during the experiment (paced breathing, training, treatment and extinction phases). In the paced breathing phase, all groups have a similar breathing rate of approximately 6 breaths per min (bpm), which is the frequency of the pacing signal. In the game-only phase, all groups showed a high breathing rate, which is again expected since no biofeedback or pacing signal was provided to them. During the treatment phase, differences between the groups start to emerge, with the CRF-GBF and

PRF-GBF groups lowering their BR. The control group did not receive any biofeedback information and (as expected) maintained a high average BR. During the extinction phase, the PRF-GBF group had a lower breathing rate than the CRF-GBF group. Once again, no significant change was observed in the control group.

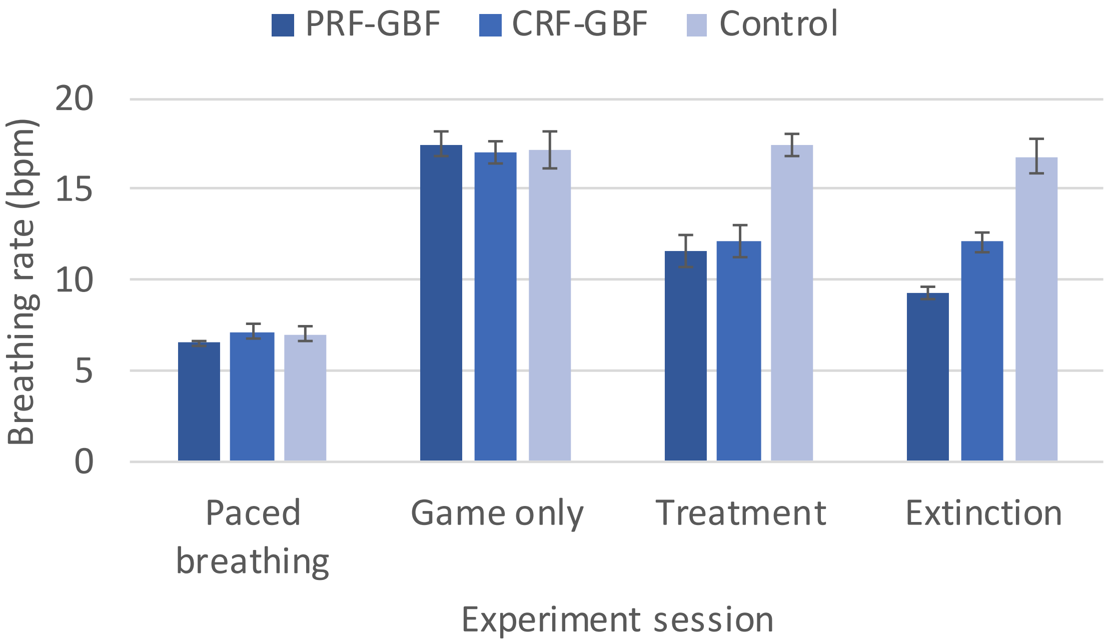

Figure 40 Average breathing rate for the three groups over the four experimental sessions. PRF-GBF: partial reinforcement game biofeedback; CRF-GBF: continuous reinforcement; GO: game only.

To further analyze this result, especially for the two GBF groups, the BR trend across the six sessions of treatment (3) and extinction (3) was studied. Results are shown in Figure 41. In the first treatment session (T1), both CRF and PRF groups showed a higher BR than during paced breathing session; CRF: 15.48 bpm, PRF: 15.14 bpm. The relatively high BR in this session for both GBF groups may be attributed to the fact that this session directly follows the game-only session, in which participants were breathing at their natural pace. Furthermore, this is the first time during the experiment when participants are exposed to the game biofeedback, and therefore are learning the game adaptation mechanism. It is also worth noting that, compared to the control group, both GBF groups showed a lower BR. The average BR continued to reduce in both GBF groups during the second and third treatment sessions (T2 and T3) with the PRF-GBF and CRF-GBF groups showing a similar trend.

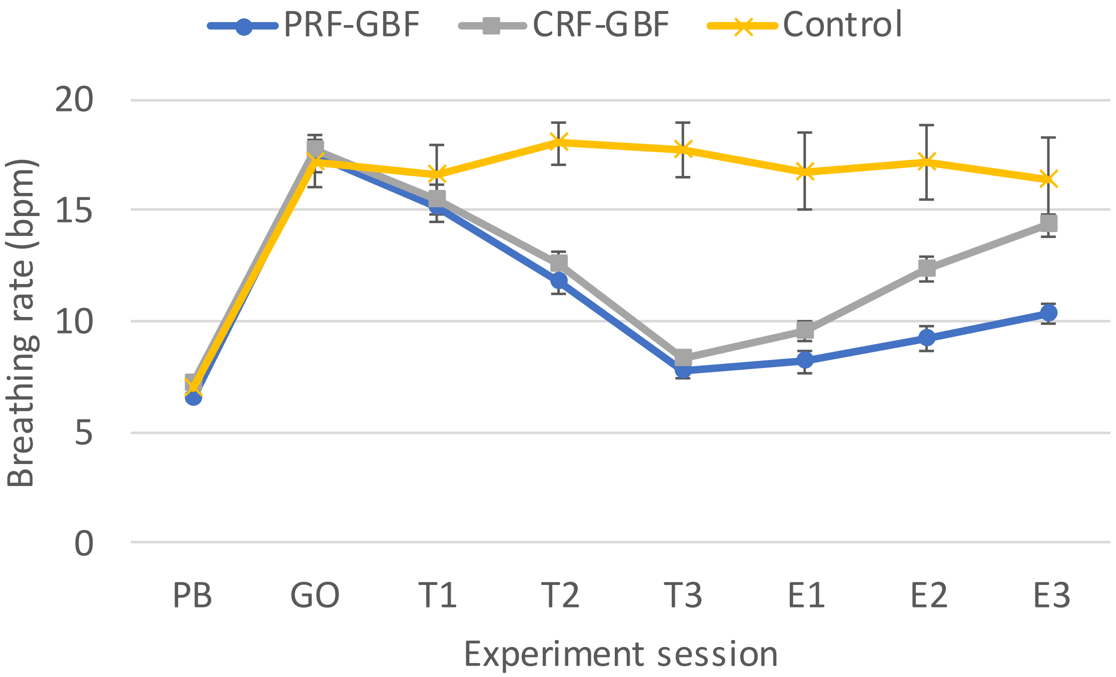

Figure 41 Breathing trend for the three groups over the course of the experiment. PB: paced breathing, GO: game only, T1-T3: treatment session, E1-E3: extinction session

Interesting trends start to emerge during the extinction phase; both GBF groups show an increase in BR values as the phase progresses, but the CRF group has a faster rate of increase. In the first extinction session (E1), the CRF group has a marginally higher BR than the PRF group (BR difference between PRF and CRF = -1.40 bpm). This trend continues in the second extinction session (E2) (BR difference = -3.13 bpm), and third extinction session (E3) (BR difference = -3.98 bpm). The BR values in the extinction phase indicate that, once the biofeedback is removed, participants in the PRF-GBF group are able to maintain a lower BR longer than the CRF-GBF group. These results indicate that partial reinforcement schedule led to a stronger resistance to extinction.

To evaluate the statistical significance of these results, a 1-way ANOVA on the change in breathing rate between the treatment phase and the extinction phase was performed. Comparing the average BR change between the two phases did not show a significant difference between the three groups: $F(2,12) = 2.03, p < 0.18$. However, a 1-way ANOVA comparing the two GBF groups showed a statistically significant difference: $F(1,8) = 14.31,\ p < 0.01$. A 2-way ANOVA between the groups was performed to compare the effect of time and treatment type. This analysis during the treatment phase showed significant main effects for both factors: treatment group: $F(2,36) = 48.8\ p < 0.01$ and time: $F(2,36) = 22.26,\ p < 0.01$ and a significant interaction effect between the two factors: $F(4,36) = 8.41,\ p < 0.01$. Similar trends are observed during the extinction phase with significant main effects for treatment: $F(2,36) = 35.7\ p < 0.01$. However, there is only a marginally significant effect of time: $F(2,36) = 18.55\ p < 0.06$, and an insignificant interaction between the two factors: $F(4,36) = 1.39\ p < 0.26$. A comparison between the F-ratio statistic between the two factors, indicates that the treatment type is a more important factor in terms of the differences observed between the BR in the three groups. This inference is further strengthened by the BR trend in the control group, which does not show much change over time.

