HEART RATE BALANCING FOR MULTIPLAYER EXERGAMES

by

Tadeusz B. Stach

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Abstract

Exergames combine physical activity and entertainment in an effort to increase people’s motivation to exercise. Multiplayer exergames attempt to include the motivating aspects of group activity by allowing two or more people to play together. In most multiplayer exergames, a player’s in-game performance is limited by her physical abilities. Less fit players are demotivated by repeated losses to more fit opponents, while fitter players face a lack of competition from unfit opponents. This situation makes it difficult for people of disparate physical abilities to play exergames together.

This research presents heart rate balancing, a novel player balancing technique to better support engaging experiences in multiplayer exergames. Heart rate balancing bases players’ in-game performance on their effort relative to fitness level rather than their raw power. More specifically, heart rate monitoring is used to set in-game performance based on how closely a person adheres to her target heart rate. Experiments with heart rate balancing show that the technique improves competition between players. A strong correlation was found between people’s perceived effort and their in-game performance with heart rate balancing. The degree to which players noticed the balancing mechanism varied depending on game type. However, heart rate balancing did not interfere with people’s ability to play exergames. These results indicate that the heart rate balancing technique is a promising approach for improving enjoyment and engagement in multiplayer exergames.
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Statement of Originality

I hereby certify that all of the work described within this thesis is the original work of the author. Any published (or unpublished) ideas and/or techniques from the work of others are fully acknowledged in accordance with the standard referencing practices.

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# Table of Contents

Abstract ................................................................................................................................. ii  
Acknowledgements .............................................................................................................. iii  
Statement of Originality ....................................................................................................... iv  

Chapter 1 Introduction ......................................................................................................... 1  
  1.1 Motivation ..................................................................................................................... 2  
  1.2 Problem ....................................................................................................................... 3  
  1.3 Solution ....................................................................................................................... 5  
    1.3.1 Hypotheses ........................................................................................................... 5  
  1.4 Steps in the Solution ................................................................................................. 6  
  1.5 Evaluation .................................................................................................................. 7  
  1.6 Heart Rate Feedback in Games ................................................................................ 7  
  1.7 Contributions .......................................................................................................... 8  
  1.8 Thesis Outline .......................................................................................................... 9  

Chapter 2 Multiplayer Exergames ..................................................................................... 11  
  2.1 Exergames ............................................................................................................... 11  
  2.2 Group Exercise ......................................................................................................... 17  
  2.3 Supporting Physical Activity in Multiplayer Exergames ......................................... 19  
    2.3.1 Aerobic Activity .................................................................................................... 19  
    2.3.2 Strength and Flexibility ..................................................................................... 21  
  2.4 Spatial Setup of Multiplayer Exergames ................................................................ 22  
    2.4.1 Co-Located ......................................................................................................... 22  
    2.4.2 Distributed ......................................................................................................... 24  
  2.5 Temporal Setup of Multiplayer Exergames .............................................................. 27  
    2.5.1 Synchronous ...................................................................................................... 27  
    2.5.2 Asynchronous .................................................................................................... 28  
  2.6 Player Interaction in Multiplayer Exergames ............................................................ 29  
    2.6.1 Cooperation ...................................................................................................... 30  
    2.6.2 Competition ...................................................................................................... 33  
  2.7 Summary .................................................................................................................. 36  

Chapter 3 Balancing Skill and Ability ............................................................................... 37  
  3.1 Static Player Balancing Techniques ........................................................................ 38  
  3.2 Dynamic Player Balancing Techniques .................................................................. 39
Chapter 5 Balance and Enjoyment of Heart Rate Balancing ......................................................... 71
5.1 Hypotheses ............................................................................................................................ 71
5.2 Study Design ........................................................................................................................ 72
  5.2.1 Apparatus ....................................................................................................................... 72
    5.2.1.1 Heart Racer Exergame .............................................................................................. 73
  5.2.2 Participants ...................................................................................................................... 75
  5.2.3 Methods .......................................................................................................................... 76
5.3 Results and Analysis ............................................................................................................. 77
  5.3.1 Balancing Competition .................................................................................................... 78
  5.3.2 Effort .............................................................................................................................. 79
  5.3.3 Enjoyment ...................................................................................................................... 81
  5.3.4 Transparency ................................................................................................................. 82
  5.3.5 Player Opinion ............................................................................................................... 84
Chapter 4 Heart Rate Balancing .................................................................................................. 47
4.1 Heart Rate Behaviour ........................................................................................................... 48
  4.1.1 Amplitude Problem ........................................................................................................ 49
  4.1.2 Quick Start Problem ........................................................................................................ 51
  4.1.3 Latency Problem ............................................................................................................ 52
  4.1.4 Summary of Problems ................................................................................................... 53
4.2 Heart Rate Balancing Algorithm .......................................................................................... 54
  4.2.1 Existing Formulas .......................................................................................................... 54
  4.2.2 Heart-Rate Banding for the Amplitude Problem ............................................................. 57
  4.2.3 Ramp-Up Window for the Quick Start Problem .............................................................. 59
  4.2.4 Logarithmic Scaling ....................................................................................................... 64
  4.2.5 Nimbleness for the Latency Problem ............................................................................. 65
  4.2.6 Algorithm Summary ...................................................................................................... 69
4.3 Summary .............................................................................................................................. 69
Chapter 3 Metrics for Evaluating Player Balancing in Exergames .............................................. 41
3.1 Balance .................................................................................................................................. 42
3.2 Enjoyment .............................................................................................................................. 43
3.3 Transparency ........................................................................................................................ 43
3.4 Exploitability .......................................................................................................................... 44
3.5 Portability ............................................................................................................................... 45
3.4 Summary ............................................................................................................................... 45
3.3 Metrics for Evaluating Player Balancing in Exergames ......................................................... 41
  3.3.1 Balance .......................................................................................................................... 42
  3.3.2 Enjoyment ...................................................................................................................... 43
  3.3.3 Transparency ............................................................................................................... 43
  3.3.4 Exploitability ............................................................................................................... 44
  3.3.5 Player Opinion .............................................................................................................. 45
List of Figures

Figure 2.1: Arcade-style exergames ................................................................. 12
Figure 2.2: Motion controllers for home consoles ........................................... 13
Figure 2.3: Wii Sports .................................................................................. 14
Figure 2.4: EA Sports Active ................................................................. 14
Figure 2.5: GrabApple exergame .............................................................. 16
Figure 2.6: Nautilus exergame ................................................................. 22
Figure 2.7: Swan Boat exergame ............................................................... 22
Figure 2.8: Age Invaders exergame .......................................................... 23
Figure 2.9: Pedal Race exergame ............................................................... 26
Figure 2.10: Breakout for Two exergame .................................................... 28
Figure 2.11: Push’N’Pull exergame ............................................................. 29
Figure 2.12: Body-Driven Firemen exergame .............................................. 29
Figure 2.13: Human Pacman exergame ...................................................... 31
Figure 2.14: Frozen Treasure Hunter exergame .......................................... 32
Figure 2.15: Remote Impact exergame ....................................................... 33
Figure 2.16: Body-Driven Bomberman exergame ....................................... 35
Figure 4.1: Graphs showing heart rate profiles of two people pedaling for five minutes ........ 48
Figure 4.2: Heart rate profile of Person A showing upper and lower target heart rate bands .... 50
Figure 4.3: Heart rate and pedal cadence profile of Person B ......................... 53
Figure 4.4: Graph showing the value range for effort $E(t)$ based on heart rate ......... 56
Figure 4.5: Graph showing the value range for effort $E(t)$ with target heart rate bounds .... 59
Figure 4.6: Graph showing the value range for effort $E(t)$ with ramp-up window .......... 61
Figure 4.7: Graphs showing the variables of the modified heart rate balancing formula ...... 63
Figure 4.8: Graphs showing example effort values without and with logarithmic scaling .......... 65
Figure 4.9: Graph showing changes in pedal cadence reflected in the final effort value .... 68
Figure 5.1: Equipment setup for the exergame system .................................... 73
Figure 5.2: The Heart Racer exergame .......................................................... 74
Figure 5.3: Visual enhancements to player’s avatar ....................................... 75
Figure 6.1: Equipment setup for the exergames used in this study .................. 92
Figure 6.2: Image of player using the exergame equipment ............................. 93
Figure 6.3: The Dust Buster exergame .......................................................... 94
Figure 6.4: The Cow Crossing exergame ..................................................... 95
Chapter 1

Introduction

Exergames combine digital entertainment and exercise in an effort to encourage people to be more physically active. Multiplayer exergames allow two or more people to play together. In most multiplayer exergames, a player’s in-game performance is based on the amount of power she is producing. For example, in exergames where a stationary bike is used as an input device, the speed of the player’s in-game avatar is typically based on pedal cadence. The faster the player pedals, the faster her avatar will move. Because of this, a player’s in-game performance is limited by her fitness level. This situation makes it difficult for people of disparate physical abilities to have an engaging experience when exergaming together. Fit players become uninterested from a lack of competition from unfit opponents, while less fit players are demotivated from repeated losses to fitter opponents. The goal of this research is to define and evaluate a novel player balancing technique for multiplayer exergames to better support engaging experiences between people of varying fitness levels.

This thesis presents *heart rate balancing* which bases players’ in-game performance on their effort relative to fitness level rather than on their raw power. *Effort* refers to the degree of exertion a person achieves in accordance with their physiological limitations. For example, two people having a foot race reach the same level of effort, however, the fitter person runs faster. Heart rate monitoring is used to scale performance depending on how closely a player adheres to her target heart rate. Two user studies were performed to test the effectiveness of heart rate balancing. The results show that the technique significantly improves competition and provides a better measure of effort compared to raw physical output. The degree to which players noticed
CHAPTER 1. INTRODUCTION

when heart rate balancing was applied varied depending on the type of game. However, the balancing mechanism did not impede people’s ability to play exergames.

1.1 Motivation
Regular physical activity has been found to be a contributing factor in preventing diseases such as cardiovascular disease, diabetes, and cancer [122]. Exergames aim to promote physical activity by combining the entertainment of video games with exercise. (The popularity of video games is reflected by the fact that 73% of American homes own a device specifically for gaming [87]). Commercial examples of exergames include Konami’s Dance Dance Revolution, Nintendo’s Wii Sports, EA Sports Active, and the Fisher Price Smart Cycle. These games support physically-active gaming using a variety of input hardware such as cameras, motion sensors, pressure sensors, and stationary bicycles [110]. Several single-player exergames have been developed for academic research; examples include the Pulse Masters Biathlon [84], Posemania [125], and GrabApple [47] exergames. For a more detailed description of exergaming see section 2.1.

Multiplayer exergames attempt to take advantage of the motivational aspects of group activity. For instance, the most preferred form of physical activity for university students is group exercise outside of a structured class [55]. However, in order to encourage active behaviour, it is important for people of various physical abilities to be engaged and entertained when playing exergames together.

People with significantly different fitness levels can have a hard time exercising together as large differences in performance can be demotivating [3]. For example, adolescents perceive a lack of competence and skill as a barrier to participation in physical activity [4, 99]. Ladders and handicapping are often used in sports to try and overcome this issue, but have several limitations.
CHAPTER 1. INTRODUCTION

These approaches require a measure of past performance, making it difficult to apply them to new players. Additionally, tournament ladders separate players, making it hard for friends and family to play together. Multiplayer exergames have the potential to better support group activity since performance can be dynamically adjusted for each player.

Basing in-game performance on individual effort relative to fitness level, instead of raw physical output, allows for engaging and enjoyable group play. For example, an unfit person running at her maximum effort reaches a slower speed than a fit person running at her highest effort. Although these two people exert the same level of effort relative to their fitness levels, their performance varies significantly. By making it easier for people of varying abilities to play together, multiplayer exergames have the potential to increase people’s motivation to participate in physical activity. Thus, people might be more willing to exercise, leading to improved health and fitness.

1.2 Problem

The problem addressed in this thesis is: In multiplayer exergames, where physical abilities are critical to player performance, it is difficult for people of different fitness levels to have an engaging experience when playing together.

Engagement refers to the user experience and a person’s involvement in a game [22, 89]. A more formal definition of engagement is “a quality of user experience with technology that is characterized by challenge, aesthetic and sensory appeal, feedback, novelty, interactivity, perceived control and time, awareness, motivation, interest, and affect” [89]. Engagement in video games has been related to immersion, presence, flow, and psychological absorption [22]. In
CHAPTER 1. INTRODUCTION

multiplayer exergames, engagement typically results from play actions between people in the game environment.

Most exergames are designed to challenge people’s level of fitness. However, the type of physical interactions required from the player varies between exergames. Games involving power-based interactions capture the raw physical energy exerted by the player to control in-game performance [110]. For example, in Frozen Treasure Hunter a player controls the speed of her avatar by pedaling on an exercise bike [127], as shown in figure 1.1. Power-based input can be applied to any game involving locomotion in a virtual environment. Many traditional video games use locomotion, such as World of Warcraft, Portal, Gran Turismo, and Half-Life. In exergames using power-based interactions, it is difficult for people of disparate physical abilities
CHAPTER 1. INTRODUCTION

to play together. For instance, players have stated that their skill level limits their ability to compete in multiplayer exergames [103]. A person with superior physical abilities tends to outperform her less capable opponents, while a person with poorer fitness is unable to keep up with more physically able players. These situations result in players facing a lack of challenge, or suffering repeated losses, both of which lead to boredom and decreased motivation.

1.3 Solution
The solution provided in this thesis is to base in-game performance on player effort as opposed to raw physical output. This is achieved with heart rate balancing which sets in-game performance relative to how closely a person adheres to her target heart rate. For example, in a racing-style exergame the player will go faster as heart rate increases.

The purpose of heart rate balancing is to better support competition between players of different fitness levels. Using this technique, players’ gaming skills are more important in determining the outcome of an exergame than physical fitness, assuming all players are working equally hard relative to their fitness levels. It is important to note that heart rate balancing is a player-balancing technique designed to compensate for the differences between players. This is different from game-balancing which attempts to ensure that the elements within a game do not provide any unfair advantages [54].

1.3.1 Hypotheses
There are two main hypotheses of the proposed solution of heart rate balancing:

1. Power-based exergames are more balanced with heart rate balancing compared to standard input, when players are putting in consistent physical effort;
CHAPTER 1. INTRODUCTION

2. People do not notice a difference in gameplay when standard power-based input is replaced with heart rate balancing.

1.4 Steps in the Solution

The two major parts of our solution are the definition of the heart rate balancing algorithm, and the application of the technique to a set of exergames. These steps performed are:

1. Formalize and define heart rate balancing. I derived the heart rate balancing algorithm from accepted and observed properties of heart rate during physical activity. The technique was designed in order to provide a similar response for all users regardless of their fitness level. The heart rate balancing algorithm is described in detail in chapter 4.

2. Develop metrics for evaluating player balancing techniques in multiplayer exergames. Prior to this research, it was unclear how to measure the performance of player balancing mechanisms in exergames. Thus, I defined a set of metrics for the evaluation of player balancing techniques. These metrics are based on previous player balancing research.

3. Implement heart rate balancing. I developed three exergames to test the implementation of the heart rate balancing technique. These included a two-player racing-style game (Heart Racer), and two single-player exergames (Cow Crossing and Dust Buster). User studies with these games were performed to evaluate heart rate balancing.

4. Summarize lessons for exergame designers. Based on the findings of two user studies, I present a set of lessons for designers. These principles can assist exergames designers in integrating heart rate balancing into games.
1.5 Evaluation
Heart rate balancing was evaluated through two separate user studies. The studies are summarized as follows:

1. **Assess the balance and enjoyment of heart rate balancing.** Because heart rate balancing is the currently the first attempt to balance players in power-based games, it is not possible to compare heart rate balancing to other techniques. In order to determine how effective the heart rate balancing technique is at balancing competition between players, a user study was performed. Pairs of participants played two versions of an exergame: a version using standard input, and a version using heart rate balancing. The results of this experiment show that heart rate balancing leads to closer competition, and better reflects people’s exertion compared to raw physical output.

2. **Test the transparency of heart rate balancing.** A second user experiment tested how noticeable heart rate balancing is to exergame players. Participants played both a standard and heart rate balanced version of two single-player exergames. The findings of this study show that heart rate balancing does not impede people’s ability to play exergames. Additionally, the transparency of heart rate balancing was found to vary depending on the type of exergame, and to be less noticeable in high-intensity games.

1.6 Heart Rate Feedback in Games
Heart rate balancing is partly inspired by previous work on using physiological input in computer systems, particularly heart rate. Although heart rate has been used in games, it has not been used to address player balancing prior to this thesis. Several researchers have suggested using heart rate for computer input [13, 102]. Heart rate monitoring can be used to add novelty to a video
CHAPTER 1. INTRODUCTION

game. For example, Tetris 64 was a commercial game for the Nintendo 64 which included a heart rate monitor that clips onto the player’s ear. The game is sped up when the player’s heart rate increases, and slowed down when the player’s heart rate decreases. Similarly, heart rate monitoring is used in the Pulse Masters Biathlon game [84]. During the skiing stage of the game, players perform an exercise of their choice. The player’s heart rate determines the speed of her avatar. In the shooting stage of the game, the steadiness of the scope is based on the player’s heart rate. The greater the heart rate, the faster the scope swings.

Heart rate monitoring can also be used to improve the quality of physical activity in exergames. The GeoKaos and Flareqoor games capture player input using motion sensors and heart rate monitors [26]. The physical movement of the player controls her on-screen avatar, and game difficulty is adjusted based on the player’s heart rate. In both games, the level of difficulty is increased if a player’s heart rate is below her target heart rate, and difficulty decreases as heart rate exceeds the target. Similarly, Masuko and Hoshino designed a single player exergame to help players maintain effective levels of exercise [74]. During the game, players perform boxing manoeuvres to fight virtual opponents. The number of virtual opponents increases if a player’s heart rate falls below her target heart rate, and opponents appear less frequently if heart rate is too high. Although these techniques use heart rate to improve exercise or add novelty, they fail to address differences in player fitness levels.

1.7 Contributions

This research contributes novel ideas and knowledge to the field of human computer interaction in the following ways:
CHAPTER 1. INTRODUCTION

- The definition of metrics for evaluating player balancing techniques in multiplayer exergames. These metrics allow researchers to evaluate current and future balancing techniques across a set of important performance criteria.

- The definition, implementation and testing of a novel player balancing mechanism using heart rate. The proposed algorithm can be used by designers in order to support heart rate balancing in exergames.

- Empirical evidence demonstrating the feasibility and performance of heart rate balancing. These experimental results highlight the benefits and limitations of the technique.

- The design, development, and hardware setup for three new power-based exergames. One game (Heart Racer) is a two-player networked game, and the other two (Cow Crossing and Dust Buster) are single player. These games were developed using C# and XNA, and are intended to work with off-the-shelf hardware.

  Secondary contributions include an improved definition and understanding of player balancing in multiplayer exergames. Additionally, results of the user studies further reinforce existing observations on the enjoyment and motivation provided by multiplayer exergames.

1.8 Thesis Outline

Chapters 2 and 3 discuss background work related to this thesis. The second chapter provides an overview of existing exergames, the motivational aspects of group exercise, and how designers combine exergaming and group activity. Chapter 3 includes a review of existing player balancing techniques, particularly in exergames; Additionally, a of set metrics for evaluating balancing mechanisms are proposed.
CHAPTER 1. INTRODUCTION

Chapter 4 derives the heart rate balancing algorithm. This includes a summary of problems associated with using heart rate as a measure of effort, and a set of proposed solutions.

Two studies were performed to evaluate the heart rate balancing algorithm. The first study, presented in chapter 5, was designed to test whether heart rate balancing improves competition between players in a high-intensity exergame. The study presented in chapter 6 investigated whether players notice a change in gameplay when heat rate balancing is applied, and whether the transparency of the technique varies depending on the type of game. Two single-player exergames are used in this experiment: a high-intensity, low-precision game, and a low-intensity, high-precision game. A summary of the results and analysis are provided.

Chapter 7 provides an overall discussion of the results and implications from the two user studies. The chapter includes guidelines and lessons for exergame designers based on the findings of this research.

Chapter 8 presents a summary of the research, the contributions of the thesis, and potential future work on heart rate balancing.
Chapter 2

Multiplayer Exergames

As discussed in chapter 1, exergames combine entertainment and exercise in an effort to encourage physical activity. Multiplayer exergames attempt to include the motivating aspects of group activity by allowing two or more people to play together. This chapter provides a summary of exergames, the effectiveness of group exercise, and how exergaming and group activity are combined in multiplayer exergames. An introduction and overview of exergames is first presented in section 2.1. The factors that influence the effectiveness of group exercise are reviewed in section 2.2. Finally, techniques for combining exergames and group activity are summarized in section 2.3.

2.1 Exergames

The most common definition of exergames are “video games that require physical activity in order to play” [17, 90]. A more precise definition of exergaming is “an experiential activity in which playing videogames requires physical exertion or movements that are more than sedentary activities and also include strength, balance, and flexibility activities” [90]. Since their inception, exergames have mostly aimed to promote physical activity [17].

The concept of exergames has existed for several decades. Early examples of commercial exergame equipment include the Amiga Joyboard and the Nintendo Power Pad [106]. The Joyboard, released in 1985, replaces a traditional joystick by having the player stand on a platform and lean in different directions [17, 92]. The Power Pad, a large pad-style controller which lies on the floor, was released in 1988 for the Nintendo Entertainment System. The pad contains a series of soft touch-sensitive buttons which players press with their feet [17]. A small
set of compatible games were released for the Power Pad. For instance, *World Class Track Meet* simulates Olympic events such as sprinting, hurdles, and long jump. Players complete each event by running in place and jumping on the Power Pad.

Arcade-style exergames using more traditional exercise equipment were released in the 1990s, as shown in figure 2.1. For example, Namco’s *Prop Cycle* and *Downhill Bikers* requires players to pedal on stationary bikes in order to control their on-screen avatars [92]. Konami’s *Dance Dance Revolution* (DDR) is one of the most successful commercial exergames. Players stand on a dance pad and perform a series of dance moves in rhythm to music and on-screen cues [75]. Several pad-style peripherals have been released for video game consoles allowing players to play DDR at home [17]. Numerous DDR sequels have been created for a variety of platforms, such as *Dance Dance Revolution Universe*, and *Dance Dance Revolution 4th Mix*. Additionally, DDR has inspired similar dance-style exergames including the open-source *Step*
CHAPTER 2. MULTIPLAYER EXERGAMES

Mania PC game, and the Dance Central and Dance Evolution games for the Microsoft Kinect system which is discussed below.

More recently, a series of peripherals have been released for game consoles which support active forms of gaming; see figure 2.2. The Nintendo Wii MotionPlus is a hand-held controller allowing players to perform arm gestures as game input. Similarly, Sony’s PlayStation Move motion-controller captures players’ upper-body movement using sensors and computer-vision.
The Microsoft Kinect sensor for the Xbox 360 enables players to interact with games using their entire body.

Sports simulation exergames are popular for motion-capture peripherals. Nintendo’s Wii Sports includes virtual golf, baseball, tennis, bowling, and boxing activities. During these games, players perform gestures mimicking the real-world actions of a particular sport. For instance, in Wii Sports tennis, a player makes forehand and backhand swings while holding the Wii remote to hit on-screen balls, as shown in figure 2.3. Similar games exist for other consoles such as Sports Champions for the PlayStation Move, and Kinect Sports for the Microsoft Kinect. Virtual training exergames have also been developed to support workout programs in the home. EA Sports Active: Personal Trainer includes an on-screen trainer who coaches players through a series of exercises such as warm-up and cool down routines, lunges, squats, arm curls, as well as simulated sports activities like rollerblading, tennis, basketball, and boxing. These activities are designed to
provide higher-impact exercise compared to sports simulation games like *Wii Sports* [116]. In *Sports Active* a player uses a *Wii* remote to perform arm gestures, and a *Wii* nunchuck peripheral is attached to the player’s leg to capture lower-body movement, as shown in figure 2.4. The game also includes a large rubber band which can be incorporated into the muscle training activities of the game. Similar virtual training programs have been released for other platforms including Ubisoft’s *Your Shape: Fitness Evolved* for the Microsoft Kinect.

Several stationary exercise bikes have been released to interface with traditional video games. For instance, the CatEye *GameBike* and the Motion Fitness *Exerbike* replace gamepad controls for the Sony PlayStation 2 [121]. Pedaling on these bikes typically replaces the throttle controls in racing games such as the *Gran Turismo* or the *Need for Speed* series. Players steer their on-screen vehicle by turning the handlebars left and right. Similarly, 3D Innovation’s *PCGamerBike Mini* is a portable set of pedals which players can use to interact with desktop computer games. While pedaling on the *PCGamerBike Mini* and using a gamepad for steering players can control avatars in first-person-shooters or role-playing games. The Fisher-Price *Smart Cycle* is an exergame system designed for children [106]. The Smart Cycle is a child-sized stationary bike which connects to a television. Players must pedal and use an attached joystick to interact with the system. Games for the *Smart Cycle* are designed to be educational (e.g., teaching math and vocabulary) while including physical activity.

In addition to existing commercial systems, several exergames have been created for academic research. For instance, the GrabApple game is designed to provide casual exergaming experiences [47]. In GrabApple, players move their whole body to control an on-screen hand. The goal of the game is use the virtual hand to collect as many falling apples as possible while
avoiding falling bombs. Player movement is captured using a Microsoft *Kinect* motion controller plugged into a desktop computer, as shown in figure 2.5. Poseania is an academic dance simulation game [125]. Players wear accelerometers on their upper and lower limbs, and must perform dance moves in rhythm to on-screen queues. Unlike Dance Dance Revolution which focuses only on foot placement, Poseania requires precise movement of a player’s entire body.

The variety of examples presented above illustrate the feasibility of combining entertainment and exercise in order to promote physical activity. Some exergames have been found to improve health and fitness [121, 118]. However, long-term adherence to exergaming decreases over time [10, 72]. One potential reason for poor participation in exergaming is that many exergames are single-player and fail to include the motivating benefits of group exercise. The following section provides an overview of the factors of group activity that encourage participation and adherence in exercise.
CHAPTER 2. MULTIPLAYER EXERGAMES

2.2 Group Exercise

Maintaining people’s adherence to physical activity is a difficult challenge. For example, fewer than 50% of Canadians maintain a sufficiently active lifestyle to improve health and fitness [111], and approximately 50% of adults who begin an exercise program stop within the first six months [100]. Exergames offer a promising approach for improving participation in physical activity by combining entertainment and exercise. However, single-player exergames fail to include the benefits of group exercise. Group activity can have a positive influence on exercise motivation and adherence [8, 12, 55]. For example, peer support [58], competition [77], and collaboration [8] have been found to be motivating factors in sports and exercise. The focus of this thesis is on supporting group exercise in multiplayer exergames, particularly among people of varying fitness levels. In order for exergames to enable group exercise, it is important that game designers understand the benefits and limitations of group activity. This section examines the factors that influence the effectiveness of group exercise.

In many contexts, adults prefer to exercise in a group over exercising alone [55]. For instance, Burke et al. found that group exercise, which does not take place in a structured class, is the most preferred form of physical activity for university students [25]. However, several factors need to be in place in order for group exercise to be effective. Group cohesion, or the “stick togetherness” of a group, is a major factor in adherence to group exercise [8, 29, 35, 43, 107]. Group cohesion is formally defined as “a dynamic process which is reflected in the tendency for a group to stick together and remain united in the pursuit of its goals and objectives” [28]. Cohesion is related to people’s individual adherence behaviours towards physical
activity [29, 43, 107]. Factors affecting group cohesion in physical activity include the type of participants, type of exercise, and the duration of an exercise program [15].

Other than group cohesion, several other factors have been found to influence people’s adherence to group exercise; These factors are summarized as follows:

- **Attendance:** group members who are less-absent often have a higher attraction to group exercise [107], whereas people’s absence from a group exercise program can lead to fears of falling behind [20].

- **Body composition:** a person’s perceived body image and self-efficacy influence the willingness to participate in group exercise [20, 58, 68, 94].

- **Compatibility:** people are more inclined to participate when there is commonality among group members, such as age [9, 20], fitness level [7, 20], and goals [30].

- **Convenience:** group exercise typically requires scheduling [67, 94, 98], travel [67, 94, 98], and cost [98], all of which can deter from participation [20, 38].

- **Interaction:** strong interaction and communication among group members is positively correlated to cohesion [30].

- **Social support:** mutual support among group members has a positive influence on a person’s perceived capabilities and self-efficacy [24]. Alternatively, a lack of peer support can have adverse effects on exercise participation [58].

- **Variety of exercise modalities:** activities involving a range of different exercises can better support group exercise among people with varying fitness capabilities [38].
Manipulating the above factors and group dynamics has been proposed as a way of promoting physical activity [35]. However, there is currently a lack of research on how to optimize these factors and assessing the degree of their influence on motivation and adherence [15].

Multiplayer exergames offer some potential solutions to the inconveniences of group exercise while including the motivational aspects of group activity listed above. For instance, networked multiplayer exergames can eliminate the inconvenience of scheduling and travel required for traditional group exercise. The following sections explore how various elements of exergame design can address the factors of group exercise presented in this section.

2.3 Supporting Physical Activity in Multiplayer Exergames

Providing a variety of exercise modalities is one important factor in promoting adherence to group exercise [38], as presented in section 2.2. Existing exergames use a variety of input hardware to support two main types of exercise: aerobic activity, and strength and flexibility training. The following sections explore how these exercise modalities are supported in multiplayer exergames.

2.3.1 Aerobic Activity

Aerobic exercise increases heart rate and breathing and promotes the circulation of oxygen through the blood. The American College of Sports Medicine (ASCM) suggests that exercise for developing and maintaining cardiorespiratory fitness should use large muscle groups, be maintained for a prolonged period, and be rhythmic and aerobic in nature [97]. Most multiplayer exergames support some degree of aerobic activity. Popular commercial and academic
CHAPTER 2. MULTIPLAYER EXERGAMES

multiplayer exergames are reviewed in detail in sections 2.4 to 2.6. A wide range of input devices are used to capture players’ aerobic activities [110], such as:

- **Accelerometers and gyroscopes** measure changes in speed and rotation. For example, the Nintendo Wii MotionPlus contains a 3-axis accelerometer and a gyroscope to report players’ arm motions; see figure 2.2.

- **Cameras** are used to capture video of player activity. Image analysis determines player position and movement. Lasko and Lasko created a set of “Body-Driven” exergames which track players using cameras [69].

- **Touch and pressure sensors** can report when a player makes contact with a surface or the amount of force applied. For instance, pressure sensors measure force and position when a player strikes a padded display in the Remote Impact multiplayer exergame [82].

- **Ergometers**, commonly known as exercise machines, measure a players physical output. Example ergometers include, rowing machines, stationary bikes, treadmills, and step machines. In the Swan Boat exergames, two players run on separate treadmills to control the speed of a virtual boat [6].

The devices listed above allow multiplayer exergames to support a variety aerobic exercise modalities. For example, the Microsoft Kinect uses cameras to provide full-body gaming; whereas, the accelerometers used in Nintendo’s Wii Sports result in mostly upper-body physical activity.

Currently there is a lack of research on the effectiveness of aerobic activity in multiplayer exergames. The ACSM recommends that exercise should be performed at 65% to 90% of
people’s maximum heart rates for a duration of 20 to 60 minutes [97]. Some studies have shown that children and teenagers playing Dance Dance Revolution do reach the minimum ACSM recommendations for exercise intensity [114, 118]. Exergames using ergometers also lead to improved health and fitness [122]. Alternatively, exergames with limited body movement, such as Wii Sports, have been found to provide insufficient exercise intensity [49, 70]. However, the physical activity in exergames is more beneficial than the sedentary behaviour of traditional video games [49].

2.3.2 Strength and Flexibility
In addition to aerobic exercise, the ACSM also recommends resistance and flexibility training in order to improve muscular strength and flexibility [97]. Few existing multiplayer exergames support this form of physical activity. Games requiring strength and flexibility often require specialized or custom input devices. For example, the Push’N’Pull exergame uses a Powergrid Kilowatt training device to capture player input [80]. Players must apply force to the Kilowatt in order to control on-screen objects; see figure 2.11. The EA Sports Active 2 game supports multiplayer strength and flexibility training. Accelerometers capture player movement, and a resistance band is used for strength training. These examples demonstrate the feasibility of supporting a variety of resistance training activities in multiplayer exergames. To date, the strength and flexibility benefits provided by these exergames have not been evaluated.
2.4 Spatial Setup of Multiplayer Exergames

Traditional group exercise requires participants to be together in the same location. Despite the advantages of the social aspects of this scenario [24, 30], it has been found to be a limiting factor in group exercise due to the coordination and scheduling needed [67, 94]. The spatial setup of multiplayer exergames can address several important factors of group activity such as social support, interaction, convenience, and body composition. Multiplayer exergames are either co-located or distributed; these two spatial configurations are examined in sections 2.4.1 and 2.4.2 below.

2.4.1 Co-Located

Players need to be in the same location to play co-located exergames. Existing multiplayer exergames support co-located play using shared displays or ubiquitous environments.

Shared displays are common in co-located multiplayer console games. For instance, the Halo Xbox 360 game splits the screen into four display areas during four-player mode. A similar
split-screen approach is used in the *Wii Sports* tennis exergame. Several academic exergames use a shared display without dividing the screen. For example, Nautilus [112] involves players taking the role of a diving bell crew on a mission to save a trapped dolphin. As shown in figure 2.6, a group of players performs physical movements in front of a large display while their actions are captured by floor sensors. A shared display is also used in Frozen Treasure Hunter [127] (see figure 2.14), and the Body-Driven exergames [69] (see figures 2.12 and 2.16). In the Swan Boat game [6], two players team up and take control of a single virtual boat by each running on separate treadmills, as shown in figure 2.7. The difference in running speed between the teammates steers their boat. For instance, to turn the boat to the right, the player on the right side

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Figure 2.8: Age Invaders exergame [66]
CHAPTER 2. MULTIPLAYER EXERGAMES

must run faster than her teammate on the left. Although players have their own screen, each screen displays the same state of the game world.

Ubiquitous computing is a model in which computer systems are integrated into everyday objects [124]. Environments containing ubiquitous objects can support multiplayer exergaming. Specialized lighting, audio, and video projection surfaces act as interfaces in the socio-ec(h)o game [120]. Co-located players use audio and visual cues in order to progress through the game. Similarly, the Age Invaders exergame requires a computer-augmented environment [66]. The game floor is comprised of a series of display tiles which provide players with game-related information, see figure 2.8. For instance, when a player fires a virtual rocket using a hand-held trigger, the rocket’s path is displayed on the floor.

The above examples demonstrate that exergames can support co-located play and exercise using shared displays or ubiquitous environments. Players must be in the same location during co-located exergaming, and thus opportunities exist for social support and interaction. These factors have been found to be important in motivation and adherence to group exercise [24, 30]. However, similar to traditional group activity, co-located exergaming can be inconvenient since people must coordinate a time and place to play. As discussed in the following section, distributed exergames can alleviate some of these issues.

2.4.2 Distributed

Distributed exergames allow people in different geographical locations to play together. However, distributed play is difficult without some shared awareness of each player. Common awareness mechanisms in distributed multiplayer exergames include audio, video, and avatars.
CHAPTER 2. MULTIPLAYER EXERGAMES

The Jogging Over a Distance exergame supports distributed play using augmented audio [81, 83]. The system allows two people, in different locations, to run together. Each runner wears a headset allowing her to communicate with her partner. Spatial audio is used to provide awareness of presence and performance. The performance of a runner, in relation to her partner, determines if her voice sounds as though it is coming from in front or behind.

Two-way video and audio transmission can also support distributed play. For example, a video conference feed in the Push’N’Pull exergame allows players to communicate and coordinate more easily [80]. Similar audio and video support is found in Breakout for Two [80] and Table Tennis for Three [79]. However, in these games, video is overlaid onto the game window (e.g., see figure 2.10). This allows players to see and hear each other as though they are separated by a pane of glass [80]. Audio and video can provide awareness of a player’s presence, identity, and actions.

Avatars – virtual representations of players – are often used in traditional multiplayer games (e.g., Halo, World of Warcraft). Similarly, avatars can be found in distributed multiplayer exergames. For example, in the Pedal Race exergame, two distributed players race by pedaling on an exercise bike [108]. Each player is represented in the game with an on-screen avatar, as shown in figure 2.9. Generally, avatars provide awareness of a player’s actions and performance.

The examples presented above show various approaches for supporting distributed group exercise in exergames, such as audio, video, and avatars. These techniques aim to provide some degree of awareness about each player. The main advantage of distributed exergames is that they can reduce some inconveniences of traditional group activity. Specifically, players can participate in group exercise without having to travel to a common area such as a gym or athletic facility.
Travel is considered a potential barrier to participation and adherence in group exercise [67, 94, 98]. Another advantage of distributed exergames is their ability to mask players’ physical appearances behind on-screen avatars [127] (e.g., Pedal Race [108]). This is potentially beneficial to players, since issues of body image influence people’s willingness to participate in group activity [20, 68, 94]. Exergames which include an audio communication channel, such as Jogging Over a Distance [83] or Push’N’Pull [80], can allow for socializing between players [83]. However, since players do not meet face-to-face in distributed exergames, there is less opportunity for social support and interaction; these factors are important motivators in group activity [24, 30].

**Figure 2.9: Pedal Race exergame [108] (avatars circled in red)**
CHAPTER 2. MULTIPLAYER EXERGAMES

2.5 Temporal Setup of Multiplayer Exergames

In order to exercise and interact together, group members need to be present at the same time. This required presence can be a demotivating factor for participation in group exercise due to issues of scheduling and attendance [67, 94, 98, 107]. Multiplayer exergames can preserve the social aspects of group exercise in both synchronous and asynchronous settings; these configuration are explored in sections 2.5.1 and 2.5.2 below.

2.5.1 Synchronous

Synchronous play occurs in the same period of time, and is the most common configuration in multiplayer exergames. For example, in Breakout for Two, two distributed players kick soccer balls at a projected wall display covered with virtual bricks [78]; see figure 2.10. Bricks are destroyed once they are hit three times with a ball, and the player who is able to destroy the most bricks is the winner. In order to play, two players must be connected at the time. Similarly, in the co-located Nautilus exergame, players need to be present at the same time when playing [112].

Interaction and social support among group members is an important motivating aspect of group exercise [24, 30]. Synchronous multiplayer exergames typically encourage interaction since most games require players to cooperate or compete together (see section 2.6). Additionally, social support is also possible among synchronous players, particularly in co-located games (see section 2.4.1). However, synchronous exergames suffer from the same problems of scheduling and attendance found in traditional group activity [67, 94, 98, 107]; for instance, it can be inconvenient for friends to schedule a time to play Nintendo’s Wii Sports together. Asynchronous exergames have the potential to address this issue, as discussed in the following section.
2.5.2 Asynchronous

Asynchronous play does not occur in real-time. For example, the Triple-Beat system allows a jogger to compete against other people asynchronously [91]. Using a mobile device, a player can see how her own performance compares to the past performance of other users. Triple-Beat is an example of a distributed asynchronous exergame game. Currently, no other asynchronous exergames exist in the literature.

It can be inconvenient for people to schedule a time to participate in traditional group activities [67, 94, 98]. This can lead to frequent absence and result in fears of falling behind in a group training program [20]. Asynchronous multiplayer exergames have the potential to address these issues since players can participate at a time which is most convenient to them. A tradeoff
of this approach is that it is difficult for group members to provide social support in real-time. This is potentially problematic since social support has been found to be a motivating aspect of group exercise [24].

2.6 Player Interaction in Multiplayer Exergames

In order for an exergame to support multiple players, people need to be able to interact in some manner. Strong interaction and communication are important aspects of cohesion in traditional group exercise [24, 30]. Multiplayer interaction patterns in traditional video games include: player versus player, multilateral and unilateral competition, cooperative play, and team competition [46]. Existing multiplayer exergames support two general modes of interaction between players: cooperation, and competition. These interaction styles are examined in sections 2.6.1 and 2.6.2 below.
CHAPTER 2. MULTIPLAYER EXERGAMES

2.6.1 Cooperation

Cooperation involves players collaborating to achieve a common goal. This mode of interaction is frequently seen in traditional multiplayer video games. For example, in World of Warcraft, players often form groups to cooperatively defeat an in-game foe. Cooperation has been found to be one motivational aspect of traditional multiplayer games [39, 86]. Existing multiplayer exergames support cooperation using one of two approaches: coordinated physical activity, or asymmetric roles.

One approach for encouraging cooperation in exergames is to require players to perform coordinated physical actions. For example, in the Push’N’Pull exergame, two distributed players use shared controls to interact [80]. Players must push or pull on their own resistance training device in order to collect on-screen items, as shown in figure 2.11. Collecting the items requires significant physical strength from a single player. However, if the two players coordinate their physical exertion, it is much easier to gather the virtual items. Coordinated physical activity is also found in co-located exergames such as the Body-Driven Firemen game. In the game, players need to move together and form a circle to save falling virtual characters [69]. Computer vision captures player movement, as shown in figure 2.12. Similarly, co-located coordinated activity is used in the Nautilus [112], Swan Boat [6], and socio-ec(h)o [120] exergames; see section 2.4.1 for an explanation of these games.

A second approach to promoting cooperation involves providing players with asymmetric roles. For instance, in the Paranoia Syndrome game, players move around a physical space and use a hand-held computer and other physical objects to interface with a virtual game environment [57]. At the beginning of the game, players choose one of three unique roles:
scientist, technician, or doctor. Since winning the game requires skills from each role, players must cooperate in order to win. In the Human Pacman game [34], players move around the real world while interfacing with an augmented-reality environment using a mobile computer. The goals of the original Pacman arcade game are replicated with players taking the roles of Pacmen and Ghosts. Pacmen must collect all the virtual pellets, while Ghosts try to catch the Pacmen. Cooperation occurs in two cases: between mobile teammates, and between mobile and remote players. Mobile Pacmen can coordinate in order to pass virtual objects to one another. Additionally, each mobile player is supported by a remote player who is able to see the entire virtual world on her terminal, as shown in figure 2.13. A mobile player can gain useful game-state information by coordinating with her remote partner. Asymmetric roles are also found in the Frozen Treasure Hunter exergame [127]. In the game, two players take control of a single avatar in attempt to collect on-screen items. As shown in figure 2.14, one player steers the avatar using a
recumbent bicycle and gamepad, while another player swats away virtual projectiles using an Nintedo Wii remote. These exergames show the scalability of asymmetric roles. Frozen Treasure hunter is a two player game with two roles [127], whereas, Paranoia Syndrome has several roles that can support three or more players [57].

Social support and interaction among participants are important factors in motivating participation in group exercise and promoting cohesion [24, 30]. Cooperative exergames support these aspects by encouraging players to work together. For instance, the required communication and coordination in the socio-ec(h)o game was found to have a positive influence on group cohesion [120]. Alternatively, the physical contact required between players in some cooperative games may introduce feelings of discomfort. For example, groups of strangers were found to be
uncomfortable with holding hands when playing Body-Drive Firemen [69]. However, to date, the effects of cooperation in exergames have not been generalized.

2.6.2 Competition

Competition involves a contest between two or more players. In some instances, competition has been found to be a motivating factor in traditional multiplayer video games [63, 119]. In particular, social-competition between people increases player engagement in games [119]. Similarly, competition can motivate participation in sports and exercise [77]. For instance, sports-based competition has been correlated to people’s motivation, interest and enjoyment in physical activity [44]. Existing multiplayer exergames support competition using several approaches: shared targets, virtual combat, or turn taking.
CHAPTER 2. MULTIPLAYER EXERGAMES

Providing shared in-game targets is one method for establishing competition in exergames. Players compete to be the first one to complete a series of targets or goals. For example, in Breakout for Two, players compete to destroy more virtual bricks than their opponent by kicking soccer balls at a large display [78]; see figure 2.10. A similar shared targeting approach is used in the Table Tennis for Three game [79]. Distributed players each use a physical paddle and ball to break virtual bricks on a projected display.

Virtual combat supports competition by allowing players to virtually struggle against each other. For instance, Remote Impact is a competitive two player game with forceful input [82]. The shadow of a player’s opponent is projected onto a screen, and a player can kick, punch and ram the padded display, as shown in figure 2.15. The more forcefully a player strikes her opponent’s shadow, the more points she scores. Similarly, in the Age Invaders game, players move along an interactive floor and shoot virtual rockets at each other using hand-held triggers [66]; see figure 2.8. Virtual combat is also found in the Body-Driven Bomberman exergame [69]. A camera captures the movement of players to control each player’s on-screen avatar. The goal of Bomberman is to strategically plant virtual bombs in order to destroy opposing players’ avatars, as shown in figure 2.16. These multiplayer exergames demonstrate that virtual combat can support competition between two or more players.

Turn-taking is another approach for supporting competition in multiplayer exergames. For instance, in XaviX Bowling, players take turns throwing a ball at virtual on-screen pins [76]. Although players compete for the highest score, a player cannot directly influence the performance of her opponents. Turn-taking can also be found in Nintendo’s Wii Sports bowling and golf.
CHAPTER 2. MULTIPLAYER EXERGAMES

The above examples illustrate the feasibility of supporting competition in multiplayer exergames. With the exception of turn-taking, most competitive exergames require players to interact. This is important since interaction is a motivating factor in group exercise [30]. Additionally, competitive exergames can include the engagement provided by player-competition in traditional gaming [63, 119]. For instance, user studies of Body-Driven Bomberman indicate that players were motivated to play due to the physical movement and fun of the competitive gameplay [69]. Similarly, experiments with Table Tennis for Three show that players enjoyed the competition involved in the game [79]. However, most competitive exergames fail to address differences in skills and abilities between players. Thus, more fit players typically have an advantage over their less fit opponents. This is problematic since compatibility between people is an important factor in group exercise. For example, people are more willing to participate when

Figure 2.16: Body-Driven Bomberman exergame [69]
CHAPTER 2. MULTIPLAYER EXERGAMES

group members are of similar fitness levels [7, 20]. Addressing compatibility in multiplayer exergames is explored in chapter 3.

2.7 Summary

This chapter reviewed the state-of-the-art in multiplayer exergames. Existing exergames can support the motivating factors of traditional group exercise discussed in section 2.2. Additionally, since physical activity in exergames is computer-mediated, it is possible to address many of the problems associated with group exercise. The large set of input hardware available for exergames can support a wide range of exercise modalities. By design, co-located and synchronous exergames preserve the motivating social support and interactions of group activity. Alternatively, distributed and asynchronous games can help to address demotivating aspects of group exercise such as convenience, attendance, and issues related to body composition. However, few existing multiplayer exergames deal with problems of compatibility. People are more willing to exercise together if there is commonality among group members [7, 20, 30]. Thus, if people of different fitness levels have difficulty playing together, then the effectiveness of multiplayer exergames suffers. Some research has been done to address issues of incompatibility between exergame players; this is explored further in the following chapter.
Chapter 3
Balancing Skill and Ability

As discussed in the previous chapter, compatibility between people is an important factor for motivating participation in group exercise. People are more willing to exercise together if they are of a similar age [9, 20] or have comparable fitness levels [7, 20]. Unfortunately, few existing exergames address issues of compatibility between players. Less fit players can be demotivated from repeated losses to more fit opponents, while fitter players can become uninterested from a lack of competition from unfit opponents. An important challenge for any game designer is to ensure that players do not find a game frustratingly difficult or so easy that it leads to boredom [41]. Thus, in order for multiplayer exergames to provide engaging experiences, gameplay should be tailored to fit each person’s physical ability.

It is difficult for game designers to balance gameplay due to the differences between players [2]. For instance, novices struggle to play against experienced gamers due to incompatible skill levels, reaction time, and strategy [113]. Exergames are designed to challenge people’s physical abilities (e.g., strength, stamina, and flexibility), making it hard for people of varying fitness levels to play together. For example, in the Remote Impact exergame, two players fight each other by kicking and punching a virtual projection of their opponent [82]. Strong and agile players can easily gain points by striking forcefully while dodging their opponent’s attacks. This configuration gives fitter players an advantage over less fit players.

This chapter explores existing balancing mechanisms designed to address issues of player compatibility, particularly in multiplayer exergames. Static and dynamic player balancing
CHAPTER 3. BALANCING SKILL AND ABILITY

Techniques are explored in sections 3.1 and 3.2, respectively. Section 3.3 proposes a series of metrics for evaluating the effectiveness of player balancing mechanisms in exergames.

3.1 Static Player Balancing Techniques
Static player balancing typically occurs at the outset of a game. Once a game has begun, no further adjustments are made to improve player balance. The advantage of this approach is that it is often simple to implement. Two common static player balancing techniques for exergames are *matchmaking* and *asymmetric roles*.

Matching groups or players by their abilities is often used to balance competition in sports and traditional games. Examples include player rankings in competitive chess, and ladders in a squash tournament. Matchmaking is also common in multiplayer online games [96]. Automated systems track people’s in-game performance in order to match players and balance teams [85]. For example, Microsoft’s *Xbox 360 Live* service includes the *True Skill* system which can accurately rank players after fewer than 20 games [56]. Based on these rankings, the True Skill system attempts to match competing players or teams so that there is an equal chance of either side winning. One limitation of matchmaking is that it requires some measure of a player’s past performance. Thus, it is hard to match players who join a game for the first time [85]. Additionally, automated matchmaking systems can make it hard for friends and family to play together since they may be separated by skill. This situation should be avoided in the context of exergames [127] since exercising with friends and family is an important motivator [58].

Providing a set of asymmetric roles is another static approach for player balancing. A variety of team sports include several roles requiring different skill sets. For instance, a basketball lineup is composed of five players filling particular roles. Guards are typically quick with good long-
CHAPTER 3. BALANCING SKILL AND ABILITY

range shooting; forwards play closer to the basket taking short-range shots; and centers rely on their height and strength to score and rebound at the basket. Because players can fill the role which best matches their abilities, basketball allows people with different skills to play together. As discussed in section 2.6.1, asymmetric roles are found in some existing multiplayer exergames. The Human Pacman exergame involves active players moving around an outdoor field who are supported by remote players seated in front of a desktop computer [34]. This setup allows players who are less physically active to interact with their active teammates. One disadvantage of this approach is that seated players fail to benefit from the intended physical activity of exergaming. Alternatively, the Frozen Treasure Hunter exergame supports two active asymmetric roles [127]. One player acts as a driver by pedaling on an exercise bike, while the other player swats away virtual projectiles using a Nintendo Wii remote. A limiting factor of asymmetric roles is that a group or team is limited by the performance of the weakest member. For example, in Frozen Treasure Hunter [127], the speed at which a team can progress through the game is determined by how quickly the driver can pedal and the effectiveness of the defender to protect the team. Additionally, asymmetric roles cannot address one-on-one competitive scenarios.

3.2 Dynamic Player Balancing Techniques

Dynamic player balancing techniques adjust competition in real time and help solve some of the problems of static player balancing. Since challenge can be customized for each player, dynamic balancing allows players of varying abilities to play together more easily.

Dynamic difficulty adjustment, or DDA, is common in many commercial video games. DDA alters in-game elements in real-time based on a player’s performance [59]. In a single-
player video game, obstacles and non-player controlled characters can be added or removed based on the abilities of a player [93]. For instance, Valve’s *Left 4 Dead* series includes an artificial intelligence “Director” which spawns in-game weapons and enemies depending on the performance of the player [71]. In a two-player game of *Pong*, DDA can modify racquet lengths, movement speed, and ball speed to support players of varying skills [60]. One limitation of DDA is that a “rubber band” effect can emerge due to swings in over-compensation and under-compensation. For example, in Nintendo’s *Mario Kart* racing game, strong in-game power-ups are given to losing players so that they have a better chance of gaining a lead. This situation can frustrate more experienced players who feel cheated by the game [85].

Few multiplayer exergames use DDA for player balancing. The Age Invaders game, presented in section 2.4.1, was designed to address differences in physical abilities between young and older relatives [66]. Game parameters such as response time, player movement, and power-ups, are automatically adjusted for each player depending on their age. For example, a younger player’s weapon fires more slowly than those of her older opponents. Unfortunately, the effectiveness of this approach has not been experimentally measured. The difficulty adjustments in Age Invaders are based on a player’s age and do not take into account differences in abilities among people of the same age. Additionally, although difficulty levels can be adjusted manually during a game, difficulty does not automatically adapt as players improve their abilities.

The *Truck Pull* exergame uses force-feedback in an attempt to make multiplayer games more competitive [108]. In the game, two players compete in a virtual tug-of-war by pedaling on recumbent bicycles. The more a player is winning, the more tension is applied to the pedals. Alternatively, the more a player is losing, the easier it becomes to pedal. This dynamic approach
CHAPTER 3. BALANCING SKILL AND ABILITY

was shown to be effective at making games more balanced [108]. However, this technique is not transparent to players, and requires exercise equipment that supports computer controlled resistance.

The heart rate balancing technique proposed in this thesis bases a player’s performance on her effort relative to her fitness level. Since each person’s heart rate behaves differently during exercise, this dynamic approach has the advantage of being automatically tailored for each player. Similarly, heart rate behaviour changes as player fitness improves. Therefore, heart rate balancing adjusts for any improvement or reduction in a person’s physical abilities. Although using heart rate for player balancing has been proposed in previous research [83, 91], these systems do not take into account the variability of heart rate in response to physical activity [37, 53]. This issue is explored further in chapter 4.

3.3 Metrics for Evaluating Player Balancing in Exergames
Currently, it is unclear how to measure the performance of player balancing techniques in exergames. Experimental comparisons of dynamic techniques are difficult since each approach can be tailored differently and may work optimally only in particular situations. Therefore, in order to evaluate player balancing techniques, a set of performance metrics is required.

To determine what characteristics of player balancing are most critical to engagement in exergames, I first performed a literature review. Research on player balancing in exergames is limited; however, some research has been done on balancing in traditional video games. Issues related to player balancing were collected from academic publications, game design articles, and game development books. The most frequently cited player balancing problems were then selected. By synthesizing the existing research, five important characteristics emerge: balance,
CHAPTER 3. BALANCING SKILL AND ABILITY

enjoyment, transparency, exploitability, and portability. I propose that these characteristics can be used as a set of metrics for evaluating the performance of player balancing techniques in exergames. The definition and reasoning behind each of the metrics are presented below.

3.3.1 Balance
The aim of player balancing in multiplayer games is to even out the performance differences between people [52]. Optimal balance results in the performance of each player being nearly equal, while poor balance leads to a large performance gap between players. Balance is an important aspect of player engagement since it is related to challenge [89] and flow in video games [31].

Dynamic player balancing has been applied in a variety of contexts, such as simple games like Pong [60], target shooting games [11], and exergames [66]. In all these cases, the main objective is to improve the balance of competition between players. However, balancing techniques assume that all players are making a similar effort. In multiplayer exergames, this means that competition should be balanced only when players are working equally hard relative to their individual fitness levels.

In order to evaluate how effective a technique is at balancing competition, a measure of players’ in-game performance is required. For example, in target-shooting games, player performance can be measured by a combination of the number of targets hit and missed [11]. In racing-style games, performance can be measured as the average speed difference between players over the course of a race [109]. Although there are currently no guidelines for measuring in-game performance, most video games use some form of scoring mechanism to rate player
CHAPTER 3. BALANCING SKILL AND ABILITY

performance. Thus, by comparing performance based on the difference in score between players, it is possible to determine the degree of balance provided by a technique.

3.3.2 Enjoyment
Enjoyment is related to people’s interest and affect, making it an important element of engagement [89]. The motivation behind player balancing is to allow people to have fun playing together in spite of differing skill and ability [11, 60, 119]. This is particularly important in exergames, since poor physical ability is often seen as a barrier to exercise participation [4, 99]. However, highly skilled players can lose their sense of achievement as the gap in in-game performance is reduced, resulting in decreased enjoyment [19, 85]. Additionally, player balancing techniques that are noticeable to the player can lead to a hollow sense of victory [2]; see section 3.2.3. Therefore, it is important to consider how a player balancing technique influences the overall enjoyment of a game.

Several techniques exist for measuring enjoyment in video games. Simple approaches include asking players to rate their enjoyment on a five-point scale [11]. Federoff proposes a set of heuristics for evaluating fun in video games [42]. The Game Experience Questionnaire (GEQ) measures enjoyment based on seven dimensions of player experience: immersion, tension, competence, flow, negative affect, positive affect, and challenge [62]. It is currently unclear which approach is optimal for measuring player enjoyment. However, any of the existing techniques should allow researchers to estimate the impact of player balancing on enjoyment.

3.3.3 Transparency
A person’s sense of control is an important part of user engagement [89]. Because of this, balancing techniques should not be obvious enough to distract players [59, 117]. However,
dynamic difficulty adjustment mechanisms are often too apparent to players [19]. For example the “Fatboy” mode in Epic Games’ *Unreal Tournament* provides player balance by changing the size of players’ avatars. A player’s avatar grows with each kill she scores and shrinks each time the player is killed [61]. Since many players do not enjoy winning when they have received an unfair advantage [2], player balancing techniques should be designed to be as transparent as possible.

Bateman et al. offer the only example published to-date of measuring transparency of player balancing mechanisms [11]. The authors determined the perceptibility of several target-assistant techniques by asking players to rate any differences in input controls on a five-point scale. Thus, surveying players on perceived differences in game controls should provide a measure of the transparency of player balancing techniques.

### 3.3.4 Exploitability

The effectiveness of a player balancing technique is reduced if players are able to exploit the balancing mechanism [2]. For example, the balancing mechanism in Nintendo’s *Mario Kart* is known to be very forgiving to losing players by giving them strong power-ups in order to capture the lead. Therefore, players often purposely fall behind to gain better power-ups [59]. This situation can impact engagement by decreasing players’ motivation [89]. Exergame designers should try to minimize the exploitability of player balancing techniques.

The degree to which a balancing technique can be exploited varies. For instance, the balancing mechanism in Age Invaders is based on a player’s age [66]. Unless a player lies about her age, she cannot exploit the system. The balancing mechanism in Truck-Pull is based on player performance [108]. Two players engage in a virtual tug-of-war by pedaling on exercise bikes. The
player who has pulled their opponent further at the end of one minute is declared the winner. Tension applied to the pedals increases the further a player pulls her opponent. Players quickly realize that this balancing mechanism is easily exploited by performing poorly in the first half of the game before pedaling more vigorously near the end [108]. One way designers can limit exploitability is to make a balancing technique transparent enough that players are unaware of any mechanism to exploit; see section 3.2.3. Exploitability can be evaluated with user testing by observing if and how players abuse a balancing mechanism.

3.3.5 Portability
A balancing mechanism should function regardless of any differences in the hardware players are using. For example, the asymmetric roles in Frozen Treasure Hunter provide player balance and can still be preserved using a variety of input devices. The player acting as the “driver” could use any ergometer such as an exercise bike, treadmill, or stepping machine. Similarly, the person playing as the “defender” can swat away virtual projectiles using a Nintendo Wii remote, Sony PlayStation Move controller, or by swinging her arms in front of a Microsoft Kinect motion sensor. Player balancing mechanisms requiring specialized hardware or software are limited in how universally they can be applied [48].

Portability plays an important role in determining the effectiveness of a player balancing technique. One way designers can ensure portability is by testing a balancing mechanism across several hardware platforms.

3.4 Summary
Player balancing is an important design challenge for exergames since differences in physical abilities limit participation in group exercise [3]. Less fit players will quickly lose interest when
facing repeated losses to more physically fit opponents. Similarly, fitter players will be bored from the lack of challenge from less fit players. In order to address this, several player balancing mechanisms have been proposed. Sections 3.1 and 3.2 summarized the player balancing techniques found in existing multiplayer exergames. To date, the effectiveness of these approaches on player balancing have not been measured in detail.

Some form of measurement is required in order to determine the effectiveness of a player balancing mechanism. The metrics defined in section 3.3 are intended to be used by designers to evaluate balancing techniques. Although the metrics do not capture all of the characteristics of player balancing, I have highlighted five important factors according to existing research: balance, enjoyment, transparency, exploitability, and portability. These five metrics offer a novel contribution to the development of balancing techniques for exergames. I hypothesize that balancing mechanisms which perform poorly under these metrics will distract from player engagement. The five player balancing metrics are used to evaluate the heart rate balancing mechanism presented in the next chapter.
Chapter 4

Heart Rate Balancing

When playing exergames, a person’s in-game performance is typically limited by her physical capabilities. For example, in the Breakout for Two exergame [80], players who can move the quickest and kick a ball the hardest have the best chance of winning. This situation fails to address compatibility issues between players: unfit players will become discouraged due to repeated losses to fitter opponents, and fit players will get bored with the lack of challenge from less fit opponents. As discussed in chapter 3, people are more motivated to participate in physical activity if there is commonality among group members, such as age and fitness level [7, 9, 20]. In this chapter, I define a technique for balancing player performance based on effort relative to fitness level.

Physical effort is reflected in heart rate [88]. For instance, heart rate is higher when a person is exercising versus when relaxing. Because of the relationship between heart rate and physical activity, heart rate can act as a measure of effort. I propose that heart rate can be used in exergames to base players’ in-game performance on effort. More specifically, heart rate monitoring is used to scale performance based on how closely a person adheres to her target heart rate. However, heart rate behaviour differs from person to person, and does not immediately reflect changes in physical exertion. In section 4.1, I describe the behaviours of heart rate and, based on these properties, I define an algorithm for using heart rate to estimate effort in exergames in section 4.2.
CHAPTER 4. HEART RATE BALANCING

4.1 Heart Rate Behaviour

Heart rate better reflects a person’s effort, relative to her fitness level, than raw physical output. However, heart rate is an imperfect measure. A person’s fitness level affects the way heart rate behaves during physical activity. For instance, with improved fitness heart rate increases more rapidly at the onset of exercise [53], and recovers more quickly when exercise is concluded [37, 53]. Additionally, the behaviour of heart rate varies from person to person. I will use two example heart rate profiles to demonstrate the problems of using heart rate to estimate effort. The graphs in figure 4.1 show the heart rates of two people pedaling on a bike for five minutes. These graphs were created from data collected from two people pedaling on stationary bikes in a lab setting. Person A is 23 years old, with a resting heart rate of 77bpm and a target heart rate of 146bpm. Person B is a 27 year old, with a resting heart rate of 86bpm and a target rate of 148bpm.
I suggest there are three problems that need to be addressed when using heart rate as an estimate of effort for exergames: amplitude, quick-start, and latency. These problems are discussed in detail in the following subsections.

4.1.1 Amplitude Problem

Target heart rate is a calculated value meant to act as a guide for exercise intensity. Reaching a target heart rate range of 50% to 60% of maximum heart rate is considered light exercise, and a target heart between 60% to 70% of maximum heart rate represents effective exercise for improving cardiovascular health [23]. A measurement of a person’s maximum heart rate is required in order to calculate target heart rate. Some methods for determining target heart rate also require a measurement of resting heart rate (e.g., [65]). Resting heart rate is easily measured when a person is sufficiently rested. Maximum heart rate represents the highest beats-per-minute a person’s heart can achieve, and is most accurately determined with a cardiac stress test [23]. However, this test can be expensive, and requires specialized equipment and medical training. Additionally, it can be exhausting and hazardous for the person being evaluated. Thus, for practical purposes, an age-based formula is often used to estimate a person’s maximum heart rate.

The most commonly used age-based formula for calculating maximum heart rate is $220 - \text{age}$. Although widely used, this formula has been shown to be inaccurate [101]. More reliable formulas have been proposed, such as the Tanaka method [115] which calculates maximum heart rate as $208 - (0.7 \times \text{age})$. However, the Tanaka formula may still underestimate or overestimate maximum heart rate. Similar formulas have been shown to have an average error of approximately $\pm 11$ bpm [45]. The Tanaka formula was used in calculating the target heart rates shown in figure 4.1.
In figure 4.1, Player A’s heart rate begins to level-off following the first minute of exercise, and remains above the target heart rate for the final four minutes. During physical activity, there are two reasons why heart rate falls above or below a target heart rate: varying levels of exertion, or errors in calculating target heart rate. If a person surpasses a target heart rate (e.g., Person A in figure 4.1), she may be exerting herself beyond what is required to reach the target. Similarly, if the person fails to reach a target heart rate, it may be a result of insufficient actual effort. A second explanation for missing a target rate is an over/underestimation of maximum heart rate used in calculating the target heart rate. As explained above, age-based estimations of maximum heart rate are inaccurate and these errors carry over into calculations of target heart rate. Thus, if maximum heart rate is underestimated, the calculated target heart rate will be below the actual target rate. For example, figure 4.2 shows the upper ($hr_{\text{target}^+}$) and lower ($hr_{\text{target}^-}$) limits for the target heart rate of Person A. These bounds take into account the potential error of $\pm 11 \text{bpm}$.
introduced by estimating maximum heart rate. Person A’s heart rate is closer to the upper band, suggesting a possible underestimation of target heart rate. Alternatively, if maximum heart rate is overestimated, the calculated target heart rate will be above a person’s true target heart rate.

Unfortunately, heart rate profiles cannot reveal if a person misses the target heart rate because of improper exertion, or due to estimation errors. However, it is important to consider these scenarios when using heart rate to estimate effort. Otherwise, some people may have to overexert themselves to reach a target heart rate, while other people may require less actual effort to reach an inaccurately calculated target heart rate.

4.1.2 Quick Start Problem
Heart rate begins to increase at the onset of physical activity. Assuming a constant work load, heart rate rises until it reaches a steady-state [126]. Clinical studies show that healthy males reach a steady heart rate within 60 to 90 seconds [40]. More generally, heart rate typically reaches a steady-state within one to two minutes following an increase in exercise intensity [126]. When using heart rate to estimate effort, it is important to consider that the time required for heart rate to settle varies from person to person. For instance, in figure 4.1, Person A’s heart rate begins to reach a steady-state around the one minute mark, whereas Person B’s heart rate takes approximately two minutes to level off. This does not necessarily imply that Person A is working harder than Person B. In fact, Person B has an average pedal cadence of 129.7rpm, while Person A has an average pedal speed of only 98.8rpm. Thus, it is also possible that Person B requires more time for their heart rate to reach a steady-state. Unfortunately, the source of the variation in the time to reach steady heart rate is difficult to determine.
CHAPTER 4. HEART RATE BALANCING

An elevated initial heart rate at the onset of physical activity can impact the time required to reach a steady-state. When a person stops exercising, it takes several minutes for her heart rate to return to rest. On average, heart rate settles back to rest at a rate of decrease of 17bpm [33]. Because of this, a person may feel at rest even though her heart rate is still elevated due to prior activity. If a person has an elevated heart rate at the onset of exercise, she may require less time to reach her steady-state heart rate. For example, both Person A and B were given over 10 minutes to rest before beginning the five minutes of exercise. However, figure 4.1 shows that Person A began with a heart rate well above his/her resting rate (33bpm above rest). Alternatively, Person B began near his/her resting heart rate (8bpm above rest).

Thus, when heart rate is used to estimate effort, it is important to consider the variation in the time required for heart rate to reach a steady-state, and the effect of starting exercise with an elevated heart rate.

4.1.3 Latency Problem
Changes in actual effort are not immediately reflected in a person’s heart rate. When a person increases her physical output, it takes several seconds before her heart rate begins to rise. Figure 4.3 below shows the heart rate and pedal cadence of Person B over five minutes. In the first 30 seconds, Person B goes from rest to a high pedal cadence above 150rpm. However, Person B’s heart rate does not immediately spike, but gradually increases following this substantial change in actual effort.

A similar latency occurs between decreases in physical effort and a corresponding drop in heart rate. When physical activity is ceased, heart rate recovers at an average rate of 17bpm [33]. In figure 4.3, Person B reduces his/her pedal cadence near the end of the third minute. This
CHAPTER 4. HEART RATE BALANCING

Figure 4.3: Heart rate and pedal cadence profile of Person B

reduction in physical effort is not reflected in heart rate until after the start of the fourth minute when Player B has increased his/her pedal cadence again.

Heart rate provides a reasonable estimate of effort, although it fails to immediately reflect changes in physical exertion. Therefore, when using heart rate to estimate effort, it is important to consider this latency.

4.1.4 Summary of Problems

Although heart rate can be used to estimate effort during physical activity, it is an imperfect measure due to three main problems. First, the amplitude problem makes it difficult to determine if a person’s heart rate deviates from the target rate due to estimation errors or variations in actual effort. Second, the quick start problem means that the time to reach a target heart rate depends on an elevated initial heart rate or differences in physiological responses to exercise. Third, latency problems result in a disconnect between changes in physical exertion and changes in heart rate. These three issues make it challenging to generalize people’s estimated efforts based on heart
CHAPTER 4. HEART RATE BALANCING

rate. For example, at the outset of physical activity, it is difficult to estimate effort from heart rate due to the quick start problem. Additionally, effort is easily over/underestimated without considering the amplitude and latency problems associated with heart rate.

4.2 Heart Rate Balancing Algorithm

In this section I derive an algorithm to base in-game performance in exergames on people’s effort relative to their fitness level. The heart rate balancing algorithm is intended to allow players of varying fitness levels to play multiplayer exergames together. The algorithm is designed primarily for power-based exergames where in-game performance is based on a player’s degree of exertion [21]. Examples of power-based exergames include Swan Boat where players run on treadmills to power an on-screen boat [6], and Pedal Race in which players pedal on stationary bicycles to control the speed of their virtual tricycle [108]. Heart rate balancing is not appropriate for gesture-based games where performance is determined by specific player motions and timing, such as a player swinging her arms in Wii Sports tennis, or completing the correct dance steps in Dance Dance Revolution. The heart rate balancing algorithm estimates effort while resolving the three main problems of heart rate behaviour presented in section 4.1. The algorithm was evaluated in two user studies presented in chapters 5 and 6.

4.2.1 Existing Formulas

Exercise is often prescribed at recommended levels of intensity. For example, the American College of Sports Medicine (ACSM) proposes that exercise be performed in the range of 65% to 90% of a person’s maximum heart rate in order to maintain and improve cardiorespiratory fitness [5]. A range of 60% to 84% of heart rate reserve is considered high-intensity [123] and
beneficial for improving cardiovascular health [23]. Heart rate reserve is calculated as the difference between a person’s maximum heart rate and her resting heart rate.

The underlying idea of heart rate balancing is to base players’ in-game performance on how closely they adhere to a target heart rate. For instance, in a racing-style exergame, the closer a player’s heart rate is to her target, the faster her on-screen car would move [109]. In order to achieve this, a target heart rate is calculated using age, resting heart rate, and maximum heart rate. This allows target heart rate to be individualized for each person. I propose using the Tanaka formula [115], as discussed in section 4.1.1, to estimate maximum heart rate $h_{r_{max}}$ as follows:

$$h_{r_{max}} = 208 - (0.7 \times age)$$

Using the calculated maximum heart rate, and a measured resting rate $h_{r_{rest}}$, the Karvonen formula [65] is applied to calculate a target heart rate $h_{r_{target}}$ as follows:

$$h_{r_{target}} = [intensity \times (h_{r_{max}} - h_{r_{rest}})] + h_{r_{rest}}$$

Where $intensity$ is the desired percentage of a person’s heart rate reserve (i.e., the difference between maximum and resting heart rate). For example, an intensity value of 0.6 would result in a target heart rate of 60% of a person’s heart rate reserve.

Finally, heart rate is normalized based on a person’s target heart rate to return a final estimated effort value $E$ at a given time $t$, as follows:

$$E(t) = \frac{h_{r}(t) - h_{r_{rest}}}{h_{r_{target}} - h_{r_{rest}}}$$
Where \( h_r(t) \) is the measured heart rate at time \( t \). The calculated effort is equal to 0 when a person is at her resting heart rate, equal to 1 when the person has reached her target heart rate, and greater than 1 when the target heart rate is surpassed (see figure 4.4). The estimated effort value can be applied to various types of exergames, such as controlling the speed of a car in a racing game, or an avatar in an action game. For example, in a role-playing exergame where a player is controlling an on-screen character, estimated effort can determine the speed at which the character moves. The character could be at rest when \( E(t) = 0 \), walking when \( 0 < E(t) < 0.6 \), and

**Figure 4.4: Graph showing the value range for effort \( E(t) \) based on heart rate**

(in this example \( h_r_{rest} = 86 \text{bpm}; h_r_{target} = 148 \text{bpm}; h_r_{max} = 189 \text{bpm} \))
running when $E(t) \geq 0.6$. In a racing-style exergame, the speed of a player’s car could be mapped directly to the effort value $E(t)$. The greater the player’s effort, the faster her car would move.

Although this initial approach to heart rate balancing provides the basic functionality of controlling in-game performance based on a player’s effort, it fails to solve the problems presented in section 4.1. In following sections, I present techniques to address the amplitude, quick start, and latency problems associated with heart rate behaviour.

### 4.2.2 Heart-Rate Banding for the Amplitude Problem

As discussed in 4.1.1, age-based estimation of maximum heart rate is inaccurate [101]. This means that a person’s maximum heart rate may be over/underestimated, resulting in an imprecise target heart rate. To address this, I propose using a target heart rate range rather than a single target heart rate value. The lower target heart rate bound ($hr_{target}^-(t)$) at time $t$ compensates for any overestimation of the target heart rate. For instance, if a person’s target heart rate has been overestimated, the lower bound will fall at or below the person’s actual target heart rate. The upper target heart rate bound ($hr_{target}^+(t)$) at time $t$ addresses underestimations of target heart rate. If target heart has been underestimated, the upper bound will be at or above a person’s true target heart rate. Therefore, a person’s actual target heart rate will fall within the target heart rate band (between $hr_{target}^-$ and $hr_{target}^+$) regardless of any estimation errors. The upper and lower bounds take into account estimation errors of maximum heart rate as follows:

$$hr_{target}^-(t) = \left[ \text{intensity} \times ((hr_{max} - \text{error}) - hr_{rest}) \right] + hr_{rest}$$

$$hr_{target}^+(t) = \left[ \text{intensity} \times ((hr_{max} + \text{error}) - hr_{rest}) \right] + hr_{rest}$$
CHAPTER 4. HEART RATE BALANCING

Here, error represents an estimation error in terms of beats per minute. Since equations similar to the Tanaka formula have been shown to have an error of ±11bpm when calculating target heart rate \[45\], I suggest using a value of 11bpm for error.

The heart rate bands are taken into account when normalizing heart rate to an effort value. The modified effort value is less than 1 when heart rate is below the lower bound, equal to 1 when heart rate falls within the band, and greater than 1 when heart rate is above the upper bound, as shown in figure 4.5. To achieve this, effort is calculated as follows:

\[
E(t) = \begin{cases} 
\frac{hr(t) - hr_{rest}(t)}{hr_{target}^- (t) - hr_{rest}(t)}, & \text{if } (hr(t) < hr_{target}^- (t)) \\
\frac{hr(t) - hr_{target}^- (t) - hr_{rest}(t)}{hr_{target}^- (t) - hr_{rest}(t)}, & \text{if } (hr(t) > hr_{target}^+ (t)) \\
1.0, & \text{otherwise}
\end{cases}
\]

Where, \( \Delta hr_{target}(t) \) represents the difference between \( hr_{target}^+ \) and \( hr_{target}^- \).

Heart rate banding is meant to address inaccuracies in calculating a target heart rate. Rather than using a single value as a target, a range of target values are used. With this approach, the target heart rate band includes the highest and lowest possible values for the majority of people’s target heart rates. This ensures that regardless of estimation errors, a person’s true target heart rate will fall within the band. The advantage of this approach is that if a player is at her actual target heart rate, the formula will return an appropriate value of effort even in the presence of estimation errors. However, it is not a perfect solution, since players whose maximum heart rates are overestimated will still require more actual effort to exceed the heart rate band compared to players whose maximum heart rates are underestimated.
4.2.3 Ramp-Up Window for the Quick Start Problem

The time it takes heart rate to reach a steady-state varies from person to person, as described in section 4.1.2. Heart rate balancing needs to take this into account, otherwise people who quickly reach their target heart rates can have an unfair advantage over people requiring additional time.

In order to address this problem, effort should be estimated differently in the early stages of physical activity compared to after a steady heart rate has been reached. A ramp-up window from the start time to a time $m$ is chosen in order to allow people sufficient time to reach their target heart rate. I propose an $m$ value of 120 seconds, since this represents an upper limit in the time it
CHAPTER 4. HEART RATE BALANCING

takes people’s heart rates to reach a steady-state following an increase in physical activity [126]. With this approach, and individual’s heart rate should be at a steady-state by the time the ramp-up window expires.

For instance, assume that based on a person’s physiology and actual effort, she requires the maximum time to reach her target heart rate (i.e., \( m=120 \text{sec} \)). Heart rate would be at the person’s resting rate at time 0, and at the target heart rate at time \( m \). This represents the worst-case scenario for heart rate to reach the intended target; most people’s heart rate should reach their target heart rate is less time. Based on this premise, the lower-bound of target heart rate is calculated by interpolating between resting heart rate at time 0, and the age-predicted target heart rate at time \( m \), as follows:

\[
h_{\text{rest}}(t) = \frac{t \times (h_{\text{target}}(m+1) - h_{\text{rest}})}{m} + h_{\text{rest}}(m+1), \text{if } (t \leq m)
\]

The hypothesis is that heart rate should fall above \( h_{\text{target}}(t) \) during the ramp-up, assuming a person is working sufficiently hard to reach her target heart rate.

The value of resting heart rate also needs to be adjusted during the ramp-up window in order avoid compressing the band between resting heart rate and the lower-bound of target heart rate. Otherwise, if a person’s heart rate is at her resting heart rate for the first few seconds, her effort would be estimated to be close to or equal to 0. To address this, resting heart rate is calculated as follows:

\[
h_{\text{rest}}(t) = h_{\text{rest}}(m+1) - \left( h_{\text{target}}(m+1) - h_{\text{target}}(t) \right), \text{if } (t \leq m)
\]
Here, $hr_{rest}$ is a person’s measured resting heart rate prior to beginning physical activity. By increasing the gap between resting heart rate and the lower bound of the target heart rate, the calculated effort value is more forgiving for people whose heart rates are slow to respond to physical activity.

As discussed in section 4.1.2, people beginning exercise with an elevated initial heart rate may be perceived as making more effort than people starting at a resting rate. In order to address this problem, the upper bound of target heart rate ($hr_{target}^+$) remains constant during the ramp-up window. This ensures that players who begin with heart rates above their resting rates do not
CHAPTER 4. HEART RATE BALANCING

receive an overestimate of effort. The bounds of the ramp-up window are shown from minutes 0 to 2 in figure 4.6.

The ramp-up window ensures that effort is not underestimated for people whose heart rate is slow to respond to physical activity. Similarly, effort is not overestimated if a person quickly reaches her target heart rate, or begins with an elevated heart rate. However, if a person requires more than the time allotted in the ramp-up window to reach her target heart rate, the calculated effort value will drop sharply as time \( t \) approaches. For instance, fit people can reach target heart rates more quickly than less fit people [53]. Thus, a less fit person’s heart rate may initially be within the bounds of the ramp-up window (i.e., \( E(t)=1 \)); but as the lower-bound of the window increases, heart rate will fall below the window resulting in a lower estimate of effort (i.e., \( E(t)<1 \)).

Heart rate balancing, including the ramp-up window and banding, can now be summarized as follows:

\[
hr_{\text{rest}}(t) = \begin{cases} 
hr_{\text{rest}} & , \text{if } (t > m) \\
hr_{\text{rest}} - \left( hr_{\text{target}}^- (m + 1) - hr_{\text{target}}^-(t) \right) & , \text{if } (t \leq m)
\end{cases}
\]

\[
hr_{\text{target}}^+(t) = \left[ \text{intensity} \times ((hr_{\text{max}} + \text{error}) - hr_{\text{rest}}) \right] + hr_{\text{rest}}
\]

\[
hr_{\text{target}}^-(t) = \begin{cases} 
\left[ \text{intensity} \times ((hr_{\text{max}} - \text{error}) - hr_{\text{rest}}) \right] + hr_{\text{rest}} & , \text{if } (t > m) \\
\frac{t \times (hr_{\text{target}}^-(m + 1) - hr_{\text{rest}})}{m} + hr_{\text{rest}}(m + 1) & , \text{if } (t \leq m)
\end{cases}
\]

62
CHAPTER 4. HEART RATE BALANCING

\[
E(t) = \begin{cases} 
\frac{hr - h_{\text{rest}}(t)}{h_{\text{target}}^-(t) - h_{\text{rest}}(t)} & , \text{if } (hr < h_{\text{target}}^-(t)) \\
\frac{(hr - \Delta h_{\text{target}}(t)) - h_{\text{rest}}(t)}{h_{\text{target}}^-(t) - h_{\text{rest}}(t)} & , \text{if } (hr > h_{\text{target}}^+(t)) \\
1.0 & , \text{otherwise}
\end{cases}
\]

Figure 4.7 shows two examples of applying this approach to the heart rate profiles presented earlier in section 4.1. Since the heart rates of both Person A and Person B mostly fall within the target heart rate bands, their in-game performance would be very similar. This illustrates the potential of heart rate balancing. In contrast, in-game performance would be very imbalanced between Person A and Person B when using raw physical output to control performance. In this case, Person B had an average cadence of 129.7rpm and therefore would grossly outperform Person A who had an average cadence of only 98.8rpm.

![Graphs showing the variables of the modified heart rate balancing formula using the profiles from figure 4.1](image)

**Figure 4.7**: Graphs showing the variables of the modified heart rate balancing formula using the profiles from figure 4.1

63
4.2.4 Logarithmic Scaling

One shortcoming of the formula for $E(t)$ presented in section 4.2.3 is that the effort value will continue to increase as a person surpasses the upper bound of target heart rate. Since heart rate balancing is meant to control in-game performance based on how closely a person adheres to her target heart rate, players should not be rewarded for overexerting themselves. In order to address this problem, I derive a formula to preserve three properties: 1) lower the returned value of effort when heart rate exceeds the target heart rate; 2) effort is reported as 0 when a person is at their resting heart rate; 3) effort is reported as 1 when heart rate falls within the target heart rate band.

The first property can be supported using the behaviour of a common logarithm: $\log_{10} X$. The graph of a logarithm increases rapidly when $X$ is between 1 and 10, and then tapers off as $X$ surpasses 10. To support properties 2 and 3, the formula must behave as follows:

$$
\log_{10}X = 0 \text{ , if } (E(t) = 0)
$$

$$
\log_{10}X = 1 \text{ , if } (E(t) = 1)
$$

This can be achieved by replacing $X$ with an equation resulting in a scaled version of effort $E_{scaled}(t)$ as follows:

$$
E_{scaled}(t) = \log_{10} [9 \times E(t) + 1] \text{ , if } (E(t) \geq 0)
$$

The above logarithmic scaling formula is applied to all positive values of $E(t)$. Since a logarithm of a negative value does not result in a real number, the formula is not used when $E(t)$ is less than zero. Logarithmic scaling preserves the property that effort is reported as 0 when a person is at their resting heart rate, and effort is reported as 1 when heart rate falls within the target heart rate band. However, the return on effort diminishes when heart rate surpasses the
Figure 4.8: Graphs showing example effort values without (left) and with (right) logarithmic scaling
(in this example $hr_{rest} = 86$ bpm; $hr_{max} = 189$ bpm; $hr_{target^{+}} = 154$ bpm; $hr_{target^{-}} = 141$ bpm)

upper bound of target heart rate so that overexertion results in less of an in-game advantage, as shown in figure 4.8. Rather than capping estimated effort at 1, with logarithmic scaling players who exceed their target heart rates still receive a minor increase in in-game performance. Otherwise players could become frustrated when they see no increase in-game performance when overexerting themselves. Another advantage of using a logarithmic function is that low values of estimated effort are pushed up, and high values of estimated effort are pushed down. Thus most estimated values of effort will fall within a narrower range. Logarithmic scaling also helps in limiting overestimates of effort when a person’s target heart rate has been underestimated, as discussed in section 4.1.1.

4.2.5 Nimbleness for the Latency Problem
As discussed earlier, the heart rate balancing algorithm is intended to be used in power-based exergames where in-game performance is based on physical output. In such games, the problem
CHAPTER 4. HEART RATE BALANCING

of latency between changes in exertion and a corresponding change in heart rate needs to be addressed (as discussed in section 4.1.3). For heart-rate based controls to feel natural, players expect their in-game performance to immediately increase as they increase their physical exertion. For instance, in a racing-style exergame using stationary bikes, players anticipate their car will accelerate as they pedal harder. Similarly, decreases in exertion should result in lower in-game performance.

To address this issue, the calculated effort is blended with changes in a person’s physical output. Since the exergames explored in this thesis involve physical activity on an exercise bike, I focus on using pedal speed as a measure of physical output. Other measurements of speed in physical output could be used, such as running pace on a treadmill or elliptical machine, climbing rate on an stepper machine, or stroke speed on a rowing machine. The idea is to provide an immediate increase or decrease in in-game performance as a player increases or decreases physical output. However, the change is performance is not permanent. If the player’s heart rate remains constant, her in-game performance will drift back to the original heart-rate based value of effort. This gives players immediate feedback on changes in physical output while having little impact on the overall in-game performance.

This functionality is achieved by adding a nimbleness component to the effort factor. Nimbleness is defined as a weighted average of acceleration over a continuously-sliding time window of \( w \) seconds. Thus, a change in exercise intensity will result in an immediate change in in-game performance; over the following \( w \) seconds, in-game performance will return to being purely based on heart rate. On an exercise bike, acceleration is calculated as the change in the player’s pedal cadence (in revolutions per second). Specifically, acceleration at time \( t \) is
calculation by comparing the current cadence \( c(t) \) with the cadence from the previous second \( c(t-1) \) as follows:

\[
a(t) = c(t) - c(t - 1)
\]

Acceleration \( A_t \) is then calculated over a sliding window of \( w \) seconds ending at time \( t \) as a weighted average of acceleration values over that window. Weight decays over time by subtracting \( i \) from \( w \) as follows:

\[
A_t = \frac{\sum_{i=0}^{w-1} [(w - i) \times a_{t-i}]}{\sum_{i=1}^w i}
\]

Since acceleration can be arbitrarily large or small, it needs to be limited to a maximum/minimum value. Clamping ensures that a value does not exceed a threshold as follows:

\[
\text{clamp}(a, -x, x) = \begin{cases} 
  a & \text{if } (-x \leq a \leq x) \\
  -x & \text{if } (a < -x) \\
  x & \text{if } (a > x)
\end{cases}
\]

To limit the effects of extreme changes in pedal cadence, acceleration is clamped to a value \( r \). Nimbleness \( n \) is then normalized to fall in the range of \([-1, 1]\) as follows:

\[
n = \frac{\text{clamp}(A_t, -r, r)}{r}
\]

A pedal cadence of 50rpm to 60rpm is reported as the most economical and efficient for recreational cyclists [73]. Therefore, I set \( r \) to a maximum acceleration of 50rpm (adjusted to 0.833 rpm/second). Informal testing of the nimbleness formula showed that a window of 5 seconds was natural for most players. However, the maximum acceleration and window size can be adjusted to suit different types of exergames.
A final effort value is calculated by blending nimbleness with the scaled heart-rate effort value as follows:

\[ E_{final}(t) = E_{scaled}(t) + (f \times n) \]

Here, \( f \) is a constant factor (0 < \( f \) < 1) applied to nimbleness in order to allow short bursts of speedups or slowdowns. Informal trials found a factor of 0.9 to be effective in making exergames controls feel responsive to changes in pedal cadence.

The effect of the nimbleness factor can be seen in figure 4.9. The effort remains close to 1, but spikes in pedal cadence are reflected in the final effort value. It is important to note that the formula for \( E_{final} \) is only applied when the player is moving (i.e. pedal cadence greater than 0rpm). This is done in order to avoid the unintuitive situation where a player sprints to increase heart rate, and then coasts through the remainder of the game.

Figure 4.9: Graph showing changes in pedal cadence reflected in the final effort value
CHAPTER 4. HEART RATE BALANCING

One limitation of nimbleness is that over time, players may begin to notice the decay in speed following an increase in exercise intensity. This is particularly problematic in low-intensity games where a person’s heart rate fails to reach the target heart rate, resulting in an estimated effort value below 1. In this scenario, players will receive a temporary boost in performance when increasing physical output. However, in-game performance will quickly drop once the nimbleness window expires. Exergames requiring frequent changes in physical output, such as repeated starting and stopping, may further expose the nimbleness factor. These issues are tested in the experiment presented in chapter 6.

4.2.6 Algorithm Summary
The proposed heart rate balancing algorithm is designed to base a player’s in-game performance on how closely she adheres to her target heart rate while taking into account the variations in heart rate behaviour between individuals. The algorithm accounts for the lack of accuracy in estimating maximum heart rate; the variation in the time to reach target heart rate; and, the latency between changes in physical output and changes in heart rate. The heart rate balancing algorithm uses a series of steps to calculate an estimated effort value $E_{\text{final}}(t)$ that is used to control in-game performance in exergames (e.g., avatar speed in a racing game).

4.3 Summary
In this chapter, I presented a heart rate balancing algorithm designed to base players’ in-game performance on how closely target heart rate is matched. The algorithm addresses several problems associated with using heart rate as a measure of effort. First, heart rate banding deals with the amplitude problems related to estimation errors of maximum heart rate. Second, a ramp-up window is used to address the quick start problem associated with the variation in the time to
reach a target heart rate. Third, nimbleness addresses the latency between changes in physical output and a corresponding change in heart rate. Additionally, logarithmic scaling is used to limit any performance benefits from surpassing target heart rate.

The heart rate balancing algorithm is evaluated in the following chapters using the player-balancing evaluation metrics presented in section 3.3. Chapter 5 evaluates how heart rate balancing affects competition between players, and how effectively the technique captures people’s effort. Chapter 6 examines the circumstances under which players notice that in-game performance is based on heart rate rather than raw physical output. Finally, chapter 7 includes a discussion on how easily heart rate balancing can be implemented across various exergame hardware, and the ways in which players can attempt to cheat by exploiting the balancing technique.
Chapter 5

Balance and Enjoyment of Heart Rate Balancing

Heart rate balancing is currently the only existing approach designed for player balancing in power-based exergames. Thus, at the outset of this experiment it was not possible to compare heart rate balancing to other balancing techniques. As discussed in section 3.3.1, the most important feature of any player balancing mechanism is the degree to which it allows for more equal competition between players. This chapter presents the design and results of an experiment used to examine the competitive balance provided by heart rate balancing.

5.1 Hypotheses

This experiment was designed to investigate several hypotheses related to the performance of heart rate balancing when compared to standard gameplay in exergames:

1. Heart rate balancing improves competition between exergame players. Specifically, heart rate balancing lowers the average difference in in-game performance between competitors, despite variations in people’s fitness levels.

2. Heart rate balancing better reflects player actual effort compared to raw physical output. The underlying hypothesis of heart rate balancing is that it sets in-game performance based on people’s effort rather than raw physical output. This means that a player’s in-game performance should be better correlated to her degree of effort.

3. Heart rate balancing leads to more enjoyable player experiences. Player balancing is typically applied in games to provide a more enjoyable experience for all players. At the outset of this study, I hypothesized that heart rate balancing improves competition, making multiplayer exergames more fun to play.
CHAPTER 5. BALANCE AND ENJOYMENT OF HEART RATE BALANCING

4. *Players do not notice when heart rate balancing is applied.* When playing an exergame, people typically expect their in-game performance to be based on their raw physical output. For example, in a racing exergame, in-game speed is often based on how quickly the player is physically moving (e.g., pedal speed on a bike, or stroke speed on a rowing machine). Although heart rate balancing sets in-game performance based on estimated effort, the nimbleness factor of the algorithm (see section 4.2.5) should make game controls feel as natural as standard exergame input.

5. *Players have a favourable impression of heart rate balancing in multiplayer exergames.* The heart rate balancing algorithm presented in this thesis offers a novel approach for player balancing in exergames. At the outset of this study it was hypothesized that players would react positively to the technique and find it to be beneficial to the overall experience of playing exergames.

5.2 Study Design
The user experiment took place in a lab setting. A within-subjects design was applied, where pairs of participants played a networked exergame. The game was designed to involve competition between players.

5.2.1 Apparatus
The exergame created for this experiment required players to pedal on a Tunturi E6R recumbent exercise bike. A projector displayed the game on a 6’x8’ screen placed in front of the bike. This experimental setup was replicated in two separate rooms to support two-player games, as shown in figure 5.1. The game ran on two networked Windows XP desktop computers and was created in C# using the Microsoft XNA 3.1 game development toolkit. To measure pedal speed, each
bipe was equipped with a XRGameKit Bike Pod attached to the internal wheel. Signals from the pod were captured using a XRGameKit PC Interface receiver connected to the computer running the game. Heart rate was measured using a Polar Heart Rate monitor worn across the player’s chest. The monitor connected wirelessly to a Sparkfun Electronics Heart Rate Monitor Interface board plugged into the game computer.

5.2.1.1 Heart Racer Exergame

The Heart Racer exergame was designed to be a head-to-head racing game between two players. Each player is represented by an on-screen car. Players control the speed of their car by pedaling on a recumbent bike. Steering is automated to remove any confounding factors in people’s ability to steer their car. In earlier studies, we discovered that players have difficulty
estimating how close a race is if they cannot see their opponent [109]. Therefore, a top-down view of the entire race track is used in Heart Racer so that both cars are visible at all times, as shown in figure 5.2.

Each game of Heart Racer lasts for five minutes. The game is broken up into five one-minute stages. Pilot studies showed that when players maintain a relatively constant speed, if one player falls behind then she has little chance of catching up. By resetting the cars at one minute intervals, each player has several opportunities to try and take the lead. The player who has completed the furthest distance at the end of one minute wins the stage. In order to motivate players, the winner of each stage receives an upgrade to the visual appearance of her on-screen car. If both players complete the same distance at the end of a stage, then both players receive

Figure 5.2: The Heart Racer exergame
(Top-right – player 1 on exercise bike; Bottom-right – player 2 on exercise bike)
upgrades. The enhancements are added to the car incrementally, as shown in figure 5.3. The car upgrades are strictly visual and have no effect on the performance of the car.

Two versions of the Heart Racer game were created. One version uses standard input controls where the speed of a player’s car is controlled by how fast she pedals. The second version controls the speed of the car using the heart rate balancing algorithm presented in chapter 4. The ramp-up window size $m$ was set to 120 seconds. The nimbleness window size $w$ was set to 5 seconds, using a nimbleness constant $f$ of 0.95, and a maximum acceleration $r$ of 50rpm. Informal pilot testing found that players preferred a high nimbleness constant in order to notice the changes in acceleration.

5.2.2 Participants
A total of 60 people (20 males and 40 females) participated in the experiment. Participants were recruited from the university community and were required to be able to perform light exercise on a recumbent exercise bike. The Physical Activity Readiness Questionnaire [27, 104] was used to
screen people who required medical counsel before performing exercise. Ages ranged from 17 to 39, with a mean age of 22. The time each participant reported playing video games varied: almost every day (3), a few times a week (10), a few times a month (15), and less often (32). The majority of participants reported taking part in physical activity at least three times a week (37), while 14 reported exercising once or twice a week, and the remainder (9) responded that they rarely or never exercised. The Healthy Physical Activity Participation Questionnaire was used to evaluate participants activity levels [123]. Most participants rated their physical activity levels as excellent (33) or very good (18); with the remainder classified as good (1) or fair (8).

5.2.3 Methods
Each pair of participants were separated into two different rooms. Participants completed a consent form and a series of questionnaires related to demographics and physical activity levels. Participants received instruction on how to wear the Polar heart rate monitor, and put the device on themselves in private. The exercise bike was then adjusted to fit each participant. Participants were asked to relax for several minutes. During this time, the experimenter recorded the lowest observed heart rate as an estimate of resting heart rate for each participant.

A single-player version of the Heart Racer exergame was shown to participants, and the experimenter explained which car a participant would control and how the game operates. Participants were given time to practice by playing the first stage of the game. Each pair of participants then played both the standard and heart rate balanced versions of Heart Racer. The players were not told what the difference between the conditions was. The order of the conditions was randomized so that half the pairs played the control version first, while the other half started with the heart rate balanced condition. The computers running the game recorded heart rate, pedal
Above game cadence, in-game speed, and in-game distance at approximately 16ms intervals. After completing a game, participants were given two minutes to cool down while pedaling at a slow speed. Participants completed a custom questionnaire measuring perceived performance and input controls (see Appendix A), and the Game Experience Questionnaire (GEQ) [62]. The GEQ is designed to measure players’ personal experiences of a game.

During the trials, participants were asked to report their perceived exertion using the Borg CR10 scale (category ratio scale); see Appendix A. The scale uses numbers from 1 to 10 with verbal anchors representing various states of physical exertion [18]. The scale was introduced to participants at the outset of the study, and all participants read through the standard CR10 instructions. When playing Heart Racer, participants were shown the Borg scale at the 30 second mark of each stage, and the experimenter recorded the exertion values reported by the participants.

After completing both conditions of Heart Racer, participants reported their preferences between the conditions. Each pair of participants was then brought into one room where a post-experiment interview was performed. Participants were then debriefed and told the differences between the two versions of Heart Racer. Finally, participants were surveyed about their opinions of applying heart rate balancing to exergames.

5.3 Results and Analysis
The data collected in the user experiment was analyzed in order to address the hypotheses presented in section 5.1. The findings are discussed in the following sections and are organized into five categories: balance, effort, enjoyment, transparency, and player opinions.
CHAPTER 5. BALANCE AND ENJOYMENT OF HEART RATE BALANCING

5.3.1 Balancing Competition

The primary hypothesis of this experiment is that heart rate balancing in exergames improves the competition between players. The degree of competition between players in Heart Racer is calculated as the distance between the on-screen cars (distance is measured in laps). Each game of Heart Racer is composed of five one minute stages. The average distance between the cars across all stages was used to measure the competition between a pair of participants. The smaller the average gap between the cars, the closer the competition is. A paired-samples t test was conducted to evaluate whether the average distance between pairs of participants was closer in the standard or heart rate balanced versions of Heart Racer. The results indicated that the mean average distance for the standard games ($M=0.13$, $SD=0.07$) was significantly greater than the mean average distance for the heart rate balanced version ($M=0.06$, $SD=0.04$) at the $alpha=0.05$ level: $t(29)=4.67$, $p<0.001$. The effect size index $d$ was 0.85, indicating a large effect size. This shows that heart rate balancing can provide closer competition between players of varying fitness levels.

After playing each condition of Heart Racer, participants were asked to rate how hard it was to maintain a lead, or to catch up, on 7-point Likert scales. A Wilcoxon Signed Rank Test found that, between the standard and heart rate balanced versions of Heart Racer, there was no significant difference in the how hard participants felt it was to maintain a lead ($Z=-0.28$, $p=0.78$, $r=0.04$). Similarly, there was no significant difference between conditions in participants’ ratings of how hard it was to catch up if they fell behind ($Z=-0.85$, $p=0.40$, $r=0.12$).

Finally, after completing both versions of Heart Racer, participants were asked which game had more equal competition. Only 11 participants perceived no difference in competition, while
CHAPTER 5. BALANCE AND ENJOYMENT OF HEART RATE BALANCING

23 found competition more equal in the standard case, and 26 found competition to be closer in the heart rate balanced version.

Although competition was significantly closer in the heart rate balanced game compared to the standard case, post-condition responses show that participants did not notice a significant difference in competition. Similarly, after playing both versions of Heart Racer, the participants were mostly split on which version had closer competition. One reason for this is that players may have perceived the version of Heart Racer in which they won more often to have better competition, even if this was not the case. As discussed in section 5.3.3, winning was an important factor in determining player enjoyment in Heart Racer. Thus, if a player won more stages in the standard condition than in the heart rate balanced version, she may have felt competition was best in the standard game. In practice, players may better notice the improved competition provided by heart rate balancing in longer game sessions. Future studies should further explore how players’ perceive competition in multiplayer exergames.

5.3.2 Effort

Heart rate balancing is intended to base in-game performance on effort, as opposed to raw physical output. The second hypothesis of this experiment is that player performance is correlated with effort when using heart rate balancing in exergames. The Borg CR10 scale was used to measure each participant’s perceived effort at one minute intervals when playing Heart Racer. By comparing in-game speeds recorded at the same time that the perceived effort values were given, it is possible to determine any correlation between perceived effort and in-game performance. The test proposed by Bland and Altman [16] was used to evaluate whether within-subject effort values correlated to in-game speed. The results indicated a large correlation between perceived
effort and speed in the heart rate balanced version of Heart Racer \((r=0.65, p<0.001)\), and only a small correlation between effort and speed in the standard version \((r=0.10, p=0.12)\). (Typically in behavioural sciences, correlation coefficients of 0.10, 0.30, and 0.50, are respectively considered small, medium, and large [51]). Since the heart rate balancing formula behaves differently during the ramp-up window (see section 4.2.3), the correlation between perceived effort and in-game speed was tested during and after the ramp-up. In the first two minutes of the game (during ramp-up), there was a large correlation between perceived effort and speed in the heart rate balancing version \((r=0.56, p<0.001)\), and a negative correlation in the standard case \((r=-0.24, p=0.07)\). During the final three minutes of each game, there was a correlation between perceived effort and in-game speed in the heart rate balanced condition \((r=0.42, p<0.001)\), and a smaller correlation in the standard case \((r=0.21, p=0.02)\). The correlation coefficient in the standard case of 0.21 is considered small [51].

In order to ensure that participants tried equally hard in both versions of Heart Racer, a independent-samples \(t\) test was conducted on the average difference of reported exertion between pairs of participants for both versions of the game. No significant difference was found in exertion between pairs for the heart rate balanced game \((M=1.55, SD=1.25)\) and the standard case \((M=1.65, SD=1.00)\) at the alpha=0.05 level: \(t(29)=0.623, p=0.54, d=0.11\). After each condition, participants were asked to rate how hard they tried on a 7-point Likert scale. A Wilcoxon Signed Rank Test of players’ responses when asked how hard they tried to win indicated that, between the standard and heart rate balanced versions of Heart Racer, there was no significant difference \((Z=-0.14, p=0.89, r=0.02)\). This indicates that the differences in the correlations found between
perceived effort and in-game performance was not a result of different exertion levels in each condition.

The larger correlation between perceived effort and in-game performance found in the heart rate balanced condition of Heart Racer is a possible result of changes in players’ fatigue. Typically when exercising, people become more tired and report higher levels of effort over time. This means that people’s pedal cadence may decrease in latter stages of physical activity due to feelings of exhaustion. In the standard version of Heart Racer, this reduction in cadence will translate to a decrease in in-game performance. However, players’ perceived exertion increases over time, resulting in a poor correlation between perceived effort and in-game performance. Alternatively, in the heart rate balanced condition, a person may remain close to her target rate even though she has begun to reduce her pedal cadence over time. Thus, in-game performance will remain high along with perceived effort, resulting in a stronger correlation.

5.3.3 Enjoyment

The third hypothesis at the outset of the user study was that heart rate balancing leads to more enjoyable player experiences. After each game, participants were asked to rate the fun they had while playing and if they would play again using 7-point Likert scales. Wilcoxon Signed Rank Tests indicated that, between the standard and heart rate balanced versions of Heart Racer, there was no significant difference in the fun experienced ($Z=-1.28, p=0.20, r=0.17$), nor in participants willingness to play again ($Z=-0.68, p=0.50, r=0.09$).

The Game Experience Questionnaire was applied after each condition to determine whether there was any difference in player experiences. Results from the GEQ show no significant difference across all dimensions: competence ($Z=-0.82, p=0.41, r=0.11$), immersion ($Z=-0.23,$
CHAPTER 5. BALANCE AND ENJOYMENT OF HEART RATE BALANCING

$p=0.82, r=0.03$), flow ($Z=-0.40, p=0.69, r=0.05$), tension ($Z=-1.21, p=0.23, r=0.16$), challenge ($Z=-1.74, p=0.08, r=0.22$), negative affect ($Z=-0.56, p=0.58, r=0.07$), and positive affect ($Z=-1.28, p=0.20, r=0.17$).

After playing both versions of Heart Racer, the participants were asked which game was more fun. More participants had more fun in the heart rate balanced version (27) compared to the standard conditions (19), while the remainder found both versions equally fun (14).

Although more participants reported having more fun in the heart rate balanced version of Heart Racer than the standard condition, measures of player experience (as reported by the GEQ and post-condition questionnaires) did not indicate any significant differences in enjoyment. The most important factor for player enjoyment appeared to be whether a person won or lost. This is illustrated by some of the participant responses, such as “I like the [standard condition] because I was always the winner”; “I won the [heart rate balance condition], I liked it better”; and “I preferred the [standard condition]. I won, I enjoy winning.” However, some comments from players support the hypothesis that closer competition leads to more enjoyment: “I prefer the [heart rate balanced condition]… I felt it was more even between the two [players], more competitive”; “in the [heart rate balanced version], the players are neck-and-neck, so it’s more interesting and stimulating to try and win”; and “the game is most fun when you feel most equal to your opponent.” Further testing is required in order to determine if closer competition can improve player enjoyment in exergames.

5.3.4 Transparency

Although participants were not told the difference between the versions of Heart Racer until the end of the study, it was hypothesized that players would not notice a difference in controls
between the two conditions. Following each version of the game, participants were asked to rate, on a 7-point Likert scale, how well the speed of their car matched the rate at which they pedaled. Results indicated that there was no significant difference between the standard and heart rate balanced games ($Z = -0.50, p=0.62, r=0.06$).

The post-experiment questionnaire asked participants which version of the game had more responsive controls. Most participants found no difference in the controls (26), while others thought that the heart rate balanced condition was more responsive (19). The remainder found the controls more responsive in the standard game (15).

The Likert-scale responses show that players perceived the speed of their car matched their pedal cadence equally well in both the standard and heart rate balanced games. This is supported by the comments of many participants who, when asked if there was a difference in controls, stated “I don’t think so, it was pretty consistent”; “no, I didn’t notice a difference, I felt they were the same”; and “I couldn’t really tell.” One potential reason that players did not notice a difference in controls is because Heart Racer is a high-intensity exergame. Each stage is essentially a one minute sprint where players can easily lose if they decrease their pedal cadence. Because of this, the participants had few opportunities to notice how the controls differed between the two conditions. For instance, one participant stated “I tried not to experiment, in case I would lose. I didn’t want to take time to try and slow down.”

Surprisingly, in the post-experiment questionnaire, more people identified the heart rate balanced version of the game to have more responsive controls than the standard case. One explanation for this might be the high nimbleness constant applied in the heart rate balancing algorithm (see section 4.2.5). Because the nimbleness constant $f$ was set to 0.95, if pedal cadence...
CHAPTER 5. BALANCE AND ENJOYMENT OF HEART RATE BALANCING

increased, then a player’s car would temporarily accelerate at a rapid rate. Responses indicate that the participants preferred to see a significant increase in acceleration when they pedaled faster: “I found [in the heart rate balanced condition], the more I put into it was making me go faster”; “things picked up more quickly [in the heart rate balanced condition], like with acceleration. Whereas [in the standard condition] I didn’t really notice when I was changing pace as much”; and “I felt the [standard condition] there was less of a connection between my speed and pedaling. The [heart rate balanced condition] felt like my pedaling was matching.” Overall, these results suggest that in high-intensity exergames the heart rate balancing algorithm provides controls that feel natural to players.

5.3.5 Player Opinion

Based on the expected benefits of heart rate balancing on player competition, we hypothesized that players would think favourably about the technique. At the end of the experiment, participants ranked their preference between the two conditions of Heart Racer. Slightly more participants preferred the heart rate balanced game (25), with 20 preferring the standard, and 15 participants equally preferring both versions.

After completing the experiment, participants were told what the difference between the conditions were and how the heart rate balancing algorithm operates. The participants were then asked their opinion regarding the use of heart rate for player balancing. An overwhelming majority felt that it was fair to balance competition by setting in-game performance using heart rate (53 out of 60). Similarly, most participants agreed that balancing competition can lead to more fun in multiplayer exergames (54 out of 60). Finally, most people stated that they would like to know if their performance is based on heart rate rather than pedal cadence (46 out of 60).
CHAPTER 5. BALANCE AND ENJOYMENT OF HEART RATE BALANCING

Comments show that participants believe that heart rate balancing can support group exercise between people of varying abilities: “whole families can play together and know it’s a fair game worth putting effort in”; “[heart rate balancing] gives the opportunity to play against any opponent”; and “[heart rate balancing] attempts to equalize fairness so that there aren't any advantages/disadvantages with factors such as age, physique, etc.”

One reason why most participants stated they would want to know if heart rate balancing is applied, is because knowing how a game operates is important in determining a winning strategy. For example, in the standard condition of Heart Racer it is possible for a fit player to scale back her effort in the first half of a stage before sprinting to the finish line. This strategy does not work well in the heart rate balanced version of the game since it can take too long for a player to reach the effort level of her opponent. This is supported by some of the participants’ comments: “games are more fun when you are aware of how the game works so that you can do your best and try to win”; “this way I know to win I need to put in more effort”; and “[by knowing how heart rate balancing works] you could create a strategy to keep your heart rate at an optimal level.” Additionally, some players stated they that it might be confusing to be unaware of the heart rate balancing, for example “most people think their performance is based on [physical] performance as opposed to effort”; and “I'd feel like I was being cheated if I didn't know.”

5.4 Summary of Results

The results of this user study support the main hypothesis that heart rate balancing improves competition between players in exergames. This was shown by the significantly closer average distances between players’ avatars in the heart rate balanced version of Heart Racer compared to the standard condition.
CHAPTER 5. BALANCE AND ENJOYMENT OF HEART RATE BALANCING

The correlation between perceived effort (reported on the Borg CR10 scale [18]) and in-game speed was higher in the heart rate balanced version of Heart Racer than the standard case. This supports the hypothesis that heart rate balancing better reflects effort compared to using players’ raw physical output in exergames.

The results of this experiment fail to clearly confirm the hypothesis that heart rate balancing leads to more enjoyable player experiences. In post-experiment questionnaires, more participants reported having more fun in the heart rate balance condition of Heart Racer than the standard version. However, measures of players’ experiences (as reported by the GEQ [62]) did not indicate any significant differences between the conditions.

When asked in post-experiment questionnaires which version of Heart Racer had more responsive controls, most participants stated there was no difference. Additionally, post-condition survey responses show that players found the speed of their car matched their pedal cadence equally well in both the standard and heart rate balanced games. These results support the hypothesis that players do not notice when the heart rate balancing technique is applied in exergames.

At the outset of this experiment, it was hypothesized that heart rate balancing would be received favourably by exergame players. Post-experiment questionnaire responses show that the majority of players agreed that the technique is a good approach for supporting group exercise between people of varying fitness levels. Participants also stated that they would want to know if heart rate balancing is applied to an exergame in order to better understand how to play.
5.5 Conclusions

The results of the user experiment presented in this chapter show that heart rate balancing leads to closer competition between players in the Heart Racer exergame. Heart rate balancing was found to better reflect people’s effort as opposed to their raw physical output. Participants did not notice any difference in the controls, suggesting that heart rate balancing feels natural to exergame players. There was no difference in player enjoyment between the standard version and heart rate balanced condition of Heart Racer. This indicates that the heart rate balancing technique does not negatively impact player enjoyment. Finally, when surveyed, participants agreed that heart rate balancing is a good idea for supporting exergaming among people of varying abilities. However, players stated that they would want to be aware of the balancing taking place in order to have a proper strategy and understanding of how the game operates.

Several factors need to be considered when generalizing the findings of this experiment. First, the Heart Racer exergame only used recumbent exercise bikes for input. The results may differ when using other forms of active input (the portability of heart rate balancing is discussed further in chapter 7). Second, the pool of participants used in the study were mostly physically fit university students. It is possible the result may differ when applied to different populations, for example, elderly or adolescent players, or people with poor health and fitness. Third, Heart Racer is a two player game, and thus the heart rate balancing technique was not tested with three or more players. Additionally, this experiment only applied heart rate balancing in a racing-style game. Heart Racer was designed to be a high-intensity competitive exergame; thus at the end of this study it was unclear how players would perceive heart rate balancing in other types of games.
CHAPTER 5. BALANCE AND ENJOYMENT OF HEART RATE BALANCING

(e.g., low-intensity exergames). The study presented in chapter 6 evaluates whether players notice heart rate balancing in different types of exergames.
Chapter 6

Transparency of Heart Rate Balancing

As discussed in section 3.3.3, one measure of the effectiveness of a player balancing technique is how transparent it is to players. It is important that a balancing mechanism does not interfere with players’ sense of game control. Additionally, players may feel they are receiving an unfair advantage if they notice that a balancing technique is being applied. Since heart rate balancing replaces traditional exergame input with controls based on estimated effort, the issue of transparency may arise. More specifically, in power-based exergames players expect their in-game performance to be controlled by the rate at which they are physically moving (e.g., running speed on a treadmill, or rotations-per-minute on a stationary bike). However, with heart rate balancing, in-game performance is based on how closely a player adheres to her target heart rate.

The study in chapter 5 showed that heart rate balancing can improve competition between people in multiplayer exergames, but failed to examine issues of transparency in different types of games. This chapter presents the design and results of an experiment used to evaluate the transparency of heart rate balancing in various types of exergames. Single-player exergames were used in this study since the focus was on issues of transparency rather than competition.

6.1 Hypotheses

This experiment was designed to test several hypotheses related to the transparency of heart rate balancing in exergames:

1. Players do not notice when heart rate balancing is applied. Rather than basing in-game performance on players’ physical output, heart rate balancing sets performance on estimated effort. However, the heart rate balancing technique includes steps intended to make game
controls feel intuitive, as discussed in chapter 4. Thus, heart rate balancing should be transparent to exergame players.

2. *Heart rate balancing does not negatively impact players’ in-game performance.* Heart rate balancing is intended to replace traditional raw-power input in exergames. The balancing technique was designed so that game controls will still feel responsive to players, as presented in chapter 4. For instance, the nimbleness factor of the algorithm should allow for adequate precision of controls. Thus, I hypothesized that heart rate balancing would not have a negative effect on players’ in-game performance.

3. *Heart rate balancing does not affect player enjoyment.* As discussed in section 3.3.3, players may not enjoy winning if they perceive that they have received an unfair advantage. Therefore, when evaluating the transparency of heart rate balancing, it is important to consider whether the perceptibility of the balancing mechanism influences player enjoyment. Heart rate balancing should be subtle enough so that it does not change players’ enjoyment of exergames.

4. *The transparency of heart rate balancing varies depending on the type of exergame.* I hypothesized that the degree of transparency of heart rate balancing would differ depending on the type of game. In exergames where players frequently start and stop their physical activity, there is more opportunity to observe the nimbleness factor of the algorithm (see section 4.2.4). Alternatively, in games where players are moving continuously, there is less opportunity to notice the subtleties of the heart rate balancing algorithm.

In order to investigate these hypotheses, a study was performed to collect quantitative and qualitative data. The experimental design, and the study results and analysis are presented below.
CHAPTER 6. TRANSPARENCY OF HEART RATE BALANCING

6.2 Study Design

The experiment was performed in a lab setting. In order to determine whether the transparency of the balancing mechanism differs between game types, participants played two exergames. A variety of game styles is possible in power-based exergames. In terms of transparency, there are two main dimensions of power-based input to consider: intensity, and precision. Intensity is the level of aerobic activity performed when playing an exergame. Some fast-paced exergames involve highly intensive exercise (e.g., Truck Pull [108]), while other exergames are less aerobically intense (e.g., Swan Boat [6]). Precision represents the degree of accuracy required from players’ physical movement. For instance, in the Frozen Treasure Hunter game, precision is needed from the player acting as the driver [127]. In this case, the player uses a stationary bike to accurately adjust her speed in order to collect virtual items. Alternatively, no precision is required in the Pedal Race exergame, since players merely pedal to cover as much distance as possible [108].

In order to determine whether the transparency of heart rate balancing differs between game types, this study tested two combinations of exergame intensity and precision. More specifically, participants played both a high-intensity, low-precision exergame, and a low-intensity, high-precision exergame. Other combinations are possible, specifically high-intensity, high-precision, and low-intensity, low-precision. Studies of these combinations are left for future work. The limitations of this approach are discussed further in section 6.6.

6.2.1 Apparatus

The two single-player exergames developed for this experiment both require players to pedal on a Tunturi E6R recumbent exercise bike; the equipment setup is shown in figure 6.1. The games
were projected onto a 6’×8’ screen in front of the bike. Both games were developed in C# using XNA 3.1 running under Microsoft Windows XP. An XRGameKit Bike Pod was attached to the internal wheel of the exercise bike in order to capture pedal speed. Signals from the Bike Pod were collected by a PC Interface receiver plugged into the experiment computer. A chest-worn Polar heart rate monitor connected wirelessly with a Heart Rate Monitor Interface board from Sparkfun Electronics. One of the exergames used in this experiment also requires a wireless Microsoft Xbox 360 controller. Both games developed for this experiment are described in further detail below. Figure 6.2 shows an image of a player using the equipment, and the player’s view of the projected display.

6.2.1.1 Heart Rate Balancing Algorithm

Two exergames were used in this study, and two versions of each game were created: a standard version using physical output, and a heart rate balanced version where in-game performance is
based on heart rate in relation to a target heart rate. It is important to note that this experiment used an earlier and simplified version of the algorithm presented in chapter 4. The heart rate balancing algorithm included normalized heart rate, logarithmic scaling, and the nimbleness factor to calculate an effort value $E(t)$. Heart rate banding was not included in this version of the algorithm. Additionally, a simplified ramp-up window was used during which a player’s current heart rate-based effort value was blended with the effort value relative to the target heart rate. The idea behind this approach is that players are expected to have reached their target heart rate (i.e., an effort value equal to at least 1) once the ramp-up window has expired. The weight of the current heart rate-based effort increases as the end of the ramp-up window is reached as follows:

$$E'(t) = \frac{(m - t) + (t \times E(t))}{m}$$
Here $m$ is the size of the ramp up window (in this study the ramp up window was set to 120 seconds). The potential limitations of using this earlier version of the heart rate balancing algorithm are discussed in section 6.6.1.

### 6.2.1.2 Dust Buster Exergame

Dust Buster is a high-intensity exergame where players pedal continuously. The game requires low-precision from players’ physical movement.

In Dust Buster, players maneuver an onscreen robot through a series of mazes. In order to progress to the next level, players must collect all of the dust balls in the current maze; see figure 6.3. The onscreen robot must make contact with a dust ball in order to collect it. Players are awarded 25 points for each dust ball they collect. Two versions of Dust Buster were implemented for the experiment. In both versions, players control the movement of the robot by pedaling on a
recumbent bike, and steer using an Xbox 360 gamepad. The standard version of the game uses a player’s pedal speed to control the velocity of the robot. In the heart rate balanced version, the speed of the robot is determined using the heart rate balancing formula summarized in section 6.2.1.1.

6.2.1.3 Cow Crossing Exergame

The Cow Crossing exergame was designed to be a low-intensity, high-precision game. Players are required to frequently start and stop pedaling at precise moments during the game.

The Cow Crossing exergame was inspired by Konami’s classic Frogger arcade game. The goal of Cow Crossing is to move an on-screen cow across as many traffic-filled streets as possible while avoiding oncoming vehicles, as shown in figure 6.4. Players receive 10 points for each street they cross, and lose 10 points when they are struck by a vehicle. Two versions of the game
CHAPTER 6. TRANSPARENCY OF HEART RATE BALANCING

were developed. In the standard Cow Crossing game, the forward and reverse speed of the cow are controlled by how fast the player pedals. In the heart rate balanced version, the speed of the cow is set using the heart rate based algorithm in section 6.2.1.1.

6.2.2 Participants
A total of 24 people (18 males and 6 females) took part in the experiment. Participants were chosen based on their ability to play video games using a gamepad, and to perform light exercise on a recumbent exercise bike. The Physical Activity Readiness Questionnaire (PARQ) [27, 104] was used to screen people who required medical counsel before performing exercise. All participants were recruited from the university community. Ages ranged from 18 to 30, with a mean of 23. The amount of time participants spent playing video games varied: everyday (7), a few times a week (4), a few times a month (5), and less often (8). Two people stated they performed physical activity rarely or never, three reported exercising once or twice per week, and 19 people reported exercising at least three times a week.

6.2.3 Methods
Participants first completed a consent form, followed by a series of background questionnaires about demographics and exercise participation. Participants received instructions on how to wear the chest-strap heart rate monitor, and then put the device on in privacy. The recumbent exercise bike was then introduced and adjusted appropriately to fit each individual participant. Participants were then asked to relax for several minutes. During this time, the experimenter monitored the participant’s heart rate to obtain an approximation of resting heart rate.

Prior to the test trials, each exergame was described, and participants were given time to practice the games. Participants then played both the standard and heart rate balanced versions of
the Dust Buster and Cow Crossing exergames. Participants were not told what the differences between the conditions were until all the trials were completed. The order of the games and the respective conditions were randomized. Each game lasted for five minutes. The experimental computer recorded game and player data at approximately 16ms intervals. This data included current pedal cadence, heart rate, and game score.

After each game, participants completed a questionnaire regarding their enjoyment of the game (see Appendix B), and the Game Experience Questionnaire (GEQ) [62]. The GEQ is intended to measure peoples’ experiences of a game over several psychological dimensions. Participants were given sufficient time to cool down before playing again (at least 5 minutes of rest). After completing both conditions of each game, players were asked about their preferences and the responsiveness of the controls between the two versions. After completing all of the test trials, a post-experiment interview was performed, and the participants were debriefed.

6.3 Results
The data collected during the user study addresses the hypotheses proposed at the outset of the experiment; see section 6.1. These results, summarized below, are organized into three categories: transparency, performance, and enjoyment.

6.3.1 Transparency
After playing both conditions of each game, participants were asked which version they felt had better controls and which version they preferred. Responses to these questions help to show how transparent the heart rate balancing was to the participants.
CHAPTER 6. TRANSPARENCY OF HEART RATE BALANCING

Dust Buster

When asked which version of the Dust Buster exergame had more responsive controls, participants were nearly evenly split. Response counts were 9 for standard controls, 8 for no difference, and 7 for heart rate balancing. There was no clear preference between the two conditions, with 15 participants stating no difference, 5 for the control condition, and 4 for the heart rate balanced version.

Cow Crossing

Most participants were split between the standard condition and no difference when asked about the responsiveness of the controls for the Cow Crossing exergame. Only four participants felt the heart rate balanced version had more responsive controls, while 10 responded with no difference, and 10 found the standard controls more responsive. Participants had similar responses when asked which version of the game they preferred: 10 no difference, 9 standard controls, and 5 heart rate balanced.

6.3.2 Performance

Analysis of data logs were used to determine whether heart rate balancing had an influence on player performance in the two exergames. Possible differences are found by comparing in-game performance between conditions.

Dust Buster

In order to determine whether heart rate balancing influenced player performance in the Dust Buster game, the scores for each condition were compared using a paired-samples t test. The mean score was slightly higher in the control case ($M=2149$) than in the heart rate balanced case
CHAPTER 6. TRANSPARENCY OF HEART RATE BALANCING

(M=2121), but the difference was not significant at the alpha=0.05 level: \( t(23)=0.55, p=0.59, d=0.09 \).

**Cow Crossing**

A comparison of the scores in Cow Crossing shows that mean score was higher in the control case (\( M=405 \)) than the heart rate balanced case (\( M=371 \)); but this difference was not significant at the alpha=0.05 level: \( t(23)=1.91, p=0.07, d=0.45 \). Score in Cow Crossing is calculated as a combination of streets crossed and the number of times the cow is hit by a vehicle. Both of these factors were compared individually using a paired-samples t-test. The mean number of streets crossed was higher in the control condition (\( M=42.0 \)) than in the heart rate balanced case (\( M=39.5 \)), but not significant at the alpha=0.05 level: \( t(23)=1.56, p=0.13, d=0.31 \). However, the mean number of times the cow was struck by a vehicle was significantly higher in the heart rate balancing case (\( M=2.29 \)) than the control case (\( M=1.46 \)) at the alpha=0.05 level: \( t(23)=2.50, p=0.02, d=0.46 \). The reported Cohen’s \( d \) value of 0.46 indicates a small to moderate effect size [32].

**6.3.3 Enjoyment**

After completing each game, participants were asked to rank how much fun they had, and if they would play the game again, on five-point Likert scales (where a low score is poor). Additionally, participants completed the Game Experience Questionnaire (GEQ) [62]. Differences in enjoyment are found by comparing player responses across the two conditions.
CHAPTER 6. TRANSPARENCY OF HEART RATE BALANCING

Dust Buster

A Wilcoxon Signed Rank Test shows that, between the standard and heart rate balanced versions of the Dust Buster game, there was no significant difference in the fun participants had (Z=0.000, p=1.00, r=0.00) or their willingness to play again (Z=1.63, p=0.102, r=0.33). Results of the GEQ show no significant difference in competence (Z=1.92, p=0.055, r=0.39), immersion (Z=0.219, p=0.827, r=0.04), flow (Z=0.401, p=0.688, r=0.08), tension (Z=1.35, p=0.176, r=0.28), challenge (Z=1.86, p=0.061, r=0.38), and negative affect (Z=0.172, p=0.864, r=0.04). There was a significant difference in positive affect (Z=2.10, p=0.035, r=0.43), where the mean ranking was higher in the control condition (M=2.81) than in the heart rate balancing version (M=2.68). The reported effect size of 0.43 indicates a small to moderate effect.

Cow Crossing

There was a significant difference in the fun participants had in the Cow Crossing game (Z=2.06, p=0.039, r=0.42), with the mean ranking for the control case (M=4.38) being higher than the heart rate balancing condition (M=4.00). There was no significant difference between the conditions for participants’ willingness to play the game again (Z=0.632, p=0.527, r=0.13). Results from the GEQ show no significant difference across all dimensions: competence (Z=1.05, p=0.293, r=0.21), immersion (Z=0.376, p=0.707, r=0.08), flow (Z=0.139, p=0.889, r=0.03), tension (Z=1.40, p=0.160, r=0.29), challenge (Z=0.961, p=0.337, r=0.20), negative affect (Z=0.121, p=0.904, r=0.02), and positive affect (Z=0.035, p=0.972, r=0.01).
6.4 Analysis and Implications

This experiment was designed to address several hypotheses regarding the performance of heart rate balancing, particularly with regard to how perceptible it is to players (as described in section 6.1). These hypotheses are addressed below based on analysis of the results of the user study.

6.4.1 Do players notice heart rate balancing?

The main hypothesis of this user study was that players do not notice when the heart rate balancing technique is applied to exergames. However, we expected poor transparency of heart rate balancing in Cow Crossing since it was designed to exploit the limitations of the technique in low-intensity, high-precision games. In the Dust Buster game, participants were generally split on their perception of the responsiveness of the controls. This indicates that the participants had trouble distinguishing any differences in controls between the heart rate balanced and standard versions of the game. Similarly, a majority of participants (15 out of 24) had no preference between the two conditions. Player comments indicate that some people did find that the speed of their avatar better reflected their pedal cadence in the standard condition. For example, one participant stated that in the standard version “pedaling faster corresponded to a faster movement of the robot,” and another said that “I felt more in control when I pedaled faster.” Additionally, a few people noticed that the speed of the robot was limited to a top speed as a result of the logarithmic scaling in the heart rate balanced version of Dust Buster. For instance, comments included “it was kind of annoying when the speed capped off in [the heart rate balanced version],” and “it seemed like I could go faster in [the heart rate balance version], but it was harder to control my speed.” Alternatively, some participants preferred the heart rate balanced version because they benefited from faster speeds as a result of the algorithm. Participants stated
CHAPTER 6. TRANSPARENCY OF HEART RATE BALANCING

that “the [heart rate balanced version] felt more like my speed was proportional to my [pedal] speed,” and “I felt the robot moved faster in regard to my [pedal] speed [in the heart rate version].” This may be a result of players’ in-game performance better reflecting their effort relative to their fitness levels. Overall, since players had difficulty indentifying differences between the two conditions, the hypothesis that players do not notice the heart rate balancing techniques is supported in the Dust Buster game.

Very few participants (4 out of 24) found the controls more responsive in the heart rate balanced version of Cow Crossing. Similarly, only a small number of participants preferred the heart rate balanced version over the standard version of the game. This suggests that participants found the controls to be less natural in the heart rate balanced case compared to the standard condition. One possible explanation for this is that Cow Crossing is a low-intensity high-precision exergame. This type of game makes it easier for players to notice a decrease in performance when their target heart rate is not reached, or when the nimbleness is applied in the algorithm. As in the Dust Buster game, transparency of heart rate balancing seems to be related to the responsiveness of the controls. This is shown in some of the comments from the participants. For instance, one participant said “while pedaling about the same in the [heart rate balanced version], the cow didn’t appear to be moving as fast as the cow in the [standard version],” and another person stated “in the [heart rate balanced version] I felt like the response of the cow was a little bit out of timing, which makes you crash more easy.” When participants preferred the heart rate balanced version, it was often because the avatar had a faster speed. This is a result of normalizing speed based on how closely a person’s heart rate is to her target heart rate. Comments included “[the cow] seems to have a higher speed limit [in the heart rate balanced
condition]” and “the cow moved to less pedaling [in the heart rate balanced condition].” These results fail to support the hypothesis that players do not notice when heart rate balancing is applied in the Cow Crossing game.

6.4.2 Does heart rate balancing impact in-game performance?
Player scores were analyzed to determine whether heart rate balancing changes peoples’ in-game performance. The hypothesis at the outset of this study was that heart rate balancing does not impact in-game performance in exergames. In the Dust Buster game, there was no significant difference in scores between the standard and heart rate balanced versions. Since the game rewards players for higher in-game speed, there is often no incentive to change intensity. Players have a better chance of reaching their target heart rate and performing at an optimal speed, and there is less opportunity for the nimbleness factor of heart rate balancing to affect performance. This is validated by the fact that when playing the heart rate balanced version of Dust Buster, average player heart rate was 41.6% of heart rate reserve over the five minutes. Target heart rate was set at 60% of heart rate reserve, and 7 of the 24 participants reached their target heart rate. Although most participants did not reach their target heart rate, on average peoples’ heart rates were elevated enough that in-game speed was close to the maximum speed. Additionally, in the heart rate balanced version of Dust Buster, players stopped pedaling an average of 11 times over 5 minutes, and only spent an average of 2.43 seconds not pedaling during the entire five minutes. Observations indicate that the participants typically only stopped when a new level was loading. Therefore, the nimbleness factor of the heart rate balancing algorithm was applied less often. These results confirm the hypothesis that heart rate balancing does not decrease players’ in-game performance in the Dust Buster exergame.
No significant difference in score was found between the standard and heart rate balanced versions of Cow Crossing. However, there was a significant difference in the number of times the on-screen cow was struck by a vehicle. More hits were recorded in the heart rate balanced version, suggesting that the controls may have been less precise. Cow Crossing was designed to be a low-intensity, high-precision game. Since the game requires players to stop and wait for traffic, in the heart rate balanced version players have less opportunity to get to their target heart rate and reach the maximum in-game speed. If current heart rate is well below the target heart rate, players will struggle to move the cow quickly enough through traffic once the nimbleness window of the algorithm expires. Data logs support this, since players averaged an intensity of 27.0% of heart rate reserve, and only two participants reached their target heart rate in the heart rate balanced version of Cow Crossing. Additionally, players stopped an average of 89 times and did not pedal on average for 108 seconds during the five minute heart rate balanced game. This means that the nimbleness factor was invoked approximately 17 times per minute, making it harder for players to precisely control the on-screen cow using heart rate balancing. This result suggests that the heart rate balancing technique decreases in-game performance for low-intensity high-precision exergames.

### 6.4.3 Does heart rate balancing affect player enjoyment?

Our third hypothesis was that heart rate balancing does not affect player enjoyment. Players reported having the same amount of fun in both conditions of Dust Buster, despite a moderate difference in positive affect according to the GEQ. There appears to be two reasons for this result: similar responsiveness of the controls, and comparable player performance. As discussed in section 6.4.1, participants had trouble distinguishing differences in the responsiveness of the
CHAPTER 6. TRANSPARENCY OF HEART RATE BALANCING

controls between the heart rate balanced and standard versions of Dust Buster. Additionally, heart rate balancing did not affect participants’ in-game performance as illustrated by the similar game scores across both conditions (see section 6.4.2). These results show that heart rate balancing does not change player enjoyment in the high-intensity Dust Buster exergame.

Based on questionnaire responses, participants had more fun playing the standard version of Cow Crossing compared to the heart rate balanced condition. Surprisingly, there was no difference between the conditions along the dimensions of the GEQ. There are two possible reasons why participants enjoyed the standard condition more. First, more participants found the controls of the standard condition to be more responsive than the heart rate balanced version, as discussed in section 6.4.1. Second, on average players performed better in the standard game of Cow Crossing, that is, the on-screen cow was struck more frequently in the heart rate balanced version of the game compared to the standard case (see section 6.4.2). These results suggest that heart rate balancing does negatively change people’s enjoyment in the low-intensity high-precision Cow Crossing game.

6.4.4 Does the type of exergame affect the transparency of heart rate balancing?

This experiment was also designed to test the hypothesis that the transparency of heart rate balancing depends on the type of exergame. The Dust Buster exergame was created to be a high-intensity low-precision game, whereas Cow Crossing is a low-intensity high-precision game. The findings discussed above show that game type does change the transparency of heart rate balancing. Heart rate balancing was less transparent in Cow Crossing compared to the Dust Buster game. This suggests that players notice a lack of precise controls when heart rate balancing is applied in low-intensity high-precision games. Heart rate balancing also affected
CHAPTER 6. TRANSPARENCY OF HEART RATE BALANCING

players’ in-game performance in the Cow Crossing game. Although there was no significant difference in score, the participants’ avatar was hit more frequently in the heart rate balanced version compared to the standard case. This shows that heart rate balancing fails to provide the precise controls needed in high-precision games. Finally, heart rate balancing affects player enjoyment in low-intensity high-precision games. This is reflected by the fact that players reported having significantly less fun in the heart rate balanced version of the Cow Crossing game. Thus, the results of this experiment support the hypothesis that the type of exergame does affect the transparency of heart rate balancing. Surprisingly, heart rate balancing did not make the Cow Crossing game unplayable. This outcome suggests that heart rate balancing can be applied to a variety of game types with some tradeoffs, as discussed further in section 6.6.2 below.

6.5 Summary of Results

As discussed at beginning of section 6.2, this experiment used two power-based exergames which varied in terms of intensity and precision. Dust Buster is a high-intensity low-precision game, and the results of the user study support three of the initial hypotheses. First, questionnaire and interview responses show heart rate balancing was transparent to players in Dust Buster. Second, players’ scores suggest that heart rate balancing did not impact in-game performance. Third, survey responses support the hypothesis that heart rate balancing does not affect players’ enjoyment of Dust Buster.

Alternatively, Cow Crossing is a low-intensity high-precision game. The results fail to support three of the hypotheses posed at the outset of this experiment. Player comments and survey responses suggest that players found the controls less precise in the heart rate balanced version compared to the standard case. Thus, the heart rate balancing technique was exposed to
players. The lack of precise controls lead to a decrease in enjoyment when heart rate balancing was applied in Cow Crossing. In-game performance also suffered with heart rate balancing since player avatars were struck more frequently than in the standard version. Surprisingly, although controls were less precise, players were able to reach comparable scores to the standard game. Additionally, players were equally willing to play both conditions of the Cow Crossing, and there was no difference in player experiences between the two conditions (according to the GEQ). Heart rate balancing was designed with higher-intensity exergames in mind. Since Cow Crossing is a low-intensity high-precision game, I anticipated that the heart rate balancing technique would severely limit people’s ability to play and lead to frustration. Therefore, it was unexpected that players achieved similar scores, and were equally willing to play both the standard and heart rate balanced versions of Cow Crossing. This suggests that it is feasible to use heart rate balancing in low-intensity high-precision games with some tradeoffs. Adjusting the variables of the heart rate balancing algorithm (e.g., nimbleness window size, and the nimbleness constant) could potentially improve controls in high-precision games; further studies are require to test this approach.

6.6 Limitations
There are two main limitations in the design of this experiment. First, an earlier and simplified version of the heart rate balancing algorithm was used. Second, only two configurations of game type were considered. These limiting factors are discussed further in the sections below.

6.6.1 Simplified Heart Rate Balancing Algorithm
As discussed in section 6.2.1.1, an earlier version of the heart rate balancing algorithm was used in Dust Buster and Cow Crossing. Included in this algorithm were heart rate normalization,
logarithmic scaling, and the nimbleness factor as described in chapter 4. One limitation of this study is that heart rate banding was not used, and a simplified ramp-up window was included. However, the differences between the algorithm used in this study and the technique presented in chapter 4 are not significant enough to impact the results of this study.

As discussed in section 4.2.2, heart rate banding is meant to address potential estimation errors when calculating target heart rate. This is particularly problematic in multiplayer exergames. If a player’s target heart rate is underestimated, she requires less effort to reach it than her actual target heart rate. Alternatively, if a player’s target heart rate is overestimated, more effort is needed to reach the estimated target heart rate than the actual target heart rate. Thus, players whose target heart rates are underestimated would have an advantage over players whose target heart rate is overestimated. Since Dust Buster and Cow Crossing are both single-player exergames, the lack of heart rate banding is not a severe limitation on the outcome and results of this experiment.

As presented in section 6.2.1.1, a simplified ramp-up window was used for heart rate balancing in this experiment. The simplified approach assumes that people will reach their target heart rate after the ramp-up window expires. A player’s current estimated effort is blended with what the effort value would be if she was at her target heart rate. The weight of a person’s current estimated effort increases from 0% at the outset to 100% at the end of the ramp-up window. As discussed in section 6.4.2, players’ average heart rates were higher in Dust Buster than in Cow Crossing. In Dust Buster, players had an overall average heart rate of 41.6% of their heart rate reserve. Although the target heart rate was set at 60% of heart rate reserve, players would not have experienced a big drop in performance when the ramp-up window expired; particularly
CHAPTER 6. TRANSPARENCY OF HEART RATE BALANCING

since logarithmic scaling compresses the difference in calculated effort between 41.6% and 60% of heart rate reserve. In the Cow Crossing game, players had an average heart rate of 27.0% of heart rate reserve, which is less than half of the target heart rate of 60% of heart rate reserve. Due to the blending in the simplified ramp-up window, the effort value would have been overestimated during the early stages of the ramp-up window. Near the end of the ramp-up window the effort value would be more heavily based on players’ current effort. Thus, players could have experienced a difference in in-game performance as the nimbleness window expired. This result is a potential limitation of using the simplified heart rate balancing algorithm in Cow Crossing. However, participants did not comment on a decrease in in-game performance over time in either the Dust Buster or Cow Crossing games. Additionally, issues related to nimbleness (see section 6.4.1) appear to have had a greater impact on the lack of transparency of heart rate balancing as opposed to the simplified ramp-up window.

6.6.2 Game Types
A second limitation of this experiment was the limited types of exergames used. The two types of games chosen represented opposite combinations of intensity and precision. Dust Buster was designed to be high-intensity with low-precision, whereas Cow Crossing is a low-intensity high-precision exergame. Future studies should consider other combinations of intensity and precision, such as high-intensity high-precision and low-intensity low-precision exergames.

6.7 Conclusions
The aim of this experiment was to evaluate how transparent the heart rate balancing mechanism is to exergame players. The results of this study provide evidence that the transparency of heart rate balancing varies depending on game type. In the context of the two games used in this
CHAPTER 6. TRANSPARENCY OF HEART RATE BALANCING

experiment, the heart rate balancing mechanism was less transparent in a low-intensity high-precision game compared to a high-intensity low-precision game. Additionally, in-game performance and enjoyment were not affected by heart rate balancing in the high-intensity low-precision game, whereas the lack of precision provided with heart rate balancing led to a decrease in performance and enjoyment in the game requiring high-precision.

Several factors need to be considered when generalizing the findings of the study. Both exergames used in this study involved players pedaling on a recumbent bike. Currently it is unknown how transparent heart rate balancing is in exergames using other input devices such as treadmills or rowing machines. The two exergames were designed to require different levels of intensity and precision. Dust Buster requires constant physical movement, whereas Cow Crossing involves long periods of inactivity. Additionally, Cow Crossing requires precise controls compared to Dust Buster. The next step in this research is to evaluate the transparency of heart rate balancing in exergames using different combinations of intensity and precision (e.g., high-intensity high-precision, and low-intensity low-precision). Further studies are needed to examine the level of intensity and precision at which heart rate balancing begins to become noticeable to players.
Chapter 7

Discussion

7.1 Summary of Results

The heart rate balancing algorithm was designed to better support multiplayer exergaming amongst people of various fitness levels. The two studies performed in this thesis evaluate the effectiveness of the heart rate balancing technique.

The experiment presented in chapter 5 examined the ability of heart rate balancing to improve player balance and enjoyment in the Heart Racer exergame. Two conditions of Heart Racer were compared: a standard version, and a heart rate balanced version. The results of the first experiment show that:

- The average distance between player avatars was significantly closer in the heart rate balanced version compared to the standard case ($p<0.001, d=0.85$);

- A correlation between perceived effort and in-game speed was found in the heart rate balanced condition ($r=0.65, p<0.001$), and no correlation was found in the standard case ($r=0.10, p=0.12$);

- No significant difference in enjoyment was found between the two conditions ($Z=-1.28, p=0.20, r=0.1$);

- No significant difference across all dimensions of the Game Experience Questionnaire [62] was found between the two conditions;

- No significant difference in the responsiveness of the input controls was found between the two conditions ($Z=-0.50, p=0.62, r=0.06$);
CHAPTER 7. DISCUSSION

- 88.3% of participants agreed that heart rate balancing is a good solution for player balancing; 90% agreed that improved competition increases enjoyment, and 76.7% would like to know if in-game performance is based on heart rate rather than pedal speed.

The experiment presented in chapter 6 was designed to test how noticeable heart rate balancing is to players in different types of exergames. Participants played two games: a high-intensity, low-precision game (Dust Buster), and a low-intensity, high-precision game (Cow Crossing).

Participants played both a standard and a heart rate balanced version of the Dust Buster exergame. Results from an experiment with this exergame show that:

- The responsiveness of the controls were found to be best by 9 players in the standard case, and 7 players in the heart rate balanced condition, while 8 players saw no difference;
- There was no significant difference in game score between the two conditions ($p=0.59$, $d=0.09$);
- There was no significant difference in the fun participants had between the two conditions ($Z=0.00$, $p=1.00$, $r=0.00$);
- There was no significant difference between conditions across all dimensions of the Game Experience Questionnaire, except for positive affect ($Z=2.10$, $p=0.04$, $r=0.43$).

Participants also played two conditions of the Cow Crossing game: a standard, and a heart rate balanced version. The results of the experiment with this exergame show that:

- The responsiveness of the controls were perceived as best by 10 players in the standard condition, and 4 players in the heart rate balanced case, while 10 players saw no difference;
CHAPTER 7. DISCUSSION

- There was no significant difference in score between the two conditions \((p=0.07, \ d=0.45)\), but players’ avatars were struck more frequently in the heart rate balanced version \((p=0.02, \ d=0.46)\);
- Participants had more fun in the standard version compared to the heart rate balanced condition \((Z=2.06, \ p=0.04, \ r=0.42)\);
- There was no significant difference between conditions across all dimensions of the Game Experience Questionnaire.

7.2 Summary of Analysis

The results of the Heart Racer study presented in chapter 5 show that heart rate balancing, compared to standard physical input, provided closer competition between players of varying fitness levels. In-game performance was correlated to player exertion with heart rate balancing, and no correlation between perceived effort and performance was found using standard input. Heart rate balancing did not feel unnatural to players, and the controls felt as responsive as the standard game. Finally, players agreed that heart rate balancing is a good solution for supporting exergaming between people of varying fitness levels. However, in future, players would like to be aware of the player balancing technique in order to better strategize how to play. The Heart Racer study evaluated the effect of heart rate balancing on competition between players; a second study was required to evaluate the transparency of the technique in different types of exergames.

The experiment of chapter 6 reveals how heart rate balancing performs in both high-intensity low-precision (Dust Buster) and a low-intensity high-precision (Cow Crossing) exergames. Controls felt natural with heart rate balancing in Dust Buster, but players found the
controls less precise than standard input in the heart rate balanced version of Cow Crossing. In-game performance did not change with heart rate balancing in Dust Buster. Alternatively, players’ in-game performance suffered with heart rate balancing in Cow Crossing. The poor controls and performance in the heart rate balanced version of Cow Crossing led to a decrease in enjoyment compared to the standard game. These results show that the transparency of heart rate balancing differs depending on game type. Heart rate balancing remains transparent to player in high-intensity, low-precision games. Conversely, players notice when heart rate balancing is applied in low-intensity high-precision games due to a lack of precise controls. Despite this limitation, players were able to achieve similar scores in both the standard and heart rate balanced version of Cow Crossing. Players were also equally willing to play both versions of the game. This suggests that heart rate balancing can be applied to low-intensity high-precision games, with the tradeoff that players will notice a difference in game controls. In low-intensity high-precision multiplayer exergames, improved player balance may be more important than the lack in transparency of the heart rate balancing technique.

7.3 Exploitability and Portability of Heart Rate Balancing

As discussed in chapter 3, exploitability and portability are important factors in the effectiveness of player balancing mechanisms. Therefore, designers need to consider the portability and exploitability of heart rate balancing in exergames. These properties are examined in more detail in the sections below.

7.3.1 Exploitability

The more players are able to exploit a balancing mechanism, the less useful it becomes. However, as presented in section 3.3.4, players can only exploit a balancing mechanism once they have
CHAPTER 7. DISCUSSION

determined how it works. The results presented in this thesis show that players did not notice heart rate balancing in the high-intensity games of Heart Racer and Dust Buster, but did notice a lack of precision in controlling the Cow Crossing game. This suggests that, at least in high-intensity exergames, players may be unaware of any balancing taking place and thus may not exploit it. However, since in-game performance is based on heart rate, it is important for designers to consider how heart rate balancing can be abused. Any exploitation of heart rate balancing would require players to intentionally elevate their heart rate. This can be achieved in three ways: physical activity, stimulants, and environmental factors.

The ramp-up window (see section 4.2.2) in the algorithm is designed so that players who begin with an elevated heart rate do not receive an unfair advantage. However, if a person performs vigorous activity in order to elevate her heart rate beyond the target heart rate, she would begin the game with a performance advantage.

Drugs such as amphetamines [105] and caffeine [50] have been found to increase heart rate. Players taking these substances would require less effort to reach or surpass their target heart rate, allowing them to exploit the heart rate balancing technique. Similarly, environmental factors such as altitude [95] and temperature [64] can also elevate heart rate.

7.3.2 Portability
Some aspects of heart rate balancing limit how universally the technique can be applied. Most importantly, exergame designers need to consider whether their target hardware platform supports heart rate monitoring devices. The exergames created for this thesis use chest-worn Polar heart rate monitors. However, heart rate balancing is not limited to this equipment and currently several
CHAPTER 7. DISCUSSION

other types of heart rate monitoring devices are available; see section 7.4.3 for further discussion on heart rate monitoring equipment.

The nimbleness factor of the heart rate balancing algorithm is designed to make interaction feel more natural, as discussed in section 4.2.4. Nimbleness ensures that players receive immediate feedback when they increase or decrease their physical output. In order to achieve this, a measure of raw physical output is required. For example, in Heart Racer, changes in pedal speed are used to gauge changes in physical output. In some exergames it is difficult to measure these changes. For instance, in the Pulse Masters Biathlon exergame [84], heart rate is the only measure of players’ exertion. In this case, it is possible to drop the nimbleness feature from the heart rate balancing algorithm. This is demonstrated in the GAIM toolkit which was designed to simplify the development of exergames [21]. GAIM supports a simplified version of the heart rate balancing algorithm presented in chapter 4. When a measure of players’ physical power is unavailable, effort is calculated using only heart rate. One disadvantage of this approach is that players may notice a lack of immediate response when they speed up or slow down their rate of exercise.

Another hardware-related issue is the precision of the data provided by input devices. Heart rate balancing relies on measurements of people’s heart rate and raw physical output. The frequency at which these variables are measured will affect the performance of the algorithm. For instance, if a device is slow to register changes in physical output, players will notice a lag between actual effort and in-game performance. Since the nimbleness factor of heart rate balancing uses a measure of physical output, this means that the responsiveness of game controls
varies depending on the precision of the input device used. Therefore, designers need to be aware that the accuracy of input data can affect the performance of the heart rate balancing algorithm.

7.4 Design Guidelines
The main lesson to be taken from this thesis is that game designers should consider using heart rate balancing to improve competition in multiplayer exergames. The experiments in chapters 5 and 6 demonstrate the feasibility of integrating heart rate balancing into exergames. The results of these studies show that heart rate balancing allows for closer competition, and provides a better measure of peoples’ exertion. The transparency of heart rate balancing was preserved in a high-intensity low-precision game, but was noticeable to players in a low-intensity high-precision exergame. However, the lack of transparency did not limit people’s ability to play. We anticipate that similar results will be possible in other multiplayer exergames. Including heart rate balancing in exergames can allow people of varying abilities to play and exercise together. When implementing heart rate balancing in exergames, designers should consider the guidelines presented in the following sections.

7.4.1 Consider Exergame Type
The type of exergame is important to consider when using the heart rate balancing technique. The experiments presented in this thesis show that heart rate balancing performs well, in terms of balance and transparency, in high-intensity low-precision games (i.e., Heart Racer and Dust Buster). However, the technique’s performance is less optimal in low-intensity games requiring precise controls (i.e., Cow Crossing). Low-intensity games do not allow players to reach their target heart rate and achieve maximum in-game performance. Second, games requiring high precision expose the nimbleness factor of the algorithm. Despite the lack in transparency of heart
rate balancing in low-intensity high-precision games, it does not render exergames unplayable. Thus, competition between players can be improved even if players are aware of the heart rate balancing mechanism. Designers should consider these tradeoffs when using heart rate balancing in low-intensity high-precision exergames. Issues of transparency could potentially be minimized by increasing the size of the nimbleness window, or by lowering the target heart rate (e.g., 40% or 50% of heart rate reserve). Other parameters of the heart rate balancing algorithm can also be adjusted for particular types of games, as discussed in the next section.

7.4.2 Calibration and Pilot Testing
The heart rate balancing algorithm presented in chapter 4 includes several constants which can be adjusted by exergame developers. The error constant is used in heart rate banding to account for errors in estimating maximum heart rate; see section 4.2.2. I suggest using 11bpm for this value based on the average error when using the Tanaka method to approximate maximum heart rate [115]. However, if a different method is used to approximate maximum heart rate, the error parameter can be set accordingly. A ramp-up window is used in heart rate balancing to give players an appropriate amount of time to reach their target heart rate; see section 4.2.3. The size of this window of time $n$ can be adjusted by exergame designers. The nimbleness factor in the heart rate balancing algorithm is used to account for the lag between changes in physical activity and associated changes in heart rate; see section 4.2.5. The nimbleness formulae include three adjustable parameters: $w$ the size of the nimbleness window, $r$ the maximum allowable change in physical work, and the $f$ constant for amplifying bursts of acceleration and deceleration. Modifying these constants adjusts how immediate changes in physical exertion affect people’s in-
CHAPTER 7. DISCUSSION

game performance. This is important when attempting to make the heart rate balancing technique transparent and intuitive to players.

Setting the constant variable presented above requires some discretion from game designers. I suggest that designers consider pilot testing their exergames to determine the performance of heart rate balancing and whether further adjustments need to be made. For example, the nimbleness factor $f$ can be tuned to provide a responsiveness to changes in pedal speed that feels appropriate for a particular game. This is similar to the way developers of traditional video games use player testing to tune avