HEALTH NINJAS: A PERSONALIZED BIOFEEDBACK GAME TO TEACH CHILDREN DEEP BREATHING AND NUTRITION KNOWLEDGE

A Thesis

by

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ABSTRACT

Children's wellbeing has been regarded as one of the primary focus of public health. Among all of the factors which have huge impacts on children's wellbeing, stress has been given a primary priority and is the one which has lifelong effects. Deep breathing is an established and evidence-based strategy for reducing stress and it has been integrated with biofeedback techniques to help adults regulate their stress. While all these biofeedback games are effective to teach adults self-regulation skills while emerged in a stressful environment, however, they are not likely to be applicable to children. Thus more could be gained if a biofeedback game typically designed for children could take consideration of child's characteristics and capability, and meanwhile provide necessary guidance and instructions.

We developed a personalized biofeedback game – Health Ninjas as a game-like intervention to teach children deep breathing and nutrition knowledge in an effective and fun way. To the best of knowledge, Health Ninjas is the first game that integrates self-regulation training with nutrition education. Health Ninjas incorporates calibration function which calculates "personalized" target breathing rate within the child's capability, and more importantly, provides intuitive visualization of desired breathing patterns for the child to follow. Additionally, Health Ninjas incorporates nutrition education to help children better discriminate between healthy and junk food.

Health Ninjas includes three game scenarios: Direct Biofeedback mode, Indirect

Biofeedback mode and Control mode. We conducted two comparative studies: one study aims at testing whether children are able to follow subtle biofeedback cues or need a more explicit feedback; the other study aims to test whether playing our nutrition education game changes children's perception of healthy vs. junk foods. Our results indicated that children need a more explicit and intuitive biofeedback strategy to better perform the desired behaviors.

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LIST OF ABBREVIATIONS

AvgBR	Average breathing rate
BPM	Breaths per minute
BF	Biofeedback
BR	Breathing rate
CWT	Color Word Test
DBF	Direct biofeedback
EDA	Electrodermal activity
HR	Heart rate
HRV	Heart rate variability
IBF	Indirect biofeedback
MaxBR	Maximum breathing rate
MinBR	Minimum breathing rate
NE	Nutrition education
RR	Respiration rate
SCL	Skin conductance level
TargetBR	Target breathing rate

1 INTRODUCTION

Stress is prevalent among children and can lead to multiple health-related issues (Anderson, C, & Breckler, 2012); one such example is emotional eating, also known as stress-induced eating, which is considered as a form of avoidant coping that has a negative impact on health over time (Adam & Epel, 2007; Blissett, Haycraft, & Farrow, 2010). Stress plays an important role in emotional eating, and it can severely limit the effectiveness of nutrition education programs (Jacquier, Bonthoux, Baciu, & Ruffieux, 2012; Zellner et al., 2006). Thus an innovative and effective solution is to combine stress reduction techniques with traditional nutrition education.

Deep breathing is an intuitive evidence-based method for reducing stress (Varvogli & Darviri, 2011). However traditional practices of deep breathing are not very engaging for children, which can lead to high attrition. Considering the appeal of videogames among children (Gentile et al., 2011), integrating deep breathing and nutrition education into videogames is more likely to improve compliance with regular practice at this critical age.

In this thesis we propose an effective and developmentally-appropriate biofeedback game that teaches children deep breathing and nutrition knowledge. This strategy is accomplished by integrating biofeedback and nutrition education into an engaging and personalized mobile game - “Health Ninjas”, which we developed as a game intervention.

The specific aims of this thesis are:

1) To test the game's effectiveness in teaching slow breathing to children in a way that is fun
2) To test whether children are able to follow subtle biofeedback cues or need a more explicit feedback, and
3) To test whether playing the game changes children's perception of healthy vs. junk foods.

The rest of the document is organized as follows. Section 2 provides the background and related work of this thesis, including stress in children, deep breathing training on biofeedback games and emotional overeating issues. Section 3 describes the pilot study we conducted to validate the effectiveness of biofeedback game on children. Section 4 presents the major work of this thesis and explains the experimental design and system implementation. Section 5 describes the user study to validate our methods and the discussion of the final result. Finally in Section 6 we conclude this thesis and provide directions for the future work.

2 BACKGROUND AND RELATED WORK

In this section, we firstly review topics concerning the effects of stress on children, and the significance of self-regulation training on children to cope with stress. Then we discuss the benefits of deep breathing in the treatment of stress and its integration with biofeedback games to promote self-regulation skills. Lastly, we review emotional eating issues on children and how self-regulation training can be used to augment the effectiveness of traditional nutrition education programs.

2.1 Stress and importance of self-regulation in children

Stress is a psychobiological process which produces biological, behavioral, mental and emotional consequences (Gunnar & Quevedo, 2007). Stress varies in its duration, severity and predictability – stressful experiences that are short, mild and predictable are more manageable than stressful experiences that are chronic, severe and unpredictable (Abbott, Schoen, & Badia, 1984). The Yerkes-Dodson Law (Robert & John, 1908) defines the relationship between stress and health and performance as a bell-shaped curve (Figure 1), indicating that optimal level of health and performance is attained when stress level is regulated at a certain optimal level. When stress is manageable, it strengthens an individual's biological functioning and promotes mastery and competence. However, when stress is unmanageable and it exceeds an individual's self-regulatory capacity, it is harmful for both health and performance (Thompson, 2014).

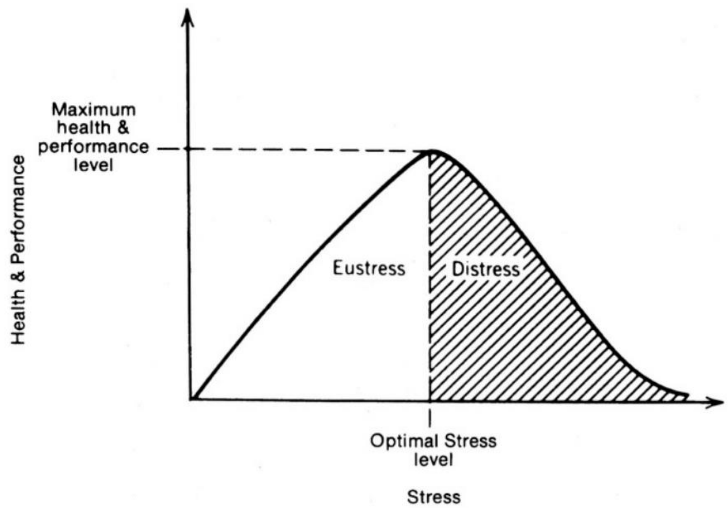


Figure 1. Yerkes-Dodson stress curve (Everly Jr & Lating, 2012).

Among all of the factors which have huge impacts on children's wellbeing, stress has been given a primary priority and is one that has lifelong effects (Shonkoff et al., 2012). Stress is prevalent among children and it can lead to severe health-related issues, such as childhood obesity, depression and autism (Anderson et al., 2012). Chronic or severe stress has significant biological effects on children, which could impair children's ability to memorize, concentrate, think and reason, all of which have negative influence on children's performance and development (Thompson, 2014).

The capability to cope with stress and regulate emotions is vital in promoting emotional and social wellbeing in children (Aldwin, 2007), and when one is faced with stress, coping refers specifically to *self-regulation* (Eisenberg, Fabes, & Guthrie, 1997). Even though the supportive presence of their parents or caregivers can help children regulate emotions (Hostinar, Sullivan, & Gunnar, 2014), however, the biological effects of stress raise emotional reactivity and undermine children's capability to *self-regulate* their emotions (Thompson, 2014). Research showed that when facing stressful situations, children with poor self-regulation abilities are more likely to experience depression and anxiety (Eisenberg, Spinrad, & Eggum, 2010; Hostinar et al., 2014; Martel et al., 2007), and even have aggressive behavior problems (Ellis, Weiss, & Lochman, 2009; Raaijmakers et al., 2008).

Given that self-regulation is learnable for children, there is a critical need for interventions (tools or games) which teach children how to manage their emotions and enhance their self-regulation skills. For example, Karisma Kidz Moodville is an education game that teaches children how to deal with stress by letting them explore a virtual world with a virtual character (Dredge, 2015). SuperBetter is a game to teach people how to deal with stress by creating and finishing quests to relax and reduce stress (MacGonigal, 2012). Tools of the mind (2015) is a project to help children develop self-regulation by role-playing with parents and adults. Although these interventions help children develop self-regulation skills, however, these skills are developed in a comparably relaxed environment, which may not be transferred to stressful scenarios (Cannon-Bowers & Salas, 1998).

Thus we propose to develop a game that teaches children self-regulations skills when they are emerged in a stressful environment. With our game, we propose to evaluate the effects of these game-like interventions to improve children's self-regulation skills.

2.2 Deep breathing training with biofeedback games

Deep breathing, also known as diaphragmatic breathing or belly breathing is an established and evidence-based strategy for reducing stress (Hazlett-Stevens & Craske, 2009; Varvogli & Darviri, 2011). Regulated, diaphragmatic breathing is also an recommended approach to treat health-related problems such as anxiety, depression, post-traumatic stress disorder and chronic pain (Lazarus & Folkman, 1984). According to recent statistics from the National Institutes of Health, 13% of adults in America have used deep breathing exercises for health purposes (NIH, 2014).

Normally, people learn breathing techniques from professional trainers or from audio and video tutorials. However traditional practices of deep breathing are not very engaging for children, which can lead to high attrition. In recent years, videogames have emerged as an effective tool for educational and training purposes (Moreno-Ger, Burgos, Martínez-Ortiz, Sierra, & Fernández-Manjón, 2008). Compared with traditional practices, videogames establish a more active learner role for the user to get emerged and engaged in a "stealth" learning environment, which enhances the user's learning and comprehending of the practice (Garris, Ahlers, & Driskell, 2002).

With the ubiquitous use of mobile devices and the versatile interactive technologies they support, mobile games are becoming a popular vehicle to convey education and training. Chittaro and Sioni (2014) have evaluated breath training on mobile games against traditional breath training methods, and the visualization of breath pattern is effective in helping people to follow the breathing instructions. Similarly, biofeedback techniques have been adopted to help people regulate their stress by providing information of their physiological data (for e.g., breathing rate, heart rate, etc.) to the user. The greater awareness of physiological functions offered by biofeedback can help people recognize and regulate their emotions (Yucha & Montgomery, 2008).

Biofeedback games have been effectively used in health care and personal training (Kato, 2010). Moreover, biofeedback has been used effectively with children with behavioral, emotional and cognitive problems (Goh, Ang, & Tan, 2008), and also to reduce food cravings (Meule, Freund, Skirde, Vögele, & Kübler, 2012). The game changes adaptively based on the user's physiological data and the user should manage his or her physiological function (for e.g., breathing rate, heart rate) well to improve game performance. Recent studies have looked at the effectiveness of mobile games or apps to teach adults relaxation skills. Parnandi, Ahmed, Shipp, and Gutierrez-Osuna (2014) presented a casual game "Chill-out" where the game becomes harder when the user is breathing too fast; Al Rihawi, Ahmed, and Gutierrez-Osuna (2014) developed a "dodging stress" game where the user steers a ball without hitting any obstacles - the number of obstacles increases with increasing breathing rate; Bhandari, Parnandi, Shipp, Ahmed, and Gutierrez-Osuna (2015) developed a music-based respiratory biofeedback application which adds noise to music when the user's respiration rate increases. While all these biofeedback games are effective to teach adults self-regulation skills while emerged in a stressful environment, however, they are not likely to be applicable to children for several reasons:

- *Single target breathing rate*: Most of these games set the target breathing rate at 6 BPM (breaths per minute), which is the best breathing rate for adults to attain maximum heart rate variability (the physiological indicator of relaxation) (Vaschillo, Vaschillo, & Lehrer, 2006). However, this will not work for children since the respiration rate varies much for children in different age groups. For example, the respiration rate varies from 12 BPM to 28 BPM for children in school age (6 to 12 years old) (Fleming et al., 2011). Thus there is a critical need to cater the game appropriately to each child's capability and personality.
- *Lack of guidance or instructions for DB*: The games listed above do not provide instructions in-game on how to perform deep breathing. Since the self-regulation capability of children is lower than adults, it will be much more helpful if the game provides some necessary in-game features (for e.g., pacing signal, intuitive pattern, etc.) to help the child synchronize his or her breathing rate with the target rate.

We propose a game to incorporate calibration function which calculates "personalized" target breathing rate within the child's capability, and more importantly, to provide intuitive visualization of desired breathing patterns for the child to follow.

2.3 Emotional eating and nutrition education

Emotional overeating is defined as eating in response to negative emotions to cope with negative affect regardless of internal state of hunger or satiety (Macht, 2008). Emotional overeating in children begins from 4 years of age and remains relatively stable in middle childhood if no intervention occurs (Ashcroft, Semmler, Carnell, Van Jaarsveld, & Wardle, 2008). Children who exhibit emotional overeating tend to have a high BMI and a less-healthy diet (Braet & Van Strien, 1997; Michels et al., 2012), so they are at high risk for developing obesity and serious health problems later in life (Webber, Hill, Saxton, Van Jaarsveld, & Wardle, 2009). According to American Psychological Association (Anderson et al., 2012): *"children and adults alike who are obese or overweight are more likely to feel stress, and only 43 percent of young people believe eating healthy food is extremely or very important…. When asked, one-third (31 percent) of American children report being very or slightly obesity*."

One form of emotional eating, stress-induced eating, has been considered as a form of avoidant coping that has a negative impact on health over time (Adam & Epel, 2007). Models of stress-induced eating posit physiological change as one of the primary mediating mechanisms between stress and eating (Greeno & Wing, 1994). Further, epigenetic influences on weight have been implicated by research showing that stress neurobiology (and subsequent influences on appetite homeostatic systems) can be shaped by learning (Gunnar & Quevedo, 2007; Patchev, Rodrigues, Sousa, Spengler, & Almeida, 2014).

Nutrition education programs are important ways to inform children about healthy food choices and eating habits, and numerous nutrition education programs have been developed to deal with childhood obesity. To name a few, Cool Food Planet is an online game to teach children knowledge of nutrition in the food (Kreisel, 2004); Grocery

Hunter is a mobile game that encourages children to adopt healthy eating habits (Kim, Kogan, Dasgupta, Novitzky, & Do, 2011); RightWay Café is a role-playing game to teach children how to build a healthy life style by building healthy diet (Peng, 2009).

However, the effectiveness of these interventions has been modest as their design tends to be ineffective at producing behavioral changes (Baranowski & Frankel, 2012) and they are associated with weaker intervention effects (Stice, Shaw, & Marti, 2006). Particularly for an intervention aimed at reducing stress-induced eating, nutrition education alone is unlikely to be effective because stress and elevated physiological arousal deplete cognitive and self-regulatory resources (Muraven & Baumeister, 2000). Thus children under acute stress are unlikely to make mindful choices by accessing and utilizing the knowledge they have about nutrition and healthy eating (Jacquier et al., 2012; Zellner et al., 2006) unless they are able to reduce their physiological arousal (stress level).

Since stress plays an important role in emotional eating, which can severely limit the effectiveness of nutrition-education programs; it will be more effective if nutrition education is combined with teaching how to cope with stress in the same time. Thus, there is a critical need for intervention that targets not only nutrition education but also self-regulation of eating behaviors, such as self-awareness of satiation, and not using food to cope with negative emotions. As an example, biofeedback has been used effectively with children with behavioral, emotional and cognitive problems (Goh et al., 2008), and also to reduce food cravings (Meule et al., 2012). Our approach aims at teaching children self-regulation with casual biofeedback games as a nutrition education and obesity prevention strategy. Our work is significant because we create an effective and developmentally appropriate biofeedback strategy that teaches children emotional self-regulation skills aimed at reducing physiological arousal in the face of acute stress. This is accomplished by embedding biofeedback into an engaging videogame.

To the best of our knowledge, our approach is the first to integrate self-regulation training into a nutrition education program to educate children to cope with emotional overeating. Our work is also significant because it combines nutrition education with game-based biofeedback strategies to promote children's healthy food choices and eating behaviors after exposure to acute stress.

3 FEASIBILITY STUDY

In this section we describe a pilot study we conducted to test the feasibility of game biofeedback on children. For this purpose, we developed “Health Ninjas”, a developmentally appropriate mobile game that integrated biofeedback with the gameplay. The result of the study supported the feasibility of keeping children engaged in deep breathing exercises during game play.

In the following subsections, we first present the design and implementation of “Health Ninjas” and explain how nutrition education and biofeedback strategies were integrated into the game. Then we explain the experimental protocol and analyze the result of our pilot study.

3.1 Health Ninjas prototype

“Health Ninjas” is a mobile game we developed as a variant of the popular game “Fruit Ninja”, which is ranked as one of the best games for children. Fruit Ninja is one of the most popular mobile games for children on both iOS and Android platform. In this game, various fruits are tossed in the air, and players must slice them by sweeping the touchscreen with their fingers while avoiding explosive objects (e.g., bombs) – see Figure 2 (a). The game has an intuitive interaction – even for children playing the game for the first time (Chang, Nunez, Roberts, Sengeh, & Breazeal, 2013), thus it can be tailored to deliver diverse nutrition-education content.

Since Fruit Ninja is a commercial game, we developed “Health Ninjas” as a variant for the purpose of this study. Health Ninjas adopted a similar approach for the child to play the game – by sweeping the screen to slice objects, additionally we integrated nutrition education and biofeedback control into the game – see Figure 2 (b).

(a)

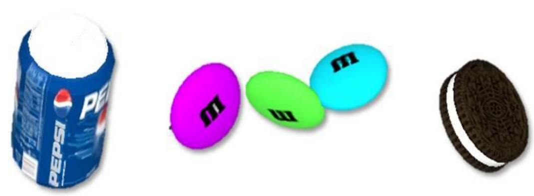
(b)

Figure 2. (a) Fruit Ninja screenshot (b) Health Ninjas screenshot.

3.1.1 Nutrition education

Health Ninjas incorporates nutrition education into the game by teaching children to correctly identify healthy foods from junk foods. For this purpose, the objects in the game are divided into two groups: fruits (apples, oranges and watermelons) and junk foods (M&M candies, cookies and soda) – see Figure 3. When the child slices a fruit, the game rewards the child by adding 2 points; when a child slices a junk food, the game penalizes the child by subtracting 5 points. To get more points, the child should slice as many as fruits as possible while avoiding junk foods. In this manner, the game promotes nutrition education by communicating the message that healthy foods lead to positive effect while junk foods cause negative effects.

(a)



(b)

Figure 3. Game objects in Health Ninjas: (a) fruits: apple, orange and watermelon (b) junk foods: soda, M&M, cookie.

3.1.2 Game biofeedback

Health Ninjas integrates biofeedback into the game by adapting the gameplay according to the child's respiration rate. We use a chest strap Bioharness 3 (Zephyr, 2014) to measure the child's respiration rate and sync it with the game, where the game then compares the respiration rate against the target breathing rate and adapt the gameplay. The biofeedback mechanism is designed as an implementation of the classical control theory (see Figure 4).

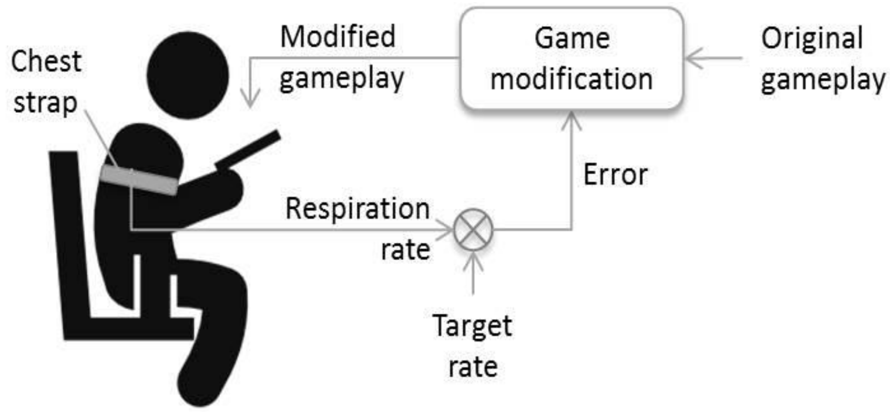


Figure 4. Game biofeedback mechanism in Health Ninjas.

Namely, the child is the target "system" to control, the chest strap is the sensor to measure the child's physiological signal (e.g., breathing rate) and the gameplay modification is the controller to monitor the difference between the actual and desired output (breathing rate) and provide instantaneous feedback in order to minimize the difference. Health Ninjas applies a positive-feedback process by penalizing high breathing rate by limiting the size of playable game area, such that the playable game screen becomes increasingly smaller with increased breathing rate.

3.1.3 Gameplay modification

In order to adapt the size of the playable game based on the child's breathing rate, we added two dynamic game elements into the game: fence and snow. The fence is used as a primary game element to limit the playable game area with its height proportional to the breathing rate, and the snow is added over the fence to further remind the child to lower down his / her breathing rate in order to continue playing the game. The snow occludes the visible game screen with its density proportional to the breathing rate of the child. The relationship between breathing rate vs. fence height and snow density is shown in Figure 5.

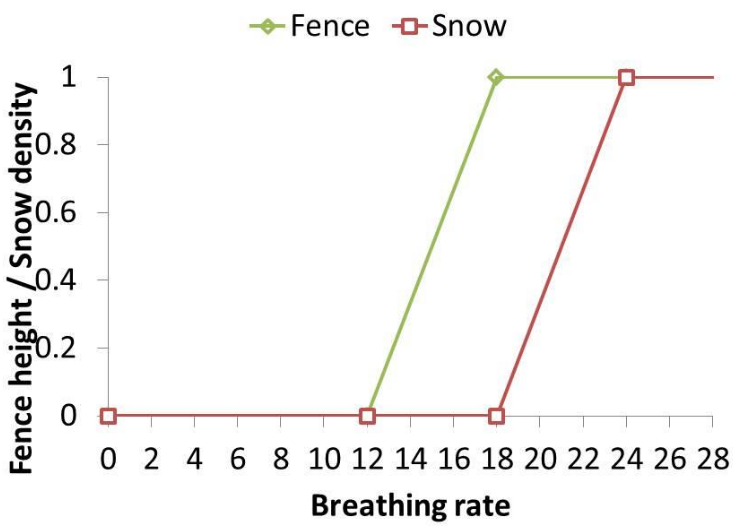
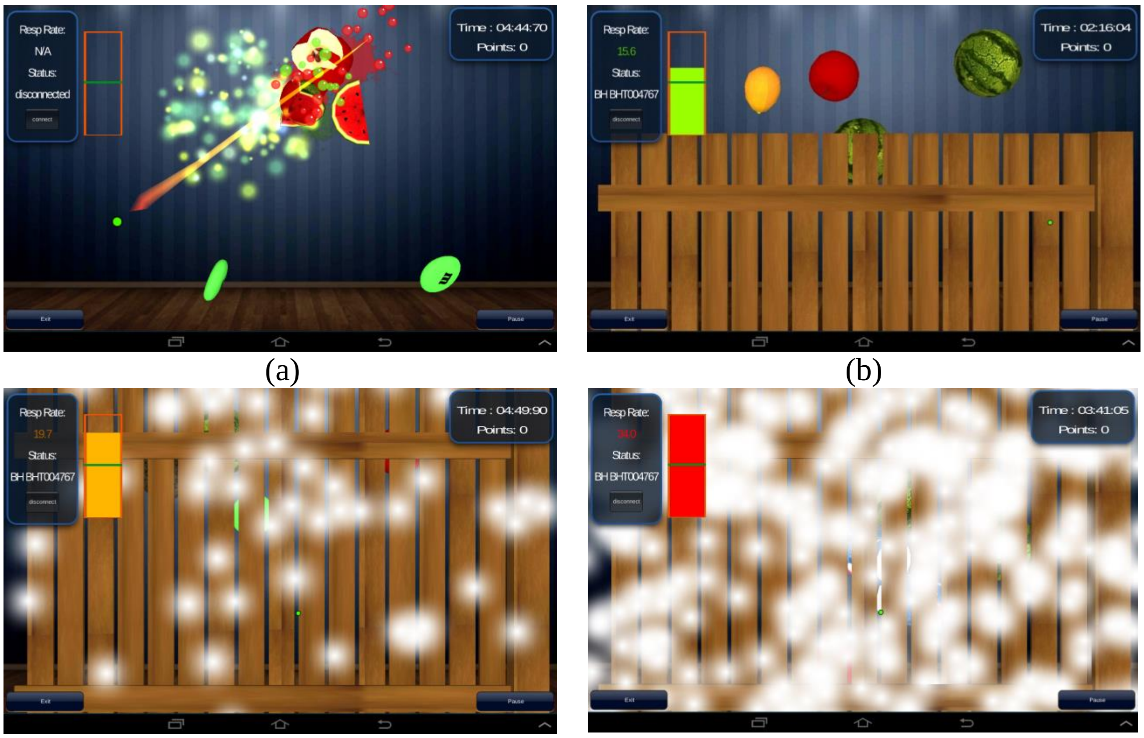


Figure 5. Relationship between breathing rate vs. fence height and snow density.

Specifically, the gameplay adapts to the child's breathing rate as follows:

- *At or below 12 BPM:* children in this range can play the game unimpeded - see Figure 6 (a).
- *Between 12 – 16 BPM:* the playable game area becomes increasingly smaller, with the height of the fence representing the breathing rate – see Figure 6 (b). The child is only able to sweep the game area above the top of the fence.

- *Above 16 BPM*: the screen becomes occluded with a snow-like texture whose density is proportional to respiration rate – see Figure 6 (c). The screen becomes fully occluded when respiration rate is higher than 24 BPM – see Figure 6 (d).



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

Figure 6. Game biofeedback in Health Ninjas: (a) At rates below 12 BPM, children can play the game unimpeded. (b) Between 12-16 BPM, the game area is covered by a fence. (c) Above 16 bpm, snow starts covering the fenced area. (d) At 24 BPM, the screen is fully occluded.

3.2 Pilot study

To validate the feasibility of Health Ninjas to keep children engaged in deep breathing exercises during game play, we conducted a pilot user study. For our study, we recruited children (N=6; 6-8 year olds) at the Children’s Museum of the Brazos Valley in Bryan, Texas.

3.2.1 Experimental protocol

In the experiment, each child was tested individually in a quiet, private space and was guided to go through the steps below:

1) *Baseline*: The child watches a neutral nature video for 5 minutes.
2) *Paced breathing*: The child performs DB for 5 minutes with the aid of an audiovisual pacing signal.
3) *Health Ninjas*: The child plays Health Ninjas for 6 minutes.
4) *Color Word Test*: The child plays Stroop CWT for 5 minutes.

In order for the children to get familiar with Health Ninjas before the experiments, we prepared training slides and videos to teach them how to play the game, for e.g., which objects should be sliced or avoided; how does the fence or the snow change based on the breathing rate; how to do deep breathing, etc.

3.2.2 Results and discussion

We calculated the average breathing rate of all the subjects in each step – see Figure 7, and the result indicated that all children were able to reach the desired target (12 BPM) during paced breathing and more importantly, maintain it during the Health Ninjas game. The preliminary results support the feasibility of keeping children engaged in deep breathing exercises during gameplay.

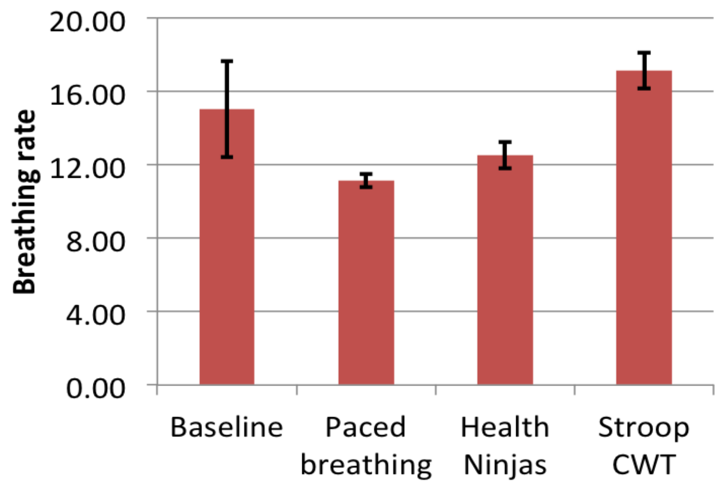


Figure 7. Average breathing rate at each step.

Based on the observations from pilot study and our tests, however, we identified several areas for improvement for the game:

- We could let the game adapts the target rate based on the child's ability to conduct slow breathing.
- Many children got lost during the game: this indicated we need to add necessary in-game guidance or instructions.
- Some children ignored the nutrition education: this suggested that we need to change the reward and penalty scheme.

We discuss these issues in detail in the next section and propose feasible solutions.

4 METHODS

In this section, we describe the improvements of Health Ninjas and the experimental design. We also present other tools and functionalities designed to help with the experiments. In the following subsections, we first present significant improvements to Health Ninjas based on observations from the pilot study. Secondly, we describe the experimental design, including the independent variables and treatment conditions. Then we present two additional games – a “Nutrition Quiz” game to test general nutrition knowledge of the child, and a paced breathing game to familiarize the child with deep breathing. Finally, we describe our experimental-friendly screens for conducting the user studies.

4.1 Improvements to the original Health Ninjas app

After a thorough analysis of all subjects’ behaviors during the pilot study, we made several significant modifications on Health Ninjas. Several new game elements and functionalities were added to the game to better communicate the desired behaviors and make it more appealing and engaging altogether. Namely, we improved Health Ninjas in the following aspects:

- *Calibration*: We let the game adapts automatically to children with different breathing rate ranges.
- *Guidance and instruction*: We implemented in-game features to provide necessary guidance and instructions for the child to perform DB.

- *Rewards and Penalty mechanism*: We increased the reward for slicing a healthy food and the penalty for slicing a junk food to emphasize nutrition knowledge.
- *Game experience:* We rewrote the biofeedback function and redesigned the game UI to provide instaneous feedback and smoother gaming experience.

4.1.1 Calibration

Six breaths per minute is the best breathing rate for adults to attain maximum heart rate variability (Vaschillo et al., 2006), and Kajander and Peper (1998) had suggested a target rate around 6 BPM to teach children slow breathing. However, the respiration rate varies from 12 BPM to 28 BPM for children from 6 to 12 years old (Fleming et al., 2011), thus for the pilot study we had set 12 BPM as the target respiration rate instead of 6 BPM.

Nevertheless, a static target rate is unlikely applicable to all children considering the large variation of breathing rate, thus the target rate needs to be adaptable to different children. To solve this issue, we developed a calibration function to obtain a "personalized" target breathing rate properly within each child's capability, in order to perform deep breathing appropriately and safely.

For this purpose, we integrated a calibration function into the game. During the calibration phase, the child is asked to perform deep breathing within his or her capability for 2 minutes - see Figure 8 (a). After that, the game analyses the calibration data and calculates the first quartile (designated Q1 or the 25th percentile) as the target rate – see Figure 8 (b). This personalized target rate is a safe and a reliable rate for the child to perform DB.

(a) (b)

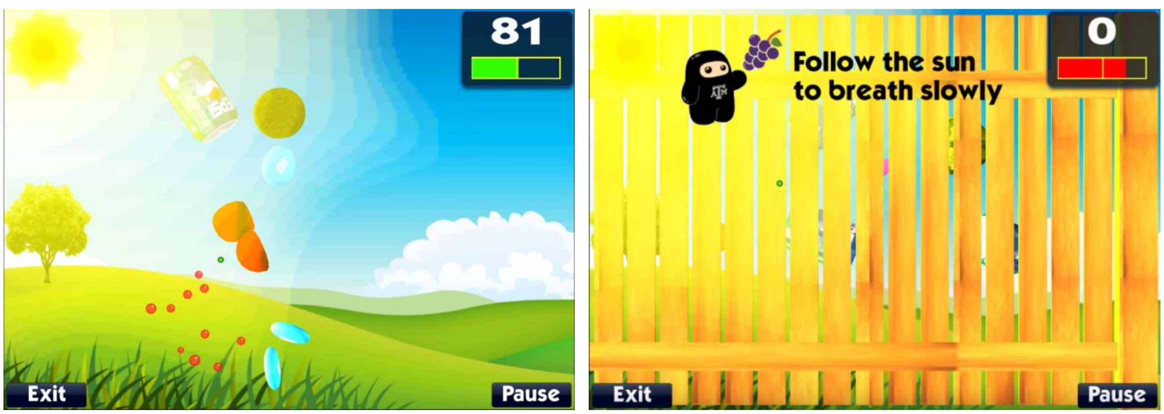
Figure 8. Calibration screens (a) during calibration, the screen shows the elapsed time (b) after calibration, the screen shows calculated target rate.

4.1.2 Guidance and instruction

During the pilot study, we noticed that several children got lost (for e.g., did not know how to control or lower down their breathing rate), which caused the game area to become occluded. We attributed this reaction to the lack of necessary in-game guidance or instructions for the child to follow. Therefore, we added the following two game elements:

- Pacing signal: we placed an animated sun on the top-left corner of the screen that expands and compresses based on the calibrated target breathing rate of the subject. The sun serves as an “all-time” pacing signal for the child to follow and synchronize their breathing rate – see Figure 9 (a). The child is supposed to inhale when the sunlight is expanding and exhale when the sunlight is compressing. To produce greater reductions in SCL, the child is guided to inhale 40% and exhale for 60% of the time (Pastor, Menéndez, Sanz, & Abad, 2008). For example, if the calibrated target rate is 12 BPM (5 seconds per breath), the sun will compress for 2 seconds and expand for 3 seconds.

- Textual instruction: When the child's breathing rate exceeds the maximum tolerance (for e.g., 6 BPM over the target rate), the game shows the text "Follow the sun to breath slowly" as a reminder for the child to breathe slowly following the pulsing sunlight – see Figure 9 (b).



(a) (b)

Figure 9. Guidance and instruction screens: (a) pulsating sun as the pacing signal. (b) text instruction.

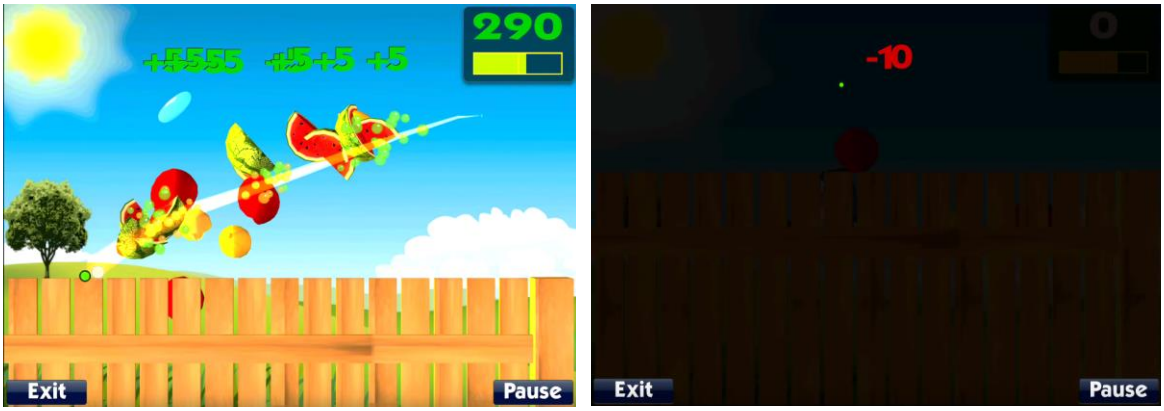
4.1.3 Rewards and penalty mechanism

Video games provide an immensely compelling and rewarding experience, which could be utilized to enhance learning and complete instructional objectives (Garris et al., 2002). In the pilot study, we noticed that some children kept swiping the screen no matter which objects (fruits or junk foods) showed up in the game area. Thus we modified the reward and penalty mechanism in the hope that the child would swipe more fruits and avoid junk foods to gain a better perception between healthy and junk food.

We added new game objects and functionalities to increase the contrast between swiping healthy foods and swiping junk foods. We also added audio feedback which made the game more appealing - see Table 1 for the updated game mechanism. Specifically we made modifications as follows:

- Rewards: We added several "super fruits" (e.g., pomegranates, cherries, grapes, kiwi, peach, pineapple, raspberry, strawberry, coconuts, etc.) into the game, which appear every 20 seconds as an element of surprise: slashing them will reward more points and generate a burst of bonus fruits – see Figure 10 (a). We also spent much effort on designing these super fruits as exquisitely made 3D models which would be more appealing to children.
- Penalty: We added a "blind screen" effect such that the screen becomes black for 2 seconds after the child slices a junk food - see Figure 10 (b). In this manner, the child is prevented from playing the game for a short period, which makes the game less interesting for them. Additionally, slicing a junk food will trigger a sound effect "Oh gross!" as an audio alert.

Compared with the prototype, the game mechanism is revised such that the behavior of slicing healthy food (for e.g., fruits) is much more encouraged and the behavior of slicing junk food is more discouraged.



(a) (b)

Figure 10. Rewards and penalty (a) slicing super-fruit generates a burst of fruits (b) the screen blinds when slicing junk foods.

	Swiping Fruits	Swiping Junk Foods	Swiping Super Fruits
Score change	+5 points	-10 points	+30 points
Audio feedback	Encouraging words	Discouraging words	Encouraging words
Rewards/Penalty	Points	Blind screen	Bonus fruits

Table 1. Game mechanism for Health Ninjas

4.1.4 Instaneous biofeedback

Most respiratory sensors synchronize breathing rate every one second, which may work in real-life training and monitoring. However, this is not applicable to a game which updates frame by frame. For example, in the prototype of Health Ninjas, the fence height changed in a rather “choppy” manner, which did not reflect the real-time breathing rate. Thus in order to attain smoother biofeedback and real-time game experience, we applies

PD control to calculate the instaneous breathing rate every frame (0.05 second) to provide real-time biofeedback. As show in equation (1), $rr(t)$ which is the respiration rate at frame t, is calculated based on previous predicted breathing rates $rr(t-1)$ and $rr(t-2)$, and the latest recorded breathing rate - rr_new which is synchronized from the sensor.

$$rr(t) = rr(t-1) - \alpha * (rr(t-1) - rr\_new) - \beta * \frac{(rr(t-2) - rr(t-1))}{dt} \quad \textbf{(1)}$$

$$\alpha = 0.035, \beta = 0.001, dt = 0.05s.$$

4.1.5 Game cosmetics

We also redesigned the cosmetics of the game to make it more appealing and more like a “real” game instead of a research tool. For example, we removed unnecessary data panel from the gameplay to keep the game simple and neat; we added floating score effect which could motivate the child to make more scores; we also used playful fonts which are more consistent with the game play. In this manner, the game becomes more interesting and fun to play.

4.2 Experimental design

With our improved game, we would like to test the following two aspects:

1) To test whether children are able to follow subtle biofeedback cues (indirect biofeedback) or need a more explicit feedback (direct biofeedback);
2) To test whether playing the game changes children’s perception of healthy vs.

junk foods.

Based on the above two objectives, we selected biofeedback strategy and nutrition education as independent variables.

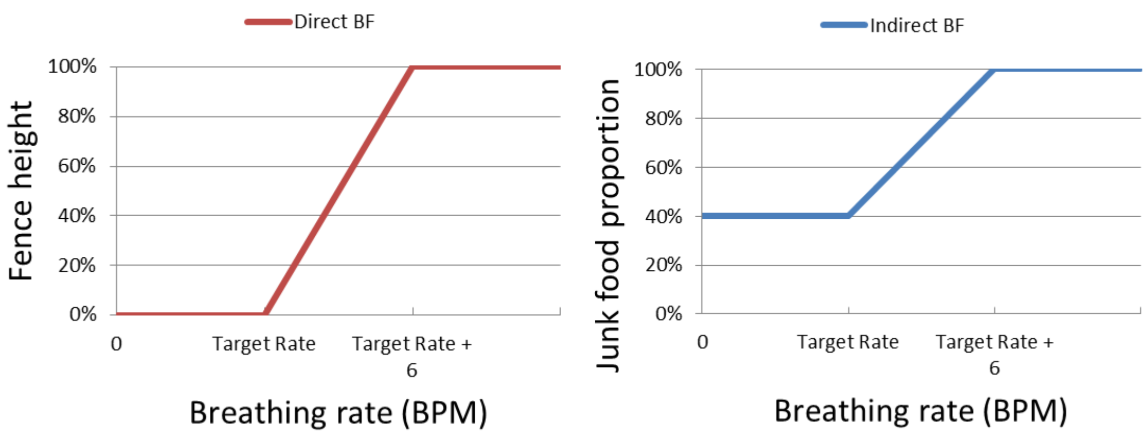
4.2.1 Biofeedback strategy

To test which type of game adaptation (biofeedback strategy) is more effective to keep children engaged, two game elements are adapted dynamically as follows:

- *Fence height (Direct biofeedback)*: the higher the breathing rate, the higher the fence stands - see Figure 11 (a). The screen will be entirely occluded by the fence if the breathing rate is out of range. We call this direct biofeedback because the game provides an intuitive and explicit feedback. The fence also serves as a forceful punishment when the child's breathing rate is out of range, as the fence fully occludes the screen and stops the child from further playing the game (e.g., swiping the fruits / junk foods).
- *Junk proportion (Indirect biofeedback)*: the higher the breathing rate, the larger the proportion of junk foods - see Figure 11 (b). There will be no fruits to slice if the breathing rate is out of range. In order to make the game challenging, the proportion of junk foods changes from 40% to 100%. Compared with direct biofeedback, the game provides a less intuitive and more implicit feedback. That is why we call this indirect biofeedback. Additionally, instead of performing direct feedback as the fence does, the indirect biofeedback only provides subtle

biofeedback cues (e.g., changes in the food proportion). Thus the child is still able to swipe when the breathing rate is out of range, however, he / she will not be able to make scores (only junk foods in the game screen).

Noticeably, unlike the prototype where the game adapts based on the static target rate 12 BPM, the improved game biofeedback adapts based on the calibrated target rate for each subject. Moreover, we set 6 BPM as the tolerance such that the penalty is maximized when the subject's breathing rate is above 6 BPM over the target breathing rate.



(a) (b)

Figure 11. Relationship between (a) fence height and breathing rate (b) junk food proportion and breathing rate.

4.2.2 Nutrition education

To test if playing the game changes the children's perception of healthy vs. junk food, we also developed a control version of "Health Ninjas", where the fruits are replaced by colorful balls (red, orange and green) and junk foods are replaced by cartoon-like bombs. In this manner, children in the control group will not be able to associate fruits / junk foods with positive / negative effects (e.g., no nutrition education). Below are the two versions of the game:

- *Fruits vs. Junk (nutrition education game)*: The child slices fruits (apple, orange, watermelon) to increase game score and avoids junk foods (M&Ms, cookies, soda).
- *Balls vs. Bomb (control game)*: The child slices colorful balls (red, orange, green) to increase game score and avoids bombs.

4.3 Treatment conditions

Based on the independent variables and our implementations of the game, we obtain the following 4 treatment conditions as follows:

- *Nutrition education game with direct biofeedback (DBF)*: Children in this condition play Fruits vs. Junk game. The fence goes up and down according to their breathing rate – see Figure 12(a).
- *Nutrition education game with indirect biofeedback (IBF)*: Children in this condition play Fruits vs. Junk game. The proportion of junk/healthy food changes according to their breathing rate – see Figure 12 (b).
- *Control game*: Children in this condition play the Balls vs. Bombs game. No biofeedback is included in the game (i.e., respiration does not affect the game) – see Figure 12 (c).
- *Biofeedback only (BF only)*: This is a training game for children to practice slow breathing with direct biofeedback. Children in this condition do not play a fruit-

slashing game. Instead, they need to follow the fence, which goes up and down according to their breathing rate – see Figure 12 (d).

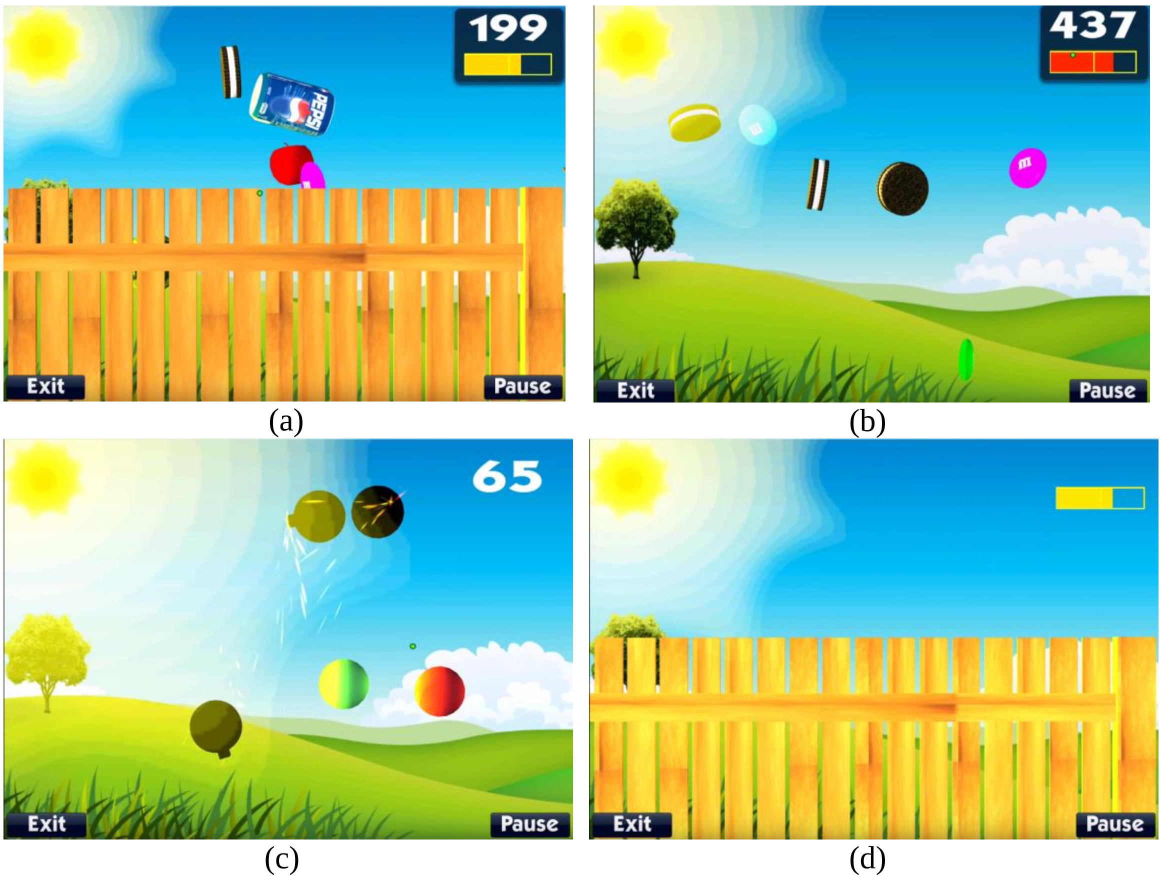


Figure 12. (a) NE+DBF: nutrition education game with direct biofeedback (b) NE+IBF: nutrition education game with indirect biofeedback (c) control game (d) BF Only: biofeedback only.

4.4 Nutrition Quiz game

We developed a game called "Nutrition Quiz" to test whether the child is able to discriminate between healthy and unhealthy foods. The game is designed based on procedures developed by Nguyen (2008), which consists of 24 target foods - 12 healthy versus 12 unhealthy food - see Table 2.

Healthy food	**Unhealthy food**
Pear	Apple pie
Carrot	French fries
Chicken	Sausage
Cheese	Ice cream
Water	Soda pop
Bread	Donut
Milk	Cupcake
Soup	Hot dog
Salad	Hamburger
Raisins	Potato chips
Strawberries	Cookies
Juice	Cake

Table 2. Heathy foods vs. unhealthy food in Nutrition Quiz.

The child scores one point for correctly identifying the healthy food in the two given foods - see Figure 13. The result provides a measure of general nutrition knowledge.

Figure 13. Nutrition Quiz game screenshot.

4.5 Paced breathing game

We developed a paced breathing game to familiarize the child with the pacing signal (pulsing sun) before playing the Health Ninjas game. In this game, the child inhales when the sun expands and exhales when the sun compresses – see Figure 14.

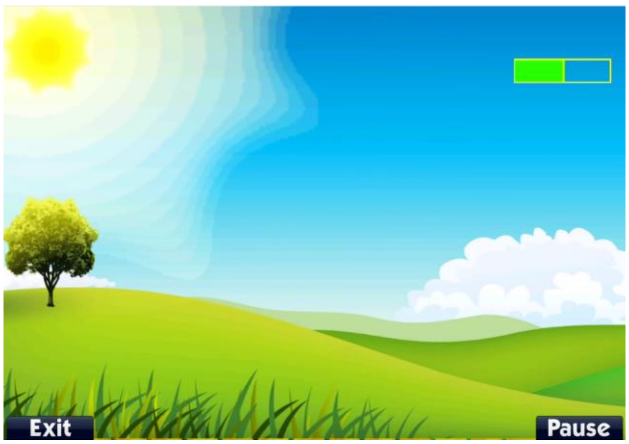


Figure 14. Paced breathing game screenshot.

4.6 Experiment-friendly screens and functionalities

To help the experiment flow better and minimize the chance of error, we implemented several experiment-friendly screens that help experimenters complete the required steps as the experiment preparation – see Figure 15.

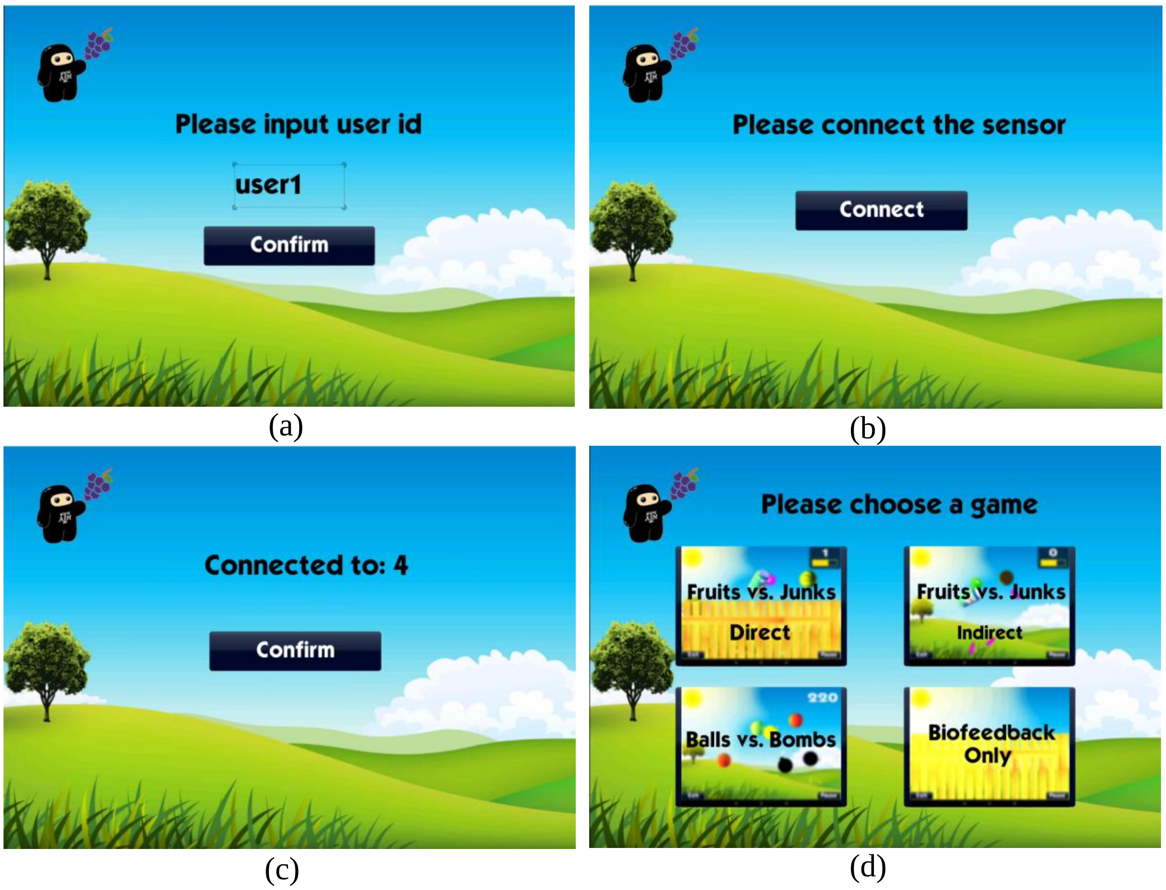


Figure 15. Instruction screens for experiments (a) input user id for the subject (b) connect the respiration sensor (c) confirm the connection (d) choose one of the treatments.

Specifically, the screens include the following steps:

1) Input the user id for the subject – see Figure 15 (a).

2) Connect the tablet with the Bioharness sensor - see Figure 15 (b).
3) Confirm the tablet is connected with the correct sensor on the child - see Figure 15 (c).
4) Start calibration phase and confirm the target breathing rate – see Figure 8.
5) Choose the correct game based on the treatment condition - see Figure 15 (d).

For safety reasons, we also developed a log functionality which monitors the game process and backups all the crucial information (for e.g., user id, treatment condition) and data (for e.g., respiration rate, time stamp) into a local text file on the device. This guarantees that all these data could be retrieved if the game crashed or the experimenter did not take down the correct information.

5 USER STUDY AND RESULTS

In this section, we describe the user study and provide a thorough analysis of the results. The user study aimed at comparing the effectiveness of different game adaptations (Direct BF and Indirect BF) in deep breathing and validating the feasibility of Health Ninjas to change the children's perception of healthy vs. junk foods. The results of the user study indicated that compared with Indirect BF, Direct BF is more effective at keeping children engaged and breathing slowly.

In the following subsections, we first describe the experimental protocol for the user study, including the detailed description of groups, conditions and the steps. Then we discuss how we preprocessed the data and explain the features we selected to interpret the data. Finally, we provide a thorough analysis of the data, and a detailed discussion of the results.

5.1 Experimental protocol

With our objectives and the treatments in mind, we divided the user study into two comparative studies A and B as follows:

A. *Control game* vs. *Nutrition education game with direct biofeedback (DBF):* This study aimed to evaluate the feasibility of Health Ninjas to change the child's perception of healthy vs. junk foods. It also evaluated the effectiveness of game biofeedback in lowering down the child's breathing rate.

B. *Nutrition education game with indirect biofeedback (IBF)* vs. *Nutrition education* *game with direct biofeedback (DBF):* This study aimed to compare the effectiveness of Direct Biofeedback and Indirect Biofeedback to keep children engaged and breathing slowly.

Specifically, each study was conducted as a within-subjects design, where each subject went through two treatments in a random order (counterbalancing). Depending on the order of treatments, study A is divided into group 1 and group 2; study B is divided into group 3 and group 4 – see Table 3.

Study	**Group**	**Treatment 1**	**Treatment 2**
Study A	Group 1	Control	DBF
	Group 2	DBF	Control
Study B	Group 3	IBF	DBF
	Group 4	DBF	IBF

Table 3. User study groups.

For our study, we recruited children (N=20; 8 – 9 year olds; 7 boys and 13 girls) and conducted the experiments at the University of Central Lancashire, U.K. The subjects were recruited from a UK primary school in a semi-rural school with a single form intake. The subjects are from a middle socio-economic class, with almost all children being in privately owned housing. Out of the 20 subjects, 8 subjects participated in Study A (5 subjects in Group 1 and 3 subject in Group 2), and 12 subjects participated in Study B (5 subjects in Group 3 and 7 subjects in Group 4).

In the experiment, each child was guided to go through the steps as below:

1. *Deep breathing calibration:* The child performs deep breathing within his or her

capability for 2 minutes.

2 *Treatment 1*: The child plays treatment 1 for 6 minutes.

3 *Nutrition Quiz*: The child plays the Nutrition Quiz game the first time.

4 *Treatment 2*: The child plays treatment 2 for 6 minutes.

5 *Nutrition Quiz*: The child plays the Nutrition Quiz game the second time.

5.2 Data collection and preprocessing

We collected the breathing rates of each subject to compare the effectiveness of different game adaptations (Direct BF and Indirect BF) in deep breathing, and collected the scores of Nutrition Quiz to validate the feasibility of Health Ninjas to change the child's perception of healthy vs. junk foods.

5.2.1 Breathing rate

We collected each subject's breathing rates throughout the experiment with a Bioharness 3 sensor (Zephyr, 2014). Since each subject went through two treatments, we calculated the minimum breathing rate (MinBR), average breathing rate (AvgBR) and maximum breathing rate (MaxBR) for each treatment. By comparing these three features, we were able to see which treatment was more effective in keeping the subject engaged and breathing slowly.

We calculated the mean and the standard deviation of the target rate for all the subjects, and we obtained an average target breathing rate = 14.9 BPM with standard deviation = 3.5 BPM. Thus, the target breathing rate varies much among different subjects. In order to eliminate this subject-dependent factor (TargetBR) so as to compare the effectiveness of each treatment, we calculated the "performance" score of each treatment as follows:

$$performance = 1 - \frac{BR - TargetBR}{ToleranceBR} \qquad \textbf{(2)}$$

$$ToleranceBR = 6\,BPM$$

As shown in equation (2), performance score is a metric that converts the absolute value of BR to a relative value measured against target rate. Performance score increases with decreased breathing rate. Thus a treatment attains better performance if it produces lower BR. Specifically, the performance score of a treatment adapts to its associated BR as follows:

- *At or below TargetBR*: The performance score is equal or larger than 1. This indicates the treatment is able to guide the child to breathe at the ideal BR.
- *Between TargetBR and TargetBR + 6*: The performance score is between 0 and 1. This indicates the treatment is able to maintain the subject breathing within the desired range.
- *Above TargetBR + 6*: The performance score is negative. This indicates the treatment is not able to guide the child to breathe within the desired range.

As an example, if the TargetBR is 12 BPM, the relationship between performance and breathing rate is shown in Figure 16 as below:

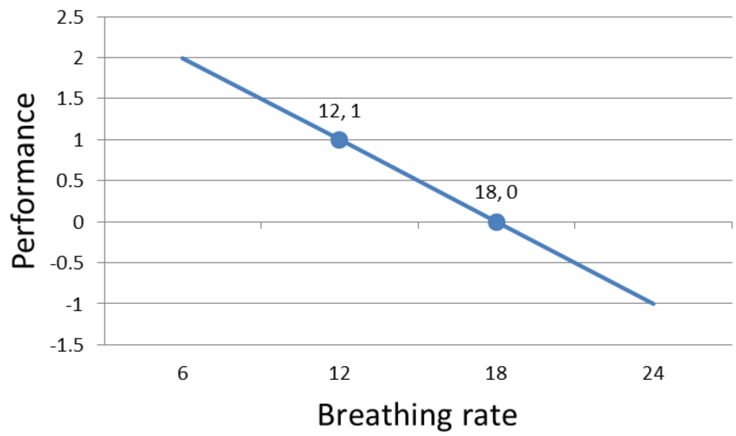


Figure 16. Example of relationship between performance and breathing rate (TargetBR = 12 BPM).

With the formula of performance, we obtain the following three performance metrics for MinBR, AvgBR and MaxBR:

- *Best performance:* This feature represents the ability of a treatment to bring the child's breathing rate at or below the target rate - see equation (3).

$$Best\ performance\ = 1 - \frac{MinBR - TargetBR}{ToleranceBR} \quad \textbf{(3)}$$

- *Average performance*: This feature represents the effectiveness of a treatment to maintain the child's breathing rate within the tolerance (+6 BPM) of the target rate - see equation (4).

$$Average\ performance\ = 1 - \frac{AvgBR - TargetBR}{ToleranceBR} \quad \textbf{(4)}$$

- *Worst performance:* This feature represents the capability of a treatment to restrict the child's maximum breathing rate within the accepted BR range – see equation (5).

$$Worst\ performance = 1 - \frac{MaxBR - TargetBR}{ToleranceBR} \quad \textbf{(5)}$$

5.2.2 Nutrition knowledge

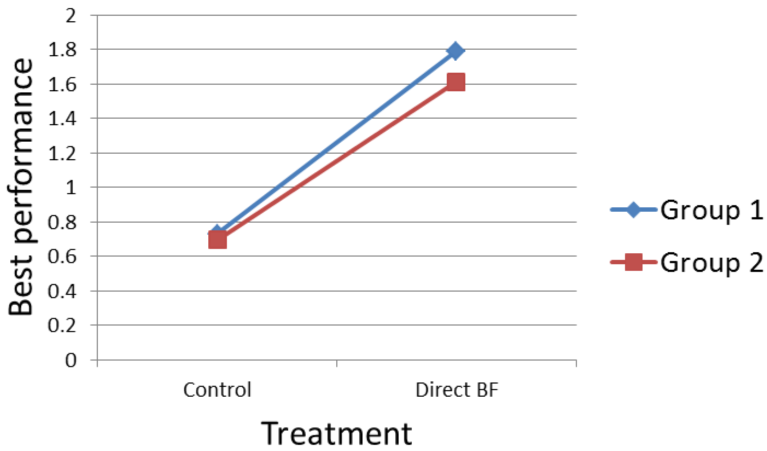
To test whether children in the nutrition education conditions will show better discrimination between healthy and unhealthy foods than those in control group, we collected the score of the Nutrition Quiz game as a measure of the child's general nutrition knowledge. We compared the average score of each treatment (Direct BF, Indirect BF and Control). Moreover, we also did a within-subject analysis for subjects in Group 1 to see if playing the nutrition education game improves their perception of healthy foods vs. unhealthy foods.

5.3 Best performance analysis

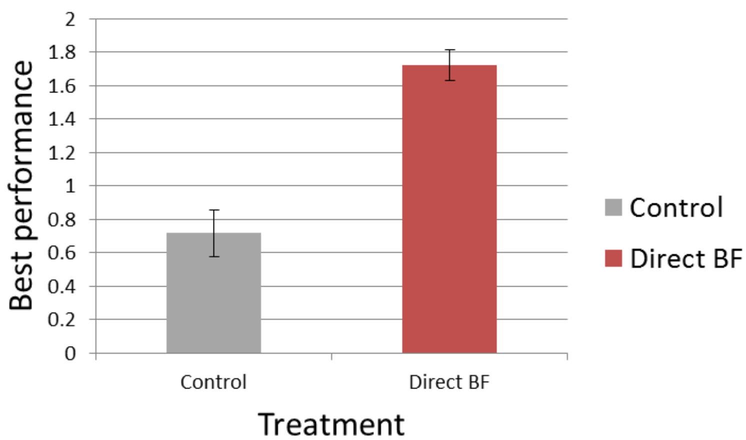
We analyze the best performance of each treatment by firstly comparing the performance of each treatment within study A and study B. Then we combine two sub studies and compare the overall best performance of each condition (Direct BF, Indirect BF and Control) to conclude which treatment is more capable of lowering down the child's breathing rate.

5.3.1 Study A. Control vs. Direct BF

We compared the best performance between Control and Direct BF treatment, as shown in Figure 17.



(a)



(b)

Figure 17. Control vs. Direct BF: (a) the best performance comparison in group 1 & 2 (b) the best performance comparison between Control and Direct BF treatment. Error bars indicate standard error.

For both groups (1 and 2), participants in the Direct BF condition performed better than those in the Control condition – see Figure 17 (a). Then we combined the two groups and calculated the overall best performance, and the result indicated that Direct BF treatment (best performance = 1.72 > 1) is able to lower down the child's breathing rate below the target rate – see Figure 17 (b).

5.3.2 Study B. Indirect BF vs. Direct BF

We compared the best performance between Indirect BF and Direct BF treatment as shown in Figure 18.

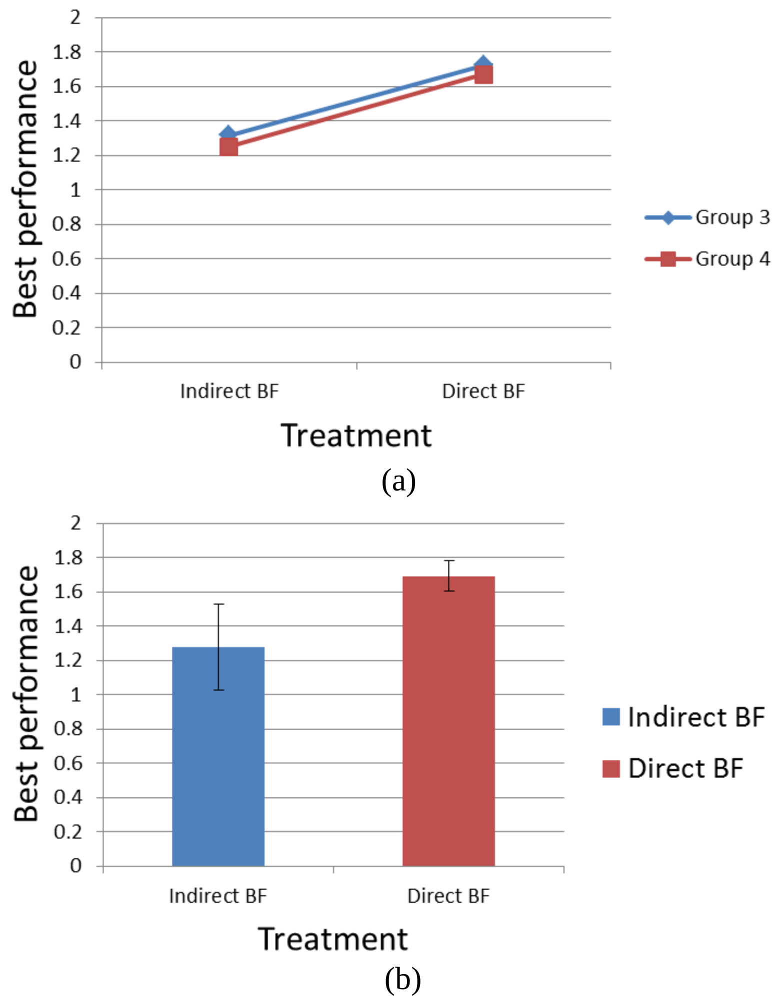


Figure 18. Indirect BF vs. Direct BF: (a) the best performance comparison in group 3 & 4 (b) the best performance comparison between Indirect BF and Direct BF treatment.

For both groups (3 and 4), participants in the Direct BF condition performs better than those in the Indirect BF treatment – see Figure 18(a). Then we combined the two groups and calculated the overall best performance, and the result indicated that both Direct BF (best performance = 1.67) and Indirect treatment (best performance = 1.25) is able to lower down the child's breathing rate below the target rate. The result also suggested that Direct BF performs better than Indirect BF treatment – see Figure 18(b).

5.3.3 Conclusion

Based on the results obtained from study A and study B, we calculated the overall best performance for each treatment among all the subjects – see Figure 19. One-way ANOVA shows a major difference in best performance by the three treatments ($F = 19.86 > F_{crit} = 3.25$, $p < 0.05$).

Specifically, Direct BF condition has an overall best performance 1.7 > 1 and Indirect BF condition has an overall best performance = 1.27 > 1, which is significantly smaller than Direct BF. Thus we can obtain the following conclusions with regard to the best performance:

- Both Indirect BF and Direct BF are effective in lowering down child's breathing rate at or below target rate.
- Direct BF is more effective in lowering down child's breathing rate at or below target rate than Indirect BF.

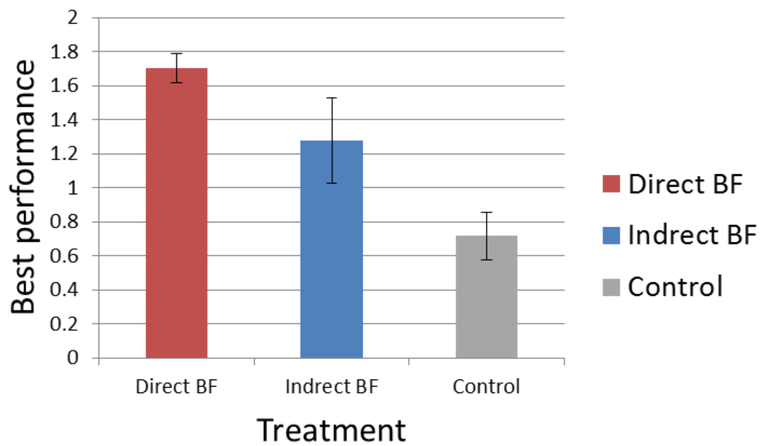


Figure 19. Best performance comparison between three conditions.

5.4 Average performance analysis

We analyze the average performance of each treatment by firstly comparing the performance of each treatment within study A and study B. Then we combine two sub studies and compare the overall best performance of each condition (Direct BF, Indirect BF and Control) to conclude which treatment is more effective in maintaining the child's breathing rate within the desired range.

5.4.1 Study A. Control vs. Direct BF

We compared the average performance between Control and Direct BF treatment as shown in Figure 20.

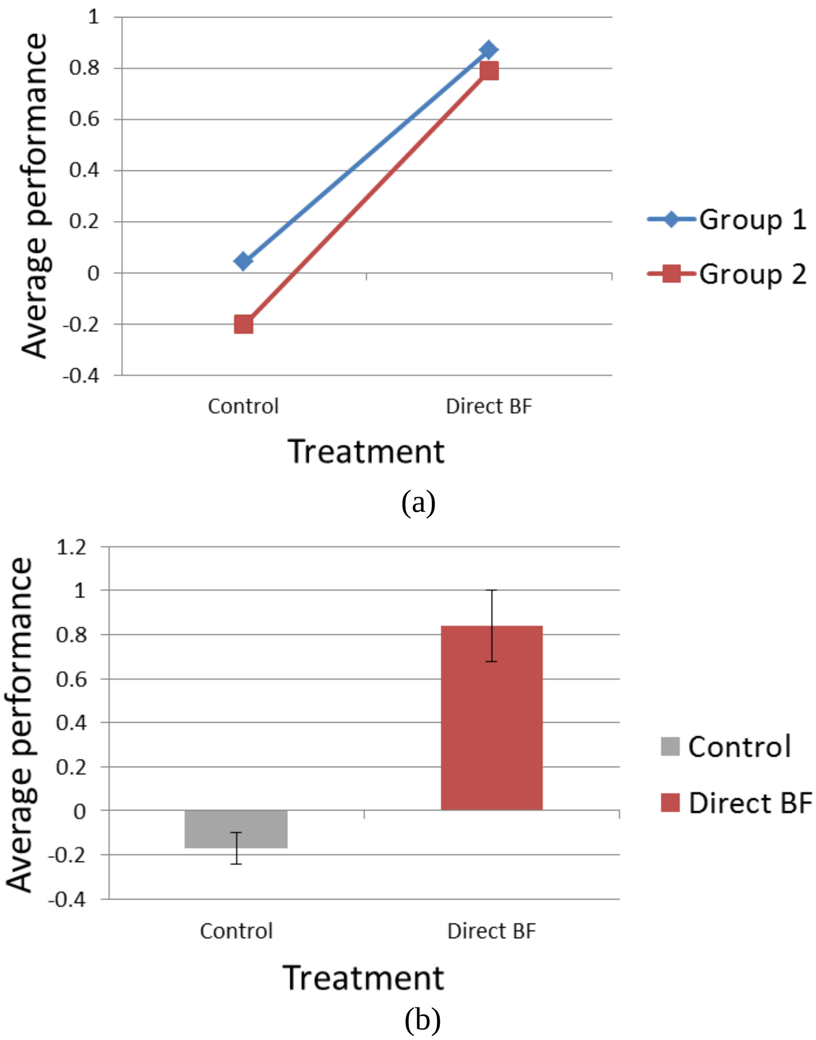
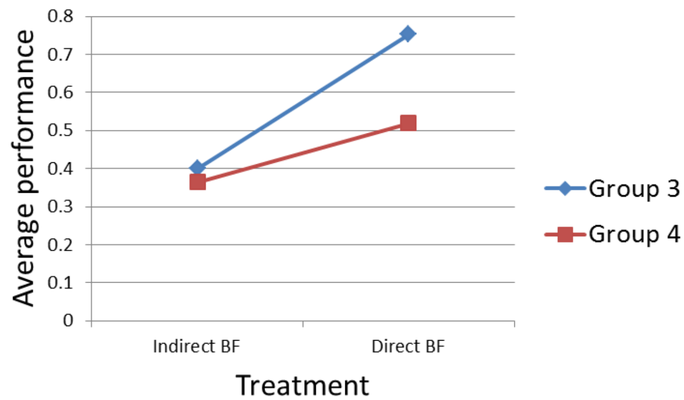


Figure 20. Control vs. Direct BF: (a) the average performance comparison in group 1 & 2 (b) the average performance comparison between Control and Direct BF treatment.

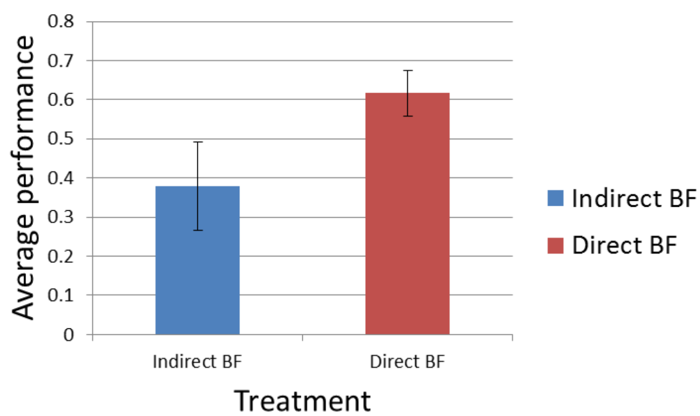
For both groups (1 and 2), participants in the Direct BF condition performed better than those in the Control condition – see Figure 20(a). Then we combined the two groups and calculated the overall average performance, and the result indicated that Direct BF treatment (average performance = 0.83 > 0) is effective in maintaining the child's breathing rate within the desired range – see Figure 20(b).

5.4.2 Study B. Indirect BF vs. Direct BF

We compared the average performance between Indirect BF and Direct BF treatment as shown in Figure 21.



(a)



(b)

Figure 21. Indirect BF vs. Direct BF: (a) the average performance comparison in group 3 & 4 (b) the average performance comparison between Indirect BF and Direct BF treatment.

For both groups (3 and 4), participants in the Direct BF condition performs better than those in Indirect BF treatment – see Figure 21(a). Then we combined the two groups and calculated the overall average performance, and the result indicated that both Direct BF (average performance = 0.62 > 0) and Indirect treatment (average performance = 0.38 > 0) is effective in maintain the child's breathing rate within the desired range. The result also suggested that Direct BF performs better than Indirect BF treatment – see Figure 21(b).

5.4.3 Conclusion

Based on the results obtained from study A and study B, we calculated the overall average performance of each treatment among all the subjects – see Figure 22. One-way ANOVA shows a significant effect on average performance based on different treatment ($F = 16.6 > F_{crit} = 3.8$, $p < 0.05$)

Specifically, Direct BF condition has an overall average performance = 0.71 > 0 and Indirect BF condition has an overall average performance = 0.38 > 0, which is smaller than Direct BF. Thus we can obtain the conclusions with regard to average performance as follows:

- Both Indirect and Direct BF are effective in maintaining child's breathing rate within the desired range of target breathing rate.
- Direct BF is more effective in maintaining a lower breathing rate than Indirect BF.

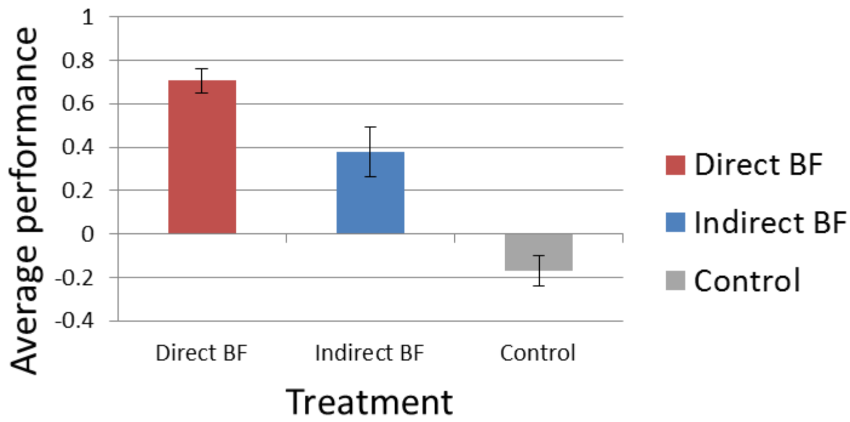


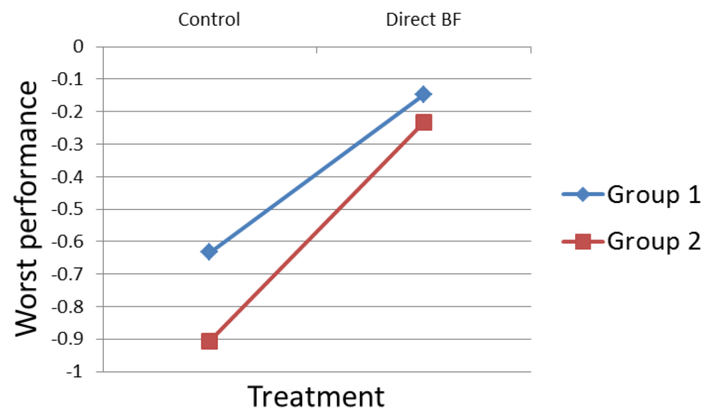
Figure 22. Average performance comparison between three conditions.

5.5 Worst performance analysis

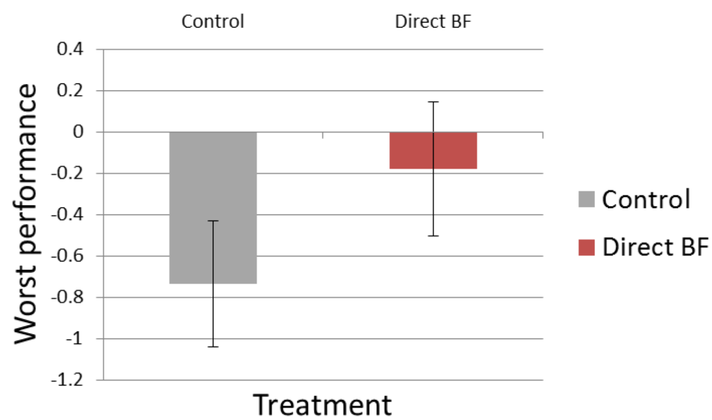
We analyze the average performance of each treatment by firstly comparing the performance of each treatment within study A and study B. Then we combine two sub studies and compare the overall best performance of each condition (Direct BF, Indirect BF and Control) to conclude which condition is more effective in restricting the child's breathing rate within the desired range (target BR + 6).

5.5.1 Study A. Control vs Direct BF

We compared the worst performance between Control and Direct BF treatment in both groups (1 and 2), and both groups indicated that Direct BF performs better than Control condition – see Figure 23(a). Then we combined the two groups and calculated the overall average performance, and the result indicated that Direct BF treatment (worst performance = -0.18 < 0) is not able to restrict the child's breathing rate within the desired range – see Figure 23(b).



(a)

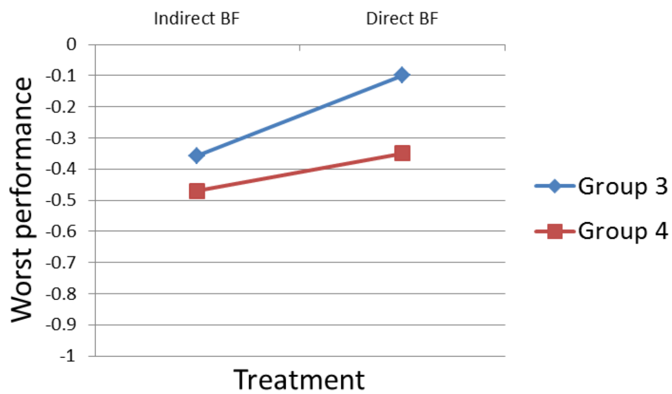


(b)

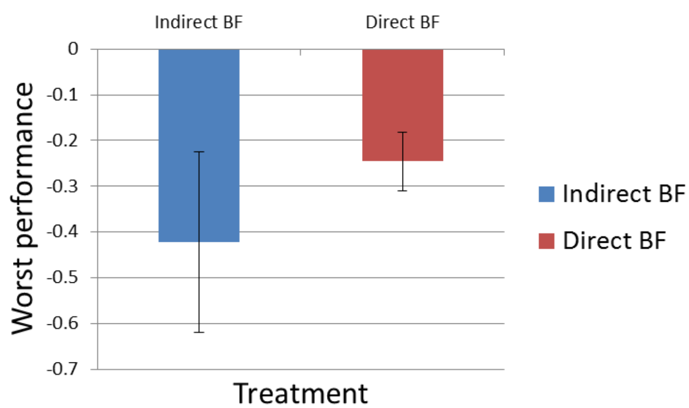
Figure 23. Control vs. Direct BF: (a) the worst performance comparison in group 1 & 2 (b) the worst performance comparison between Control and Direct BF treatment.

5.5.2 Study B. Indirect BF vs. Direct BF

We compared the average performance between Indirect BF and Direct BF treatment in both groups (3 and 4), and both groups indicated that Direct BF performs better than Indirect BF treatment – see Figure 24(a). Then we combined the two groups and calculated the overall average performance, and the result indicated that both Direct BF (worst performance = -0.25 < 0) and Indirect treatment (worst performance = -0.42 < 0) is not effective in restricting the child's breathing rate within the desired range. The result also suggested that Direct BF performs better than Indirect BF treatment – see Figure 24 (b).



(a)



(b)

Figure 24. Indirect BF vs. Direct BF: (a) the worst performance comparison in group 3 & 4 (b) the worst performance comparison between Indirect BF and Direct BF treatment.

5.5.3 Conclusion

Based on the results obtained from study A and study B, we calculated the overall worst performance for each condition among all the subjects – see Figure 25. One-way ANOVA shows a significant effect on worst performance based on different treatments ($F = 4.4 > F_{crit} = 3.25$, $p < 0.05$).

Specifically, Direct BF condition has an overall performance = - 0.2 < 0 and Indirect BF condition has an overall performance = - 0.4 > 0, which is smaller than Direct BF. Thus we can obtain the conclusions with regard to performance as follows:

- Neither Indirect nor Direct BF is able to prevent the child's maximum breathing rate from ever exceeding the tolerance (6 bpm above the target rate).
- However, direct BF is more effective in restricting the child's maximum breathing rate than Indirect BF.

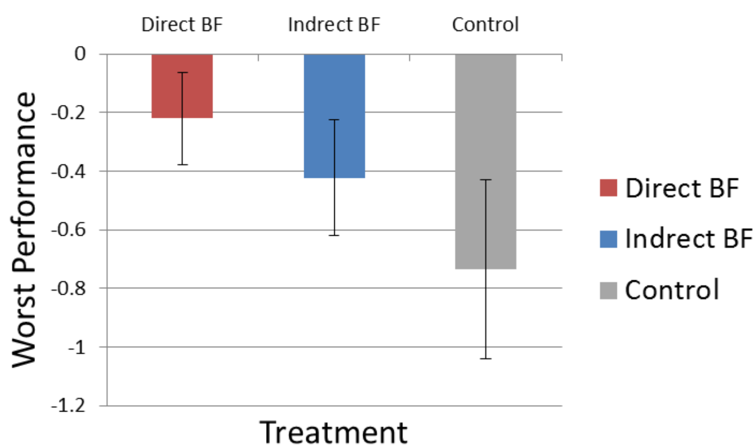


Figure 25. Restriction comparison between three conditions.

5.6 Nutrition knowledge analysis

To test whether children in the nutrition education conditions will show better discrimination between healthy and unhealthy foods than those in control group, we collected the score of the Nutrition Quiz game as a measure of the child's general nutrition knowledge. We observed that most of the subjects were able to correctly identify all the healthy foods. We compared the average score for each treatment by averaging the subjects who took first time nutrition quiz score – see Figure 26. The results indicated that all three conditions can produce a very high score (children in each condition can correctly identify more than 11 of the 12 questions), and there was no significant difference between the effects of different treatment on nutrition quiz score.

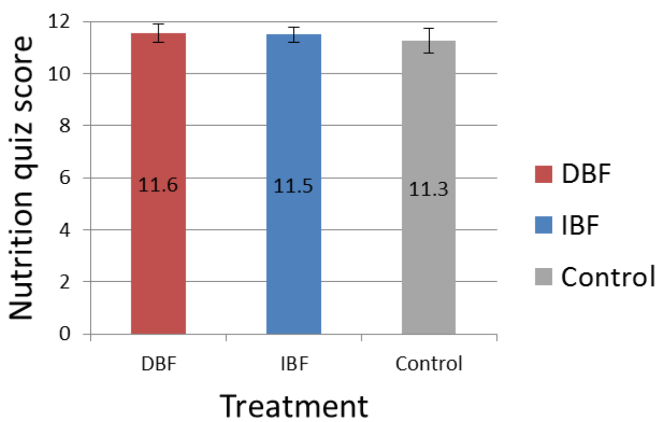


Figure 26. Average Nutrition Quiz score of each treatment. Error bars indicate standard error.

5.7 Discussion

5.7.1 Performance

Combining the results of all three aspects of performance analysis, we can obtain the following conclusions:

- Both Indirect and Direct BF strategy are able to lower down the child's breathing rate at or below the target BR, and more importantly, maintain the child's target rate within the desired range (target BR + 6).
- Direct BF performs better than Indirect BF on all three aspects of performance (best, average and worst).

During the experiments, we noticed that some subjects in the Direct BF condition were unable to control their breathing at first, and saw the fence coming up all the way until it occluded the whole screen. As indicated by Professor Read, who conducted the experiments: "some children would stare at the fence hoping it would go down - we advised them to look away and think of kittens and beaches." This phenomenon can be eliminated by training or playing the game several times.

5.7.2 Nutrition knowledge

The results of Nutrition Quiz indicated that subjects in all three conditions can produce a very high score. We attributed this result to the fact that the Nutrition Quiz is very easy and children generally do not need the nutrition education intervention to correctly identify all the healthy foods in the quiz. We may need a more difficult test to evaluate the effectiveness of our nutrition education.

6 CONCLUSIONS AND FUTURE WORK

In this thesis, we have presented a personalized biofeedback game, Health Ninjas, to teach children deep breathing and nutrition knowledge. With the promising result of our user study, Health Ninjas has been proved as an effective game to keep children engaged in deep breathing exercises during gameplay. More importantly, the comparison between direct biofeedback and indirect biofeedback modes in Health Ninjas also indicates that children need an intuitive, explicit biofeedback strategy to better perform the desired behaviors.

In this section, we discuss the significance / innovation of our work and some potential future directions to improve our work.

6.1 Contributions

This thesis is innovative in two important respects. First, it integrates biofeedback with games such that children learn to regulate their emotion or stress response while performing an engaging task. In this fashion, children have little opportunity for boredom that would otherwise lead them to stop their practice. This is unlike traditional approaches to biofeedback wherein the user attempts to relax in a calm atmosphere that may or may not accurately reflect daily life. Second, our research is innovative because it is able to test, for the first time, the relative contributions of game-based emotional self-regulation and nutrition education in children exposed to acute stress. We expect that this work will lead to new technological interventions that allow children to achieve better self-regulation through biofeedback gameplay anytime, anywhere, using low-cost mobile devices. Lastly, our thesis is innovative because it is able to test and compare between different biofeedback strategies, e.g., subtle cues vs. direct feedback. Our results provide useful insights into the future development of biofeedback games for children.

The capability to cope with stress and regulate emotions is vital in promoting emotional and social wellbeing in children (Aldwin, 2007). We propose an effective game intervention to teach children how to manage their emotions and enhance their self-regulation skills when they are immersed in a stressful environment. Our proposed work is significant because we create an effective and developmentally appropriate biofeedback strategy that teaches children emotional self-regulation skills aimed at reducing physiological arousal in the face of acute stress, accomplished by embedding biofeedback into an engaging videogame. More importantly Health Ninjas is a biofeedback game designed for children because it takes consideration of children's abilities, while providing necessary guidance and instructions. To the best of knowledge, ours is the first to incorporate calibration function into the game to obtain a "personalized" target breathing rate within the child's capability, and more importantly, to provide intuitive visualization of desired breathing patterns for the child to follow.

Our work is also important because it integrates self-regulation training with nutrition education. Health Ninjas aims to teach children self-regulation with casual biofeedback games as a nutrition education and obesity prevention strategy. To the best of our knowledge, Health Ninjas is the first game to integrate self-regulation training into a nutrition education program to educate children to cope with emotional overeating. Health Ninjas also combines nutrition education with game-based biofeedback strategies to promote children's healthy food choices and eating behaviors after exposure to acute stress.

6.2 Stress reactivity measurement

Our study measures breathing rate (BR) as the major indicator of physiological arousal during the game. For future experiments, it will be more helpful if we collect heart rate variability (HRV) and electrodermal activity (EDA) as follows:

- Heart rate variability (HRV): HRV is the physiological state of variation in the time interval between each heartbeat. HRV is measured by the variation in the beat-to-beat interval and it provides important information of the state of the autonomic nervous system. Higher HRV indicates better functioning of the human body, and better emotional regulation (Berntson et al., 1997).
- Electrodermal activity (EDA): EDA is also known as skin conductance. EDA measures are strong indicators of autonomic activity.

With the analysis of HRV and EDA, we will be able to explore the effects of different biofeedback strategies on physiological state.

6.3 Food choice measurement

Research has been looking at the relationship between stress and eating and it is been shown that food selection changes under stress - people under stress tend to consume more unhealthy high fat foods than health low fat foods (Adam & Epel, 2007; Dallman, 2010; Wallis & Hetherington, 2009). Specifically, Zellner et al. (2006) conducted two studies, indicating that stress causes changes in more consumption of M&Ms and less consumption of grapes. Thus, instead of completing a quiz game to evaluate the effect of our intervention, we could utilize the same measurement to evaluate whether playing Health Ninjas is able to let the child make better food choice. For example, we could test children's consumption of M&M's vs. Grapes after our game intervention. This will also test the relative contributions of game-based emotional self-regulation and nutrition education on food choice and eating behaviors in children exposed to acute stress.

6.4 Improvements of Health Ninjas

Health Ninjas is a personalized biofeedback game to teach children deep breathing and nutrition knowledge, and we believe it could be improved as follows:

- *User profile:* We could set up a user profile to store the user's activity information, For example, the changes in their target rate over time, the maximum score they have attained, and the changes in average breathing rate over time, etc. A server-client infrastructure could be applied such that the user could login to different devices while playing the game synchronized with their progress.
- *Incorporate more food objects*: Health Ninjas now has 18 in-game objects: 3 fruits, 3 junk foods and 12 super fruits. We could add more 3D game objects into Health Ninjas to make it more appealing and fun to play.

- *Sensor-less game:* Research have shown that respiration could be measured accurately via the camera on mobile devices (Garde, Karlen, Ansermino, & Dumont, 2014). Thus, Health Ninjas could be eventually deployed (at large scale, for free) as an app without requiring external sensors. This is also a low cost way to get breathing data in so the game could be marketable in the future.

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