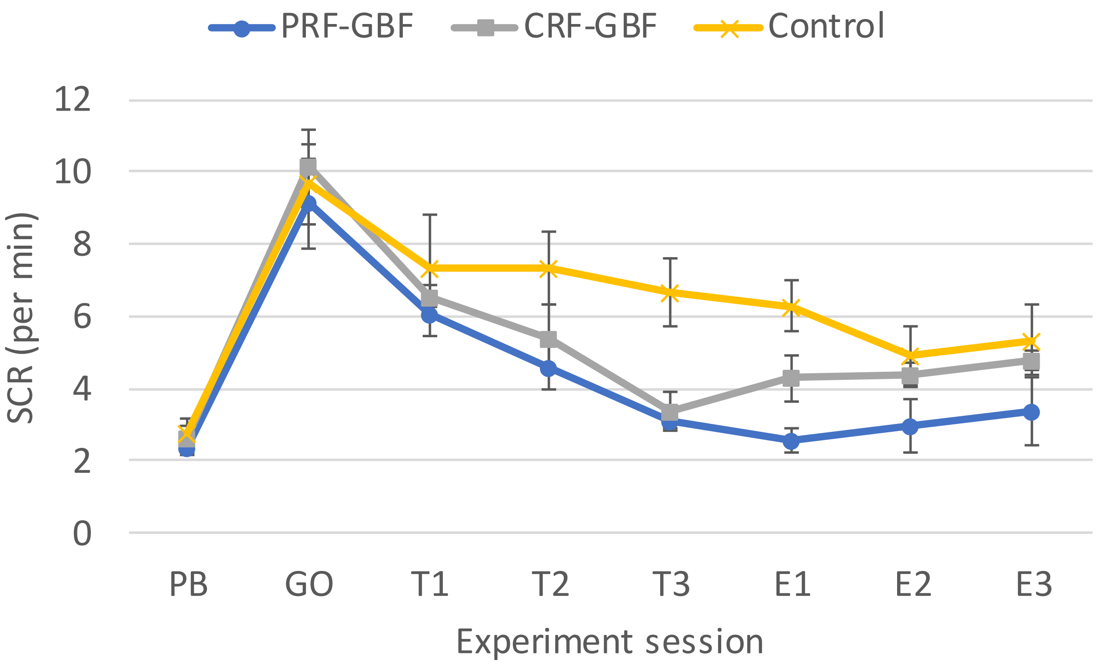

Figure 42 Average skin conductance response (per min) trend over the course of the experiment. PB: paced breathing, GO: game only, T1-T3: treatment session, E1-E3: extinction session

Physiological arousal was studied by measuring the skin conductance responses of participants during the treatment and extinction phase; these results are shown in Figure 42. During the paced-breathing session, all participants show a low SCR count. The SCRs rise to a higher value during the game only session. Differences between the three groups start to emerge as the treatment phase begins. During the three treatment phases, both game biofeedback groups show a reduction in SCR, with the CRF group showing a marginally higher SCR count than PRF group. The two biofeedback groups reach similar SCR count in the third treatment session (T3). This trend corroborates with those observed in breathing rates for the three groups.

During the extinction phase, the two GBF groups present some differences. In the first extinction session (E1), the CRF group shows an increase in the SCR levels attained during the final treatment session (T3). In contrast, the PRF group shows a reduction in the SCR count. As the extinction progresses (E2 and E3), both biofeedback groups show an increase in the SCR with the CRF group having a faster rise compared to PRF. This is consistent with the breathing rate trends, and indicates that the PRF group had marginally higher resistance to extinction. In contrast with the two GBF groups, the control group consistently has a higher average SCR count for all the treatment and extinction sessions. Participants in the control group showed a slow but steady reduction in SCR as the experiment progresses. This decrease may be attributed to the SCR habituation effect – a gradual reduction in sudomotor activity (SCR count and amplitude) and eventual disappearance with a repeated stimulus (Roth, Dawson et al. 2012).

A 1-way ANOVA comparing the three groups on the change in the SCR count between treatment and extinction phases did not show a statistically significant difference between the three groups, $F(2,12) = 0.86, p < 0.45$. A 2-way ANOVA between the three groups with treatment type and time as the two factors during the treatment phase showed a significant main effect for the treatment type, $F(2,36) = 8.43, p < 0.01$ and time, $F(2,36) = 6.04, < 0.01$. There was no interaction between the two factors during treatment, $F(4,36) = 0.78, p < 0.54$. Performing a 2-way

ANOVA during the extinction phase, revealed a significant main effect for the treatment type, $F(2{,}36) = 11.35, p < 0.01$, an insignificant effect for time, $F(2{,}36) = 0.22, p < 0.81$ and no interaction between the two factors, $F(4{,}36) = 0.63, p < 0.65$. This statistical analysis corroborates with the results observed for breathing rate and again indicates the importance of treatment type during treatment and extinction.

6.4.1 Subjective analysis

Subjective ratings from the participants were also collected using the Dundee Stress State Questionnaire (DSSQ) (Matthews, Szalma et al. 2013); see Appendix B. DSSQ provides an assessment scale for states associated with stress, arousal and fatigue and is a reliable (Helton 2004) and valid (Grier, Warm et al. 2003) measure of subjective stress state. Participants were asked to complete the questionnaire before the start of the treatment session, and again after the completion of the extinction session. Figure 43 presents the DSSQ ratings for two factors: relaxation and anxiousness. These results indicate that participants in the two biofeedback groups showed a marginal increase in the perceived levels of relaxation and reduction in anxiety. These changes were the highest for the PRF group followed by the CRF group, while the control group did not show any change between the pre- and post-assessment. Performing a 1-way ANOVA, resulted in a statistically insignificant difference between the three groups for relaxation $F(2{,}12) = 0.62, p < 0.56$ and anxiousness $F(2{,}12) = 0.4, p < 0.68$.

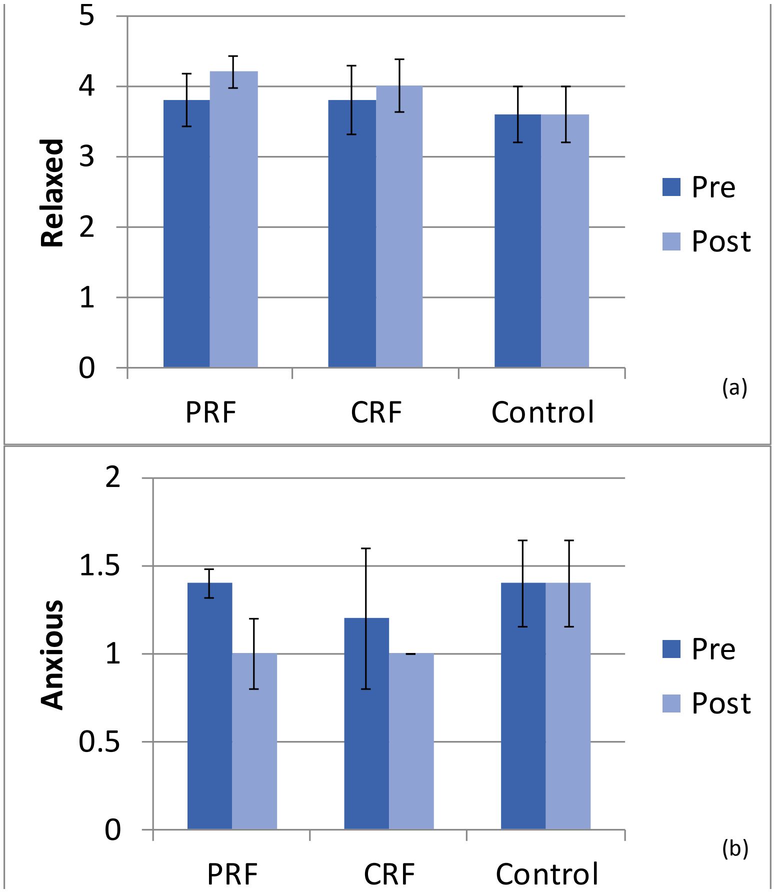

Figure 43 Dundee stress state questionnaire results prior and after the treatment. (a) Relaxation (b) Anxious

6.5 Discussion

Previous studies have generally used continuous schedules of reinforcement for biofeedback (Schwartz and Andrasik 2015), including those studies reviewed in the prior work sections in this dissertation (see Chapters 4 and 5), where reinforcement in the form of game penalty was presented for high arousal. While PRF schedules have previously been successful in improving resistance to extinction (Gatchel 1974, Hatch 1980, Cohen, Richardson et al. 2001, Voerman, Sandsjö et al. 2004), these studies have not investigated reinforcement schedules for adaptive biofeedback games for teaching relaxation skills.

This chapter studied the effects of reinforcement scheduling in game biofeedback for stress training, especially for increasing the resistance to extinction of deep breathing skills. The primary aim of this study was to compare the effectiveness of a variable-ratio partial reinforcement schedule with a continuous reinforcement schedule in their ability to help participants acquire relaxation skills and promote skill transfer. The results indicate that reinforcement schedules during biofeedback are an important factor for improving resistance to extinction.

During the treatment session, both partial and continuous biofeedback schedule groups showed a reduction in BR and arousal. A comparison between the pace of skill acquisition (i.e. how quickly the participants were able to lower their BR) showed that both CRF and PRF schedules have similar rate of acquisition of deep breathing skills. This contradicts hypothesis H2 and prior work on the influence of reinforcement schedules on skill acquisition (Gamble and Elder 1982, Cohen, Richardson et al. 2001). These studies have shown that CRF schedules leads to faster rates of acquisition due to higher exposure to the reinforcers. The results observed in this chapter may be attributed to the 3s duration used for CRF-GBF i.e., game penalty of 3s for fast breathing and no game penalty for slow breathing. This may have reduced the number of times the participants were exposed to the reinforcer (game penalty) compared to a continuous schedule where breathing is checked every second (i.e., the sampling rate of the sensor) and the reinforcement is provided accordingly.

The analysis on resistance to extinction showed that partial reinforcement leads to higher resistance, as measured by retention of deep breathing skills following treatment. This result validates hypothesis H1, and can be explained by the partial reinforcement extinction effect (PREE) (Wagner 1961, Domjan 2014). PREE states that the less frequently a behavior is reinforced, the harder it is to extinguish. The explanation behind PREE is that a lack of reinforcement is easier to detect following a CRF schedule than following after a PRF schedule, which is known as discrimination hypothesis (Amsel 1962). As noted by (Domjan 2014), if the user is provided with a reinforcement (reward or penalty) after every response during training (i.e. CRF schedule), they implicitly expect the reinforcement stimulus to guide their behavior after the training, as well. In other words, a CRF schedule leads to a greater expectation of reinforcement compared to PRF. This can have a frustrating effect during the extinction phase (Amsel 1962, Domjan 2014) and, in turn, lead to a more rapid extinction of the learned skills. In contrast, during training with a PRF schedule, only a percentage of randomly chosen responses are reinforced. PREE experiments in the past have shown that a PRF schedule has fewer frustrating reactions and that participants elicit the desired behavior longer compared to a CRF schedule during training (Mackintosh 1974, Cohen, Richardson et al. 2001, Sangha, McComb et al. 2002).

While this study showed encouraging results for both acquisition and retention of skills, it is difficult to compare these findings with prior work, especially those of extinction since there has been minimal research on studying extinction in a biofeedback-game setting or for teaching deep-breathing skills. Another difficulty, as noted by Cohen, Richardson et al. (2001), arises when comparing these results with the prior work on schedule reinforcement. Much of the prior work on this topic used animal (e.g. a mouse) to perform lever press operation (instrumental response) to get a reward. In these experiments, the animal has to move around and/or operate an external device. This is in contrast with a biofeedback mechanism, such as the one used in GBF, where the participant controls an internal physiological variable. Furthermore, operations such as lever pressing are discrete in time whereas breathing and gameplay are both continuous processes.

6.6 Conclusion

Feedback is important in the process of learning and can be considered a form of instrumental conditioning, as first described by Skinner (1953). An important variable in instrumental conditioning for skill retention is the schedule of reinforcement (Hatch 1980, Cohen, Richardson et al. 2001), which describe the relationship between responses and reinforcement. The current study integrated partial reinforcement scheduling with game biofeedback and tested its effectiveness for increasing resistance to extinction of deep breathing skills. The results from the experimental trials indicate that training with partial reinforcement scheduling does not reduce skill acquisition rates compared to training with a continuous schedule. More importantly, the PRF schedule led to higher resistance to extinction, as observed in both BR and EDA measurements. This paradigm of partial reinforcement in GBF can be easily extended to other games and biofeedback systems, and be used in the home and workplace for long term practice and skill retention.

7. CONCLUSIONS FROM THIS DISSERTATION

Videogames have been shown to have desirable outcomes in terms of behavior change, stress recovery, and other health-related changes (Baranowski, Buday et al. 2008). This prior work was a main motivation for using videogames to teach stress self-regulation and develop behavioral interventions for stress training. The proposed approach, termed GBF, combines the concepts of biofeedback and instrumental conditioning with games. The approach consists of monitoring user's physiology during gameplay, mapping them into estimates of stress levels, and adapting the game in a way that promotes relaxing behavior such as slow, deep breathing.

Within this broad framework, this dissertation focused on three research goals. In the first goal, this dissertation evaluated various physiological signals (breathing rate, heart rate variability, and electrodermal activity) that span across the dimensions of degrees of selectivity in measuring arousal and voluntary control in their effectiveness in lowering arousal. With this, the physiological signals appropriate for stress training and the associated bio-signal processing techniques for real-time arousal estimation were identified. The second goal investigated different methods of biofeedback presentation (e.g. visual feedback, game adaptation) during gameplay. Selection of an appropriate biofeedback mechanism is critical since it provides the necessary information to improve the perception of visceral states (e.g. stress) to the user and guide them towards the target state. Finally, the third goal focused on retention of skills and compared the effect of reinforcement scheduling (partial and continuous reinforcement) in a game on skill learning and retention.

7.1 Summary of findings

7.1.1 Physiological modalities for relaxation skill transfer in biofeedback games

Chapter 4 evaluated the effectiveness of various physiological signals in GBF for stress training and skill retention. The study compared three physiological signals (*EDA*, *HRV*, and *BR*) for biofeedback in the game. These signals can be measured noninvasively with commercial wearable sensors and allows for an examination of the tradeoffs in the selectivity vs. voluntary-control space. The experimental trials compared the three biofeedback modalities for game adaptation against a control group (game only) and a standard treatment (deep breathing) by their ability to teach relaxation skills and promote skill retention during mild stressors immediately following the GBF training session. The results show that breathing-based game biofeedback is more effective than the other groups in terms of lowering breathing and physiological arousal (measured by EDA, and HRV) during the GBF treatment session and transferring relaxation skills to a subsequent cognitive stressor. A statistical analysis of the results showed that, compared to selectivity in measuring arousal, the degree of voluntary control is a more important factor in facilitating skill learning and retention.

7.1.2 Visual biofeedback and game adaptation for relaxation skill transfer

Chapter 5 examined three biofeedback mechanisms in GBF (*visual biofeedback*, *game biofeedback* and *combined biofeedback*), and studied their effectiveness in assisting users with stress self-regulation. In *visual biofeedback*, the physiological information is presented by displaying the player's physiological variables on the game screen, but the game does not adapt to the player's arousal level. In contrast, in *game biofeedback*, the game adapts based on player's physiology but this information is not overtly presented to the player. The third method, *combined biofeedback*, delivers visual and game biofeedback simultaneously. A study was conducted with the three biofeedback groups as independent variables and physiological indicators of stress as dependent variables. Here, a *game-only* group, where participants played a game with no biofeedback, served as a control group. Experimental results indicate that *GBF* outperforms *visual biofeedback* in terms of lowering arousal during treatment and transferring these skills to a subsequent cognitively demanding task not used during treatment. However, these experiments also indicated that delivering simultaneously both forms of biofeedback leads to higher skill acquisition and transfer than delivering them in isolation. Finally, the learning curve of each form of biofeedback in the game cognitively demanding tasks was also evaluated and showed that *combined biofeedback* methods leads to a faster acquisition of skills compared to the other groups.

7.1.3 Partial reinforcement in biofeedback games for resistance to extinction

Chapter 6 explored the effectiveness of reinforcement schedules to teach relaxation skills and promote resistance to extinction. Skill retention over time depends not only on the training method and dosage requirements but also on the reinforcement schedule. This chapter focused on the resistance to extinction of deep breathing skills once the biofeedback is removed. It compared two reinforcement schedules: continuous and intermittent reinforcement. An experimental trial showed that both schedules of reinforcement in GBF showed similar pace of acquisition of deep breathing skills. In contrast, the PRF schedule significantly higher retention of deep breathing skills during the extinction phase compared to the CRF schedule.

7.2 Limitations

While this dissertation presented some encouraging results in highlighting the effectiveness of the GBF approach in reducing arousal and promoting skill transfer, there are a few shortcomings which are discussed next.

Controlled settings: The experimental trials were conducted in a controlled lab setting with cognitive stressors that may not capture the complexity of real-world scenarios. Furthermore, the studies focused on short-term treatment sessions and assessment of skill transfer on immediate subsequent tasks. Additional work is needed with extended multi-session training in real world, ambulatory settings to determine the long-term effects of game biofeedback.

Training protocol for physiological signals: The experiments in Chapter 4 compared three physiological signals for biofeedback: EDA, HRV, and BR. Results indicated that for a short-term GBF training session, BR is well suited as a biofeedback modality. However, further work is needed to develop appropriate biofeedback training paradigms for other physiological signals (i.e., EEG, EMG) including those that are under minimal voluntary control. This will include investigating the effect of treatment durations, since longer training periods may be needed to help improve the perception of certain visceral responses (e.g. states of high arousal) and to teach participants control of signals that are not under complete voluntary control.

Prior experience with deep breathing: The majority of the participants in the studies did not have any experience with deep breathing, meditation or familiarity with biofeedback devices. However, this information was not used as an inclusion/exclusion criterion, and the effect of prior knowledge on self-regulation methods was not considered during data analysis.

Effects of instructions: During the experimental trials, participants were instructed to perform each task (e.g. gameplay, pre- and post-tests, deep breathing); see Sections 4.3.1, 5.3.2, and 6.3.1. However, the studies did not evaluate the effects of instructions on skill acquisition and retention of these skills (i.e., whether their performance would be affected based on the instructions), and remains open for further investigation.

Evaluator effects: Studies that are conducted in the lab can lead to e*valuator effect*, where the presence of the evaluator or experimenter may influence participant's behavior (Moraveji 2012). In these situations, the participants tend to perform in a way the examiner wants them to, in this way helping or at least trying to help the examiner. While these effects were minimized by providing scripted instructions to the participants during each phase of a study and minimizing interaction during the experiments, the possibility of evaluator effects in these results cannot be entirely ruled out.

Novelty factor: Most participants in the studies presented in this dissertation had no prior experience with biofeedback systems, biofeedback games or stress training methods. Therefore, it is reasonable to assume that the GBF system may have had novelty effects[40] on the user. However, this was not considered during the experimental trials and remains open for investigation.

7.3 Future work

The primary goal of this dissertation was to evaluate the effectiveness of biofeedback games in reducing arousal and promoting skill transfer. The studies lead to some interesting results and presented new directions for further investigation.

Respiratory parameters in GBF: Experiments in Chapter 4, showed that breathing rate as a biofeedback modality was effective in reducing arousal during gameplay and promoting skill transfer. For breathing-based game biofeedback, special consideration may be given to the ratio of expiration time to inspiration time (E/I ratio). As an example, using controlled breathing trials, Strauss Blasche, Moser et al. (2000)

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[40] Novelty effect refers to the improvement in performance when a participant is introduced to a novel technology. It has been posited that this occurs not due to an increase in learning but in response to the interest in the new technology.

have shown that short inspiration followed by long expiration leads to higher RSA (respiratory sinus arrhythmia) than long inspiration followed by short expiration. This is primarily because rapid inspiration inhibits vagal activity and increases the phasic HR, while exhaling activates the vagus nerve and therefore decreases HR. While participants during the experiments were guided to use a large E/I ratio during the paced breathing session (4-sec inspiration, 6-sec expiration), further training may be needed to teach effective breathing technique. The issue of hyperventilation is also pertinent to the GBF intervention. The normal (i.e., spontaneous) breathing rate for healthy adults is in the range of 12-20 breaths/min, and it is known that deliberate slow breathing can lead to disordered cardio-vascular regulation and even anxiety (Vaschillo, Vaschillo et al. 2006), which in turn inhibits parasympathetic activity and decreases HRV. In addition to BR, there are other respiratory variables including tidal volume, end-tidal CO_2, inspiration and expiration time, and breathing effort. Controlling these breathing parameters will require extended practice and may require a modified training protocol. Using these respiratory parameters for biofeedback will allow the experimenter to guide the user towards a slow deep rhythm while avoiding the unhealthy breathing patterns that lead to hypo or hyperventilation. Combined, issues of optimal E/I ratio, hyperventilation, and other respiratory parameters for biofeedback point to a need for further research on training protocols to teach proper deep-breathing technique.

Negative vs positive reinforcement instrumental conditioning: The GBF approach uses concepts of negative reinforcement i.e., eliciting desired behavior removes the aversive stimulus. In this setup, the users must lower their arousal level to progress in the game. This has been used in prior work for teaching stress self-regulation skills in military settings (Cannon-Bowers 1998). An orthogonal approach to this would be to use positive reinforcement. This would involve reducing game difficulty if the user is stressed and vice-versa. In a related prior work, Parnandi and Gutierrez-Osuna (2014) presented a biofeedback car racing game to assist a player maintain an optimum arousal level determined during a calibration phase. During gameplay, the game difficulty was reduced if the player’s arousal increased, and vice-versa. More recently, Wang, Parnandi et al. (2016) presented an approach to use commercial videogames for biofeedback games for stress self-regulation. The authors used a car racing game and modified the speed of the car to provide positive reinforcement to the user i.e., reduced speed when stressed and increased speed when relaxed. Experimental trials compared positive reinforcement (speed feedback) with a negative reinforcement visual overlay feedback and showed that both biofeedback groups were able to promote deep breathing and reduce arousal during treatment and post-test. These results are encouraging and point towards a deeper investigation of both positive and negative reinforcement in GBF for stress training. In a related study, Sonne and Jensen (2016) presented a breath-controlled biofeedback game with positive reinforcement to help children with ADHD relax in situations of acute stress. The authors reported significant increases in average HRV values in the ChillFish group compared to other activities (talking and playing Pacman). However, no significant differences in HRV were observed compared to a relaxation group where the participants were asked to relax. While the authors presented encouraging results, it remains to be validated whether biofeedback games with positive reinforcement can be used to improve skill acquisition and retention.

Combining physiology and game performance for GBF: The studies presented in this dissertation used arousal, as measured by various physiological signals, for game adaptation. In contrast, a number of prior work in adaptive games have used the player's performance to adapt game difficulty[41] (Hunicke 2005, Liu, Agrawal et al. 2009). This is known as dynamic difficulty adjustment (or dynamic game balancing). While using player's arousal level for feedback GBF led to promising results in stress training, player's emotional experience and engagement are also important in gameplay (Pagulayan, Keeker et al. 2003). This is in agreement with Hook's affective loop theory, which argues for involving both mind and body as the basis for designing interactive affective systems (Höök 2008), and Yannakakis' studies on affective physical interaction (Yannakakis 2009). Recent studies have explored the use of physiological measures as a way to capture facets of the player's gameplay experience; these measures can then be transformed into control signals to adapt game parameters, in what has been described as a biocybernetic loop (Fairclough 2009). Future work will involve combining the three dimensions: user's physiology, engagement, and performance level in game adaptation.

Effect of game difficulty: This dissertation integrated various factors (e.g., physiological signals, biofeedback modalities, and reinforcement scheduling) in GBF and studied their effectiveness in teaching relaxation skills. Integration of these factors

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[41] A classic example is the "rubber band" used in car-racing games (e.g., Mario Kart): players who fall behind in the race will encounter more bonuses (and fewer obstacles) than those who dominate the race.

may have resulted in different difficulty levels in the game and gameplay experience across the various groups. The studies did not investigate the effects of game difficulty on skill acquisition and retention. Lomas, Patel et al. (2013) studied the effects of game challenge level in maximizing engagement and learning in an educational game. The authors observed that the participants found easier game levels to be more engaging. They also noted that the easier levels resulted in lower learning rates while moderate difficulty levels improved the learning. Prior work by Konrad, Bellotti et al. (2015) has shown the importance of balancing self-efficacy (not too difficult) and maintaining motivation (not too easy) to maximize compliance and development of self-regulation skills. Future work will study self-efficacy, motivation, and challenge levels in the context of GBF with an aim to maximize the acquisition and retention of deep breathing skills while maintaining engagement in the game.

Reinforcement scheduling in GBF: Chapter 7 combined the concept of reinforcement scheduling with biofeedback games and the results showed that a partial reinforcement schedule results in increased resistance to extinction. Partial reinforcement schedules can be implemented in several ways including variable ratio (VR), fixed ratio (FR), variable interval (VI), and fixed interval (FI). In FR schedule, the user must produce the target response a predetermined fixed number of times before the reinforcement is presented. In contrast, a VR schedule (as used in Chapter 7) requires an unpredictable but on average constant number of responses for reinforcement; the average number of responses governs the schedules. A FI schedule is similar to FR except that along with an elicitation of the response, a fixed amount of time has to elapse before presenting the user with reinforcement. Finally, VI schedule requires a response and a varying time interval before reinforcement is applied; the average interval defines the schedules. A number of prior studies have shown that variable schedules (i.e. VI and VR) lead to higher resistance to extinction compared to fixed schedules (Cohen, Richardson et al. 2001, Voerman, Sandsjö et al. 2004). This may again be attributed to the probabilistic nature of VI and VR methods where only certain randomly chosen responses are reinforced. Future work will involve studying other schedules in the context of biofeedback games. Another interesting direction will be to modify different game elements using different scheduling paradigm.

Along similar lines, during GBF gameplay the player is provided the biofeedback information in two ways: as a visual display for their breathing rate and through game adaptation. Here, the former acts as information feedback while the latter acts as the reinforcement. In the proposed implementation, the PRF schedule was integrated in the game in a way that it scheduled only the game adaptation process, while the players were provided with the information feedback throughout the experiment. Future work will also involve studying the effect of reinforcement scheduling on both game adaptation and information biofeedback (i.e. presenting or withdrawing the visual display of physiology based on a probabilistic schedule) on skill learning and skill retention.

Along with scheduling of reinforcement, other factors may determine the effectiveness of a training method in increasing resistance to extinction, including history of reinforcement, magnitude of the reinforcer, degree of deprivation, previous experience with extinction, and distinctive signal for extinction. While researchers have found reinforcement scheduling as an important factor in improving resistance to extinction (Hatch 1980, McKinney, Geller et al. 1980, Cohen, Richardson et al. 2001, Voerman, Sandsjö et al. 2004), it will be worth investigating the other variables in the context of a biofeedback game and how they impact skill acquisition and retention.

Effect of instructions: During the experiments, participants were instructed on how to perform deep breathing before the GBF session, and were also provided information about the game adaptation process (see Section 5.3.2). This dissertation, however, did not evaluate the effect of these instructions in the learning process. A relevant prior study by Conrad, Müller et al. (2007) has shown that simple instructions to alter breathing do not lead to changes in respiratory or autonomic measures of relaxation. Similarly Raaijmakers, Steel et al. (2013) studied the effect of EDA and HRV biofeedback games on user's affective state. During experiments, participants were not informed about the biofeedback modality (i.e. EDA or HRV) controlling the game and were not given any instructions on how to modify their EDA and HRV response. Their results showed no effect of biofeedback on the user's affective state. Based on these results, it may be tempting to conclude that instructions do not play an important role in teaching self-regulation skills with games and GBF; however, more work is needed to study the effectiveness of instructions during GBF training. In fact, past research has shown that classical and instrumental conditioning concepts can be used to train users to control visceral responses –including those of HRV and EDA (Miller 1969). One end of this would be to provide the user with no instructions about the game adaption mechanism or the self-regulation process with GBF and allow them to explore the GBF system i.e., a purely bottom-up process of learning, and evaluate the effects on skill acquisition. This will require a longer training period but may potentially result in users being able to better perceive visceral states, as prior studies have shown (Miller 1978, Brener 1986), learn better voluntary control of physiological signals and potentially develop long-term persistence effects.

Comparison with yoked control: The experiments in this dissertation did not evaluate the effect of a yoked control on relaxation skill acquisition. In a yoked control design, a participant is yoked[42] with a participant in one of the treatment groups to receive the same biofeedback information (including game penalty). In other words, the yoked participants' will see the game adapt but their own physiology will have no influence on the game. This manipulation allows the experimenter to study the influence of randomized or response-independent feedback in the game and whether it leads to the participants learning the relationship between their perceived arousal level and the game adaptation process.

Collaborative and competitive GBF: Another interesting line of future research on biofeedback games is in the direction of social gaming. Recent work by Munafò, Palomba et al. (2014) has shown that, compared to traditional biofeedback, a competitive biofeedback enhanced the training efficacy and resulted in increase in participants' RSA and restored cardiac autonomic balance. This approach of competitive biofeedback takes

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[42] In some yoked designs, a participant in the yoked control group is provided with feedback or response averaged over all the participants in a treatment group.

advantage of competition as a motivation and challenge players to enhance their self-regulation skills. Given that a large percentage of videogames can be played in multiplayer model (either competitive or cooperative), the idea of competitive biofeedback can be easily extended to biofeedback games. In fact, a team of undergraduates at Texas A&M developed a robot based biofeedback game where two players competed to control the robot with their breathing pace (i.e., lower the breathing rate of a player, the higher control on the robot they maintain). They achieved encouraging results, and further work will be required to build it into a stress self-regulation method.

Reinforcement learning controller for GBF: As observed in prior studies (Parnandi and Gutierrez-Osuna 2014, Wang, Parnandi et al. 2016), different game mechanics and game controllers can influence individuals' physiology in different ways. This implies that the game adaptation process can be framed as a multi-arm bandit problem with each arm being a game parameter that can be modified based on user's current arousal, performance, affective state, cognitive load or other variables (Paredes, Gilad-Bachrach et al. 2014). Therefore, given a user with an initial physiological state, the controller will select a set of states in the game that maximize the probability of the user reaching and maintaining a relaxed state. Over time, the controller will learn an intervention by leveraging the tradeoff between exploring various game elements available for manipulation and exploiting the ones that are most effective in reducing user's arousal while maintaining engagement levels. In this way, the learning algorithm will potentially lead to an individualized model for each user resulting in a more personalized treatment.

Procedural content generation in GBF: The idea of framing GBF as a multi-arm bandit problem can also be used in conjunction with procedural content generation (PCG). PCG refers to the creation of game content automatically through algorithmic means (Yannakakis and Togelius 2011). In the past, PCG has been used to create and deliver new game content in real-time for enhancing user's enjoyment level (Drachen, Canossa et al. 2009, Yannakakis and Togelius 2011, Hendrikx, Meijer et al. 2013). The use of PCG methods has been growing in commercial and research games. A good example is Minecraft (Persson and Bergensten 2011), which is almost entirely a PCG game and has been used for learning purposes (Schifter and Cipollone 2013). PCG allows a game developer to account for player's behavior, cognitive state, physiology and affective state and create personalized content in a way that leads them towards the desired behaviors or state.

Pavlovian instrumental transfer with GBF: In recent years, the concept of Pavlovian Instrumental transfer (PIT) has captured the attention of researchers to improve learning of skills beyond what can be achieved using the traditional methods of classical and instrumental conditioning (Talmi, Seymour et al. 2008, Nadler, Delgado et al. 2011, Cartoni, Puglisi-Allegra et al. 2013). According to the PIT hypothesis, a conditioned stimulus that is associated with reinforcement can be used to modify (increase or decrease) the operant conditioned behavior. PIT occurs when the conditioned stimulus during classical conditioning is paired with a reward during the instrumental conditioning phase. This leads to increased instrumental responding than a purely instrumental conditioning based learning. While the GBF approach, like most biofeedback methods, was designed based on instrumental conditioning concepts, future work may explore if the instrumental responses learned during GBF training can be improved using PIT.

Long term retention of skills: This dissertation focused on short-term training and immediate assessment of skill retention and did not address the issue of long term retention of relaxation skills. Gentile, Groves et al. (2014) noted that repeated exposure to a training process can lead to diverse long term effects. In fact, one of the main challenges in building a stress training system is that individuals exposed to similar stressful conditions react differently (McGrady 2007). In addition, learning theories have shown that individuals learn in different ways and at different pace and a number of factors including task complexity, learning ability, individual's perception of visceral states etc. influence the effectiveness of a stress intervention. This implies that there may not be a single solution for stress self-management that is effective for all users. An effective learning routine may include multi-dimensional training, as suggested in (Rose, Buckey et al. 2013, Konrad, Bellotti et al. 2015). These programs comprise of activities such as meditation, exercise, videos/animations, and videogames to delivers self-guided stress management training and therefore may cater to a wider population. Therefore, an evaluation of long-term persistence effects of GBF intervention will require multiple training sessions with a multi-dimensional intervention methodology in real-world ambulatory settings. Future work will also involve detecting user stress levels in real world settings and triggering an intervention when needed. This is also known as just-in-time (JIT) behavioral intervention and would require development of other signal processing and estimation methods for stress detection in the wild.

7.4 Concluding remarks

Videogames help provide users with a sense of autonomy and control. To do well in a game, the players need to process all the information they are being offered as they navigate the game world. This provides an important modality for training and education, which can be used to change behaviors in individuals (Baranowski, Buday et al. 2008). The objective of this dissertation was to develop an engaging intervention using games to allow individuals to practice stress management. To achieve this goal, this dissertation proposed a game biofeedback approach which uses instrumental conditioning and a positive feedback loop for acquisition and retention of stress self-regulation skills. The results presented here show that short-term sessions with GBF can lead to significant reductions in arousal. The proposed approach of game adaptation with a positive feedback loop is closely related to traditional biofeedback, but has two fundamental differences. First, in traditional biofeedback the user has explicit access to his physiological state (e.g., via visual display); in contrast, in biofeedback game the user engages in the game while the physiological signals are available implicitly (e.g. via game adaptation). Hence the user must focus on the game rather than monitor his bio-signals, which makes the training more engaging. Second, game biofeedback teaches relaxation techniques while performing a task (i.e. a game) that is designed to increase the user’s arousal level. And herein lies the main difference with traditional relaxation methods, which encourage practice in quiet settings that do not reflect the environments encountered in daily life. As a result, and as demonstrated in this dissertation, game biofeedback leads to better transfer of relaxation skills to other tasks. This hypothesis is also supported by prior research on stress exposure training in military settings, which shows that normal training procedures do not improve performance when the task is later performed under stress (Bouchard, Bernier et al. 2012).

The studies presented in this dissertation examined the effect of a short-term treatment on breathing behavior (i.e. deep breathing). Such brief treatments are relevant in both home and workplace settings with time constraints. Early research showed that even short and “easy” deep relaxation exercises can positively impact workers’ cardiac autonomic function (Toivanen, Länsimies et al. 1993). Consequently, relaxation exercises embedded in a videogame and played frequently for a few minutes each session may allow users to achieve sustained health benefits while also maintaining their productivity over the long-term and improving overall quality of life. Furthermore, GBF treatment may also overcome geographical barriers and address the issues of shortage of therapists and equipment since GBF can potentially be used in the privacy of one’s home or even office setting. The system described in this dissertation can enable new forms of gameplay and applications including entertainment, game-like health interventions, and affective interfaces.

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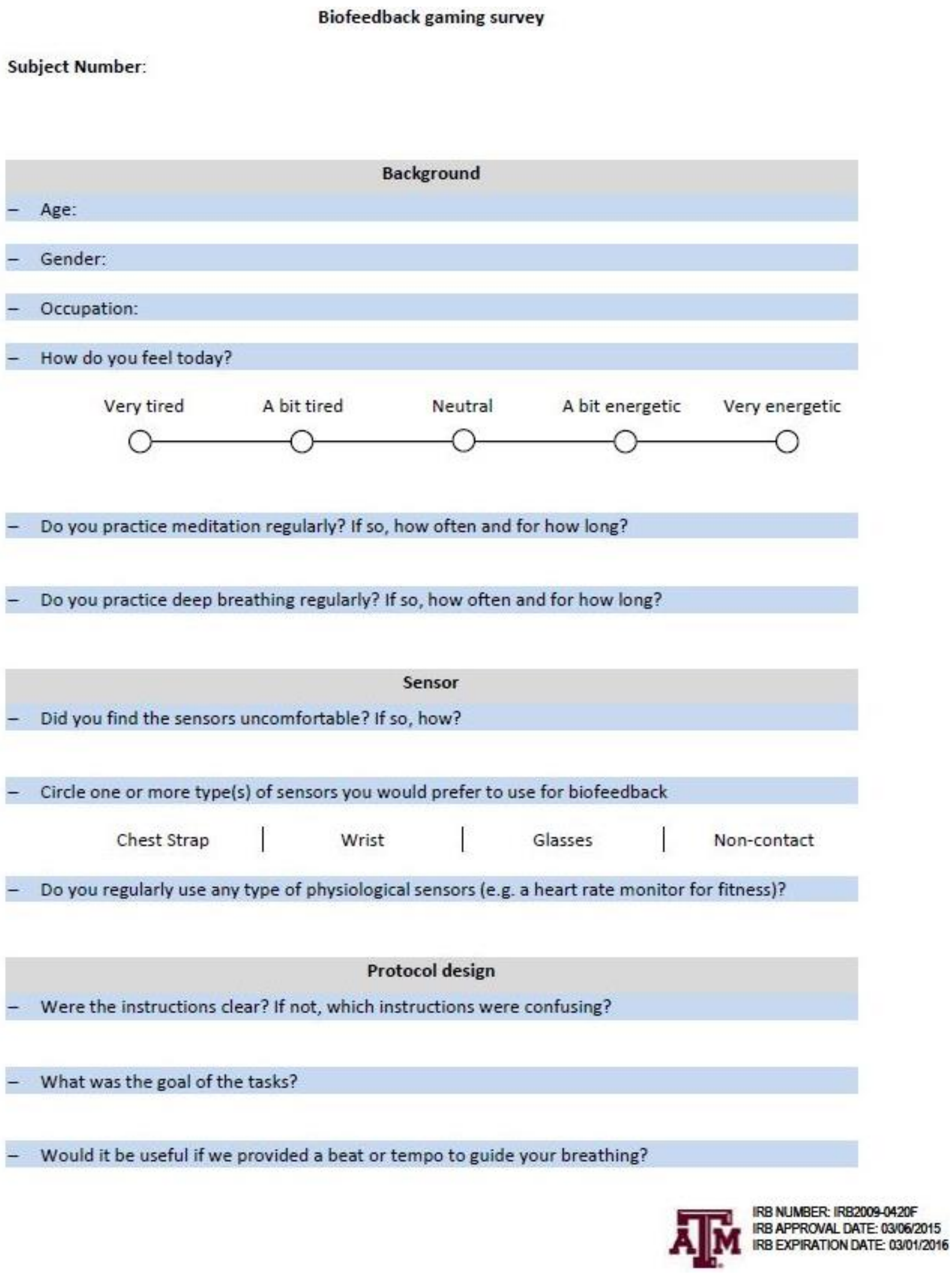
APPENDIX A: GAME BIOFEEDBACK QUESTIONNAIRE



Biofeedback gaming 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?

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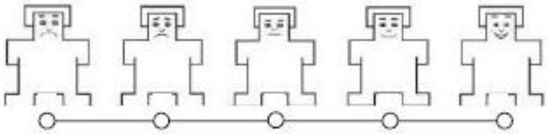
– How hard was it for you to follow the breathing pace during the task?

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

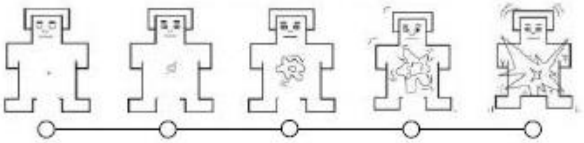
Deep Breathing (Relaxation)

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

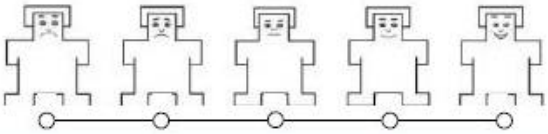
– Valence: How positive or negative did you feel before the deep breathing session?



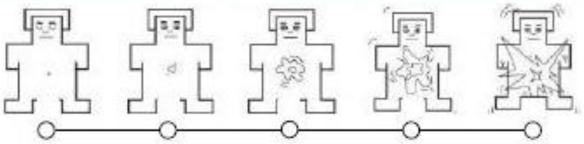
– Arousal: How calm or excited did you feel before the deep breathing session?



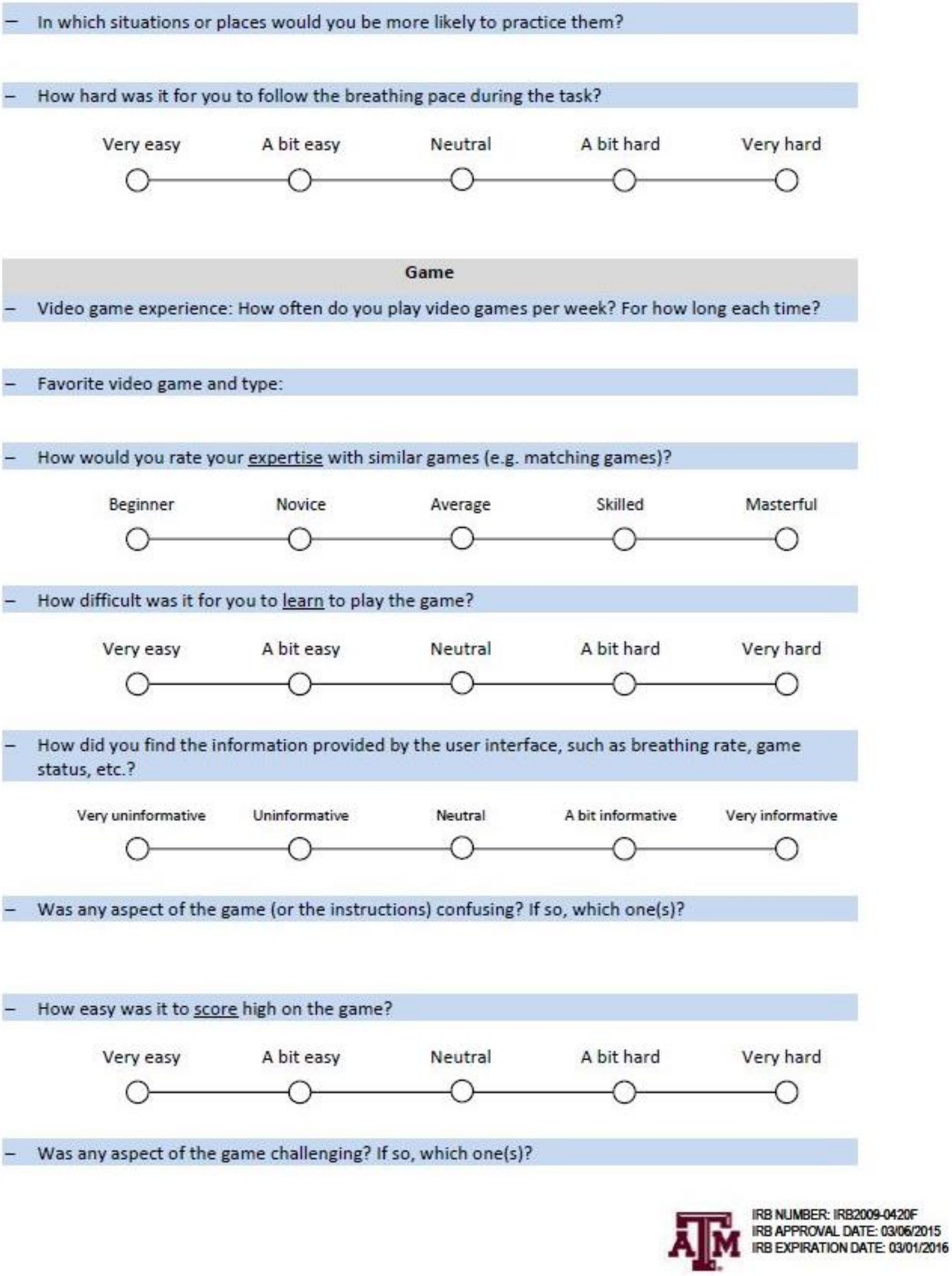
– Valence: How positive or negative did you feel after the deep breathing session?



– 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)?

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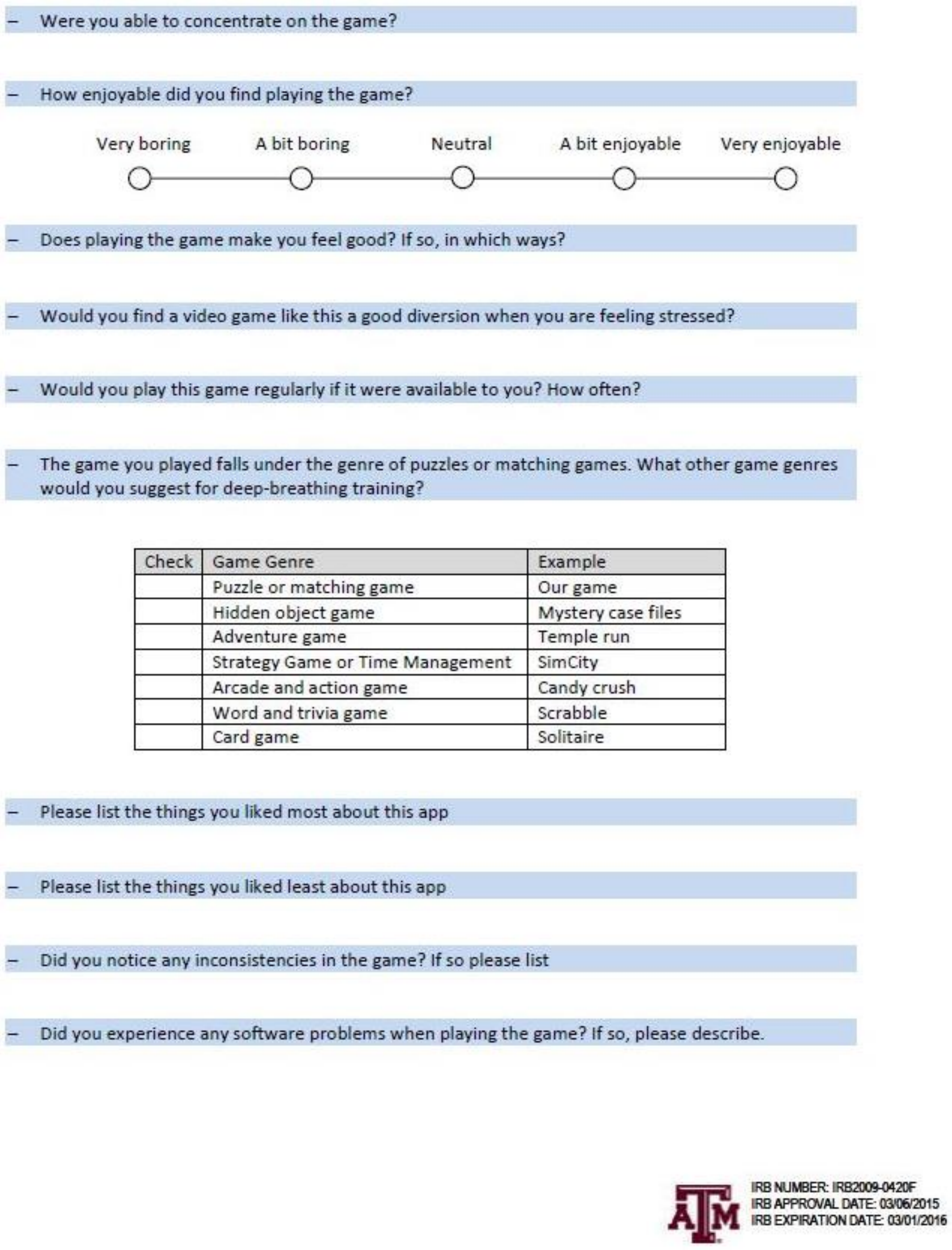

- Were you able to concentrate on the game?

- 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.

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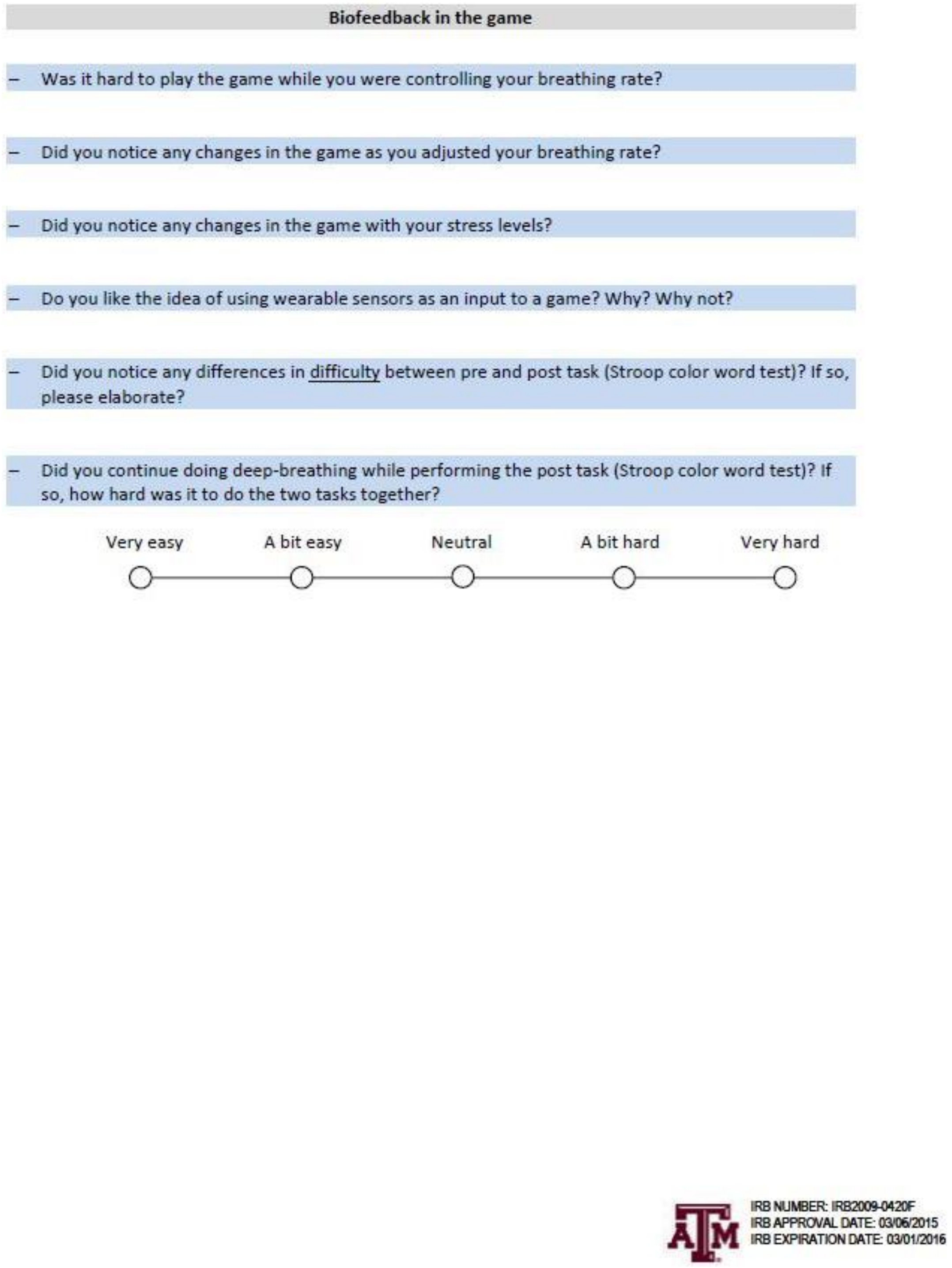

Biofeedback in the game

- 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 difficulty 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
○	○	○	○	○

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APPENDIX B: DUNDEE STRESS STATE QUESTIONNAIRE

Dundee Stress State Questionnaire

General Instructions. This questionnaire is concerned with your feelings and thoughts. Please answer every question, even if you find it difficult. Answer, as honestly as you can, what is true of you. Your answers will be kept entirely confidential. You should try and work quite quickly. The first answer you think of is usually the best.

Please indicate how well each word describes how you feel right now (circle the answer from 1 to 5).

Not at all = 1 A little bit = 2 Somewhat = 3 Very much = 4 Extremely = 5

Energetic	1	2	3	4	5
Relaxed	1	2	3	4	5
Alert	1	2	3	4	5
Nervous	1	2	3	4	5
Passive	1	2	3	4	5
Tense	1	2	3	4	5
Jittery	1	2	3	4	5
Sluggish	1	2	3	4	5
Composed	1	2	3	4	5
Restful	1	2	3	4	5
Vigorous	1	2	3	4	5
Anxious	1	2	3	4	5
Unenterprising	1	2	3	4	5
Calm	1	2	3	4	5
Active	1	2	3	4	5
Tired	1	2	3	4	5

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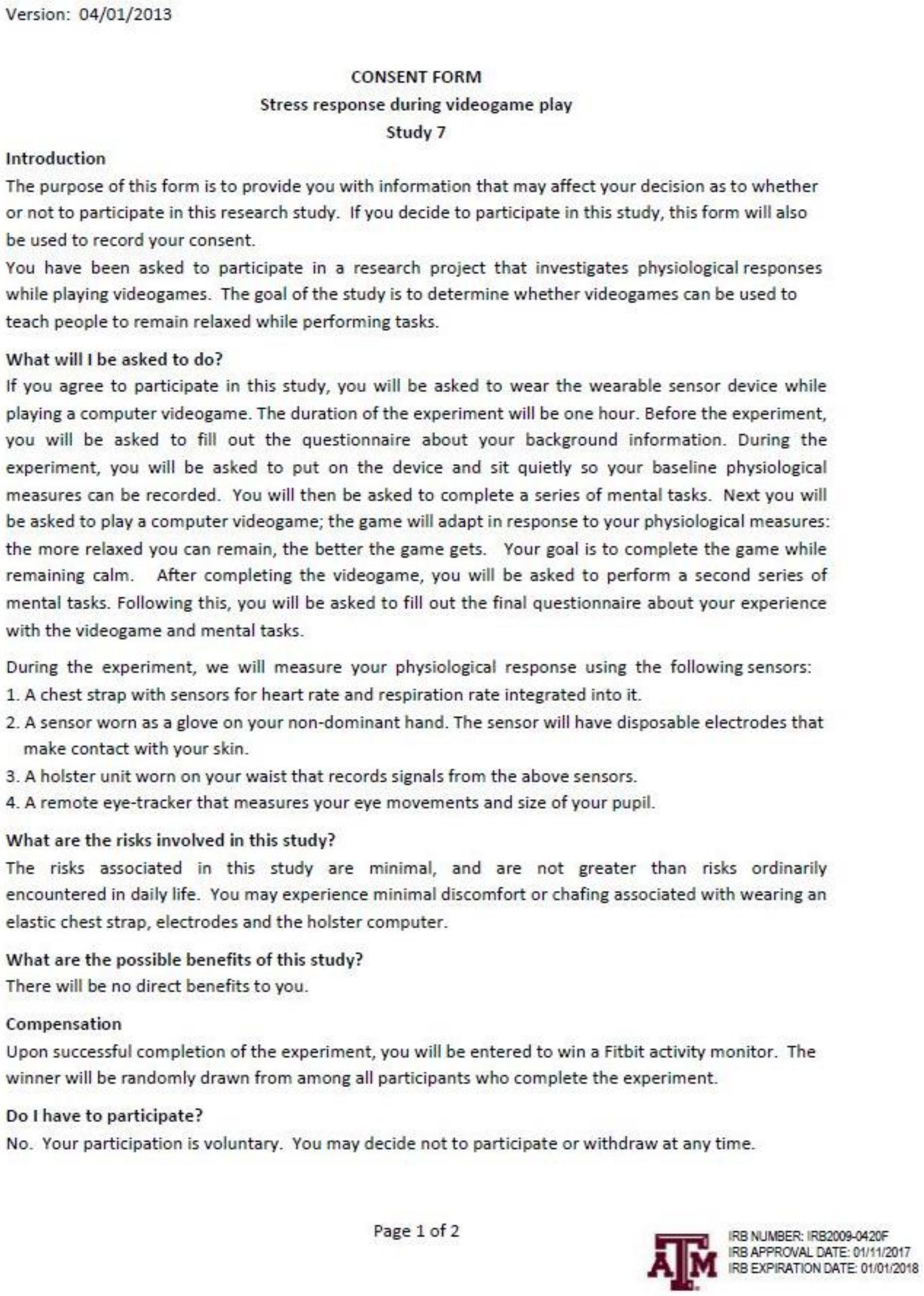
Please indicate roughly how often you had each thought during the task.

Never = 1 Once = 2 A few times = 3 Often = 4 Very Often = 5

I thought about how I should work more carefully.	1	2	3	4	5
I thought about how much time I had left	1	2	3	4	5
I thought about how others have done on this task	1	2	3	4	5
I thought about the difficulty of the problems	1	2	3	4	5
I thought about my level of ability	1	2	3	4	5
I thought about the purpose of the experiment	1	2	3	4	5
I thought about how I would feel if I were told how I performed	1	2	3	4	5
I thought about how often I get confused	1	2	3	4	5
I thought about members of my family	1	2	3	4	5
I thought about something that made me feel guilty	1	2	3	4	5
I thought about personal worries	1	2	3	4	5
I thought about something that made me feel angry	1	2	3	4	5
I thought about something that happened earlier today	1	2	3	4	5
I thought about something that happened in the recent past (last few days, but not today)	1	2	3	4	5
I thought about something that happened in the distant past	1	2	3	4	5
I thought about something that might happen in the future	1	2	3	4	5

APPENDIX C: IRB CONSENT FORM



Version: 04/01/2013

CONSENT FORM
Stress response during videogame play
Study 7

Introduction

The purpose of this form is to provide you with information that may affect your decision as to whether or not to participate in this research study. If you decide to participate in this study, this form will also be used to record your consent.

You have been asked to participate in a research project that investigates physiological responses while playing videogames. The goal of the study is to determine whether videogames can be used to teach people to remain relaxed while performing tasks.

What will I be asked to do?

If you agree to participate in this study, you will be asked to wear the wearable sensor device while playing a computer videogame. The duration of the experiment will be one hour. Before the experiment, you will be asked to fill out the questionnaire about your background information. During the experiment, you will be asked to put on the device and sit quietly so your baseline physiological measures can be recorded. You will then be asked to complete a series of mental tasks. Next you will be asked to play a computer videogame; the game will adapt in response to your physiological measures: the more relaxed you can remain, the better the game gets. Your goal is to complete the game while remaining calm. After completing the videogame, you will be asked to perform a second series of mental tasks. Following this, you will be asked to fill out the final questionnaire about your experience with the videogame and mental tasks.

During the experiment, we will measure your physiological response using the following sensors:

1. A chest strap with sensors for heart rate and respiration rate integrated into it.
2. A sensor worn as a glove on your non-dominant hand. The sensor will have disposable electrodes that make contact with your skin.
3. A holster unit worn on your waist that records signals from the above sensors.
4. A remote eye-tracker that measures your eye movements and size of your pupil.

What are the risks involved in this study?

The risks associated in this study are minimal, and are not greater than risks ordinarily encountered in daily life. You may experience minimal discomfort or chafing associated with wearing an elastic chest strap, electrodes and the holster computer.

What are the possible benefits of this study?

There will be no direct benefits to you.

Compensation

Upon successful completion of the experiment, you will be entered to win a Fitbit activity monitor. The winner will be randomly drawn from among all participants who complete the experiment.

Do I have to participate?

No. Your participation is voluntary. You may decide not to participate or withdraw at any time.

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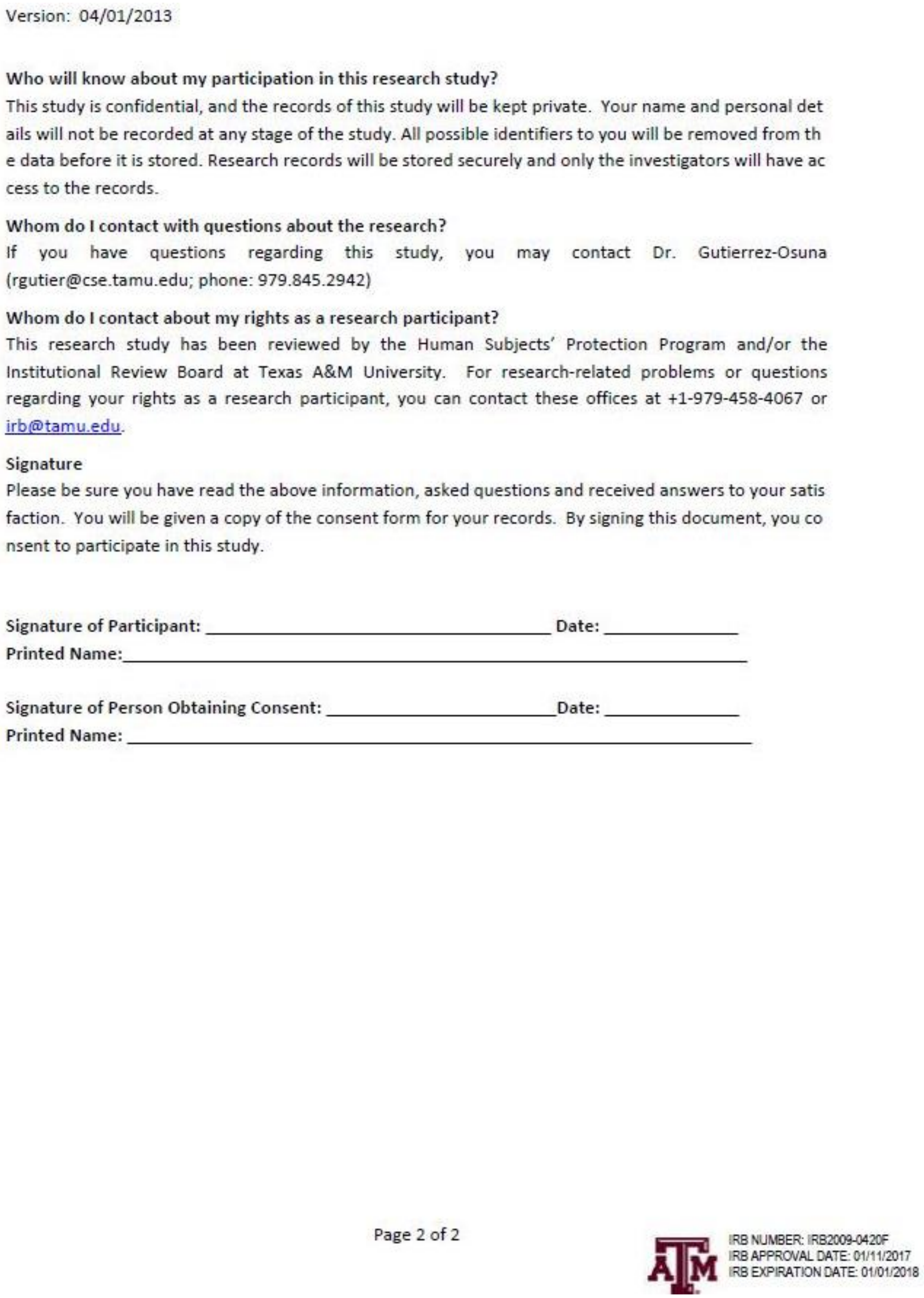

Version: 04/01/2013

Who will know about my participation in this research study?

This study is confidential, and the records of this study will be kept private. Your name and personal details will not be recorded at any stage of the study. All possible identifiers to you will be removed from the data before it is stored. Research records will be stored securely and only the investigators will have access to the records.

Whom do I contact with questions about the research?

If you have questions regarding this study, you may contact Dr. Gutierrez-Osuna (rgutier@cse.tamu.edu; phone: 979.845.2942)

Whom do I contact about my rights as a research participant?

This research study has been reviewed by the Human Subjects' Protection Program and/or the Institutional Review Board at Texas A&M University. For research-related problems or questions regarding your rights as a research participant, you can contact these offices at +1-979-458-4067 or irb@tamu.edu.

Signature

Please be sure you have read the above information, asked questions and received answers to your satisfaction. You will be given a copy of the consent form for your records. By signing this document, you consent to participate in this study.

Signature of Participant: ______________________________ **Date:** ____________

Printed Name:____

Signature of Person Obtaining Consent: ____________________**Date:** ____________

Printed Name: ____

IRB NUMBER: IRB2009-0420F
IRB APPROVAL DATE: 01/11/2017
IRB EXPIRATION DATE: 01/01/2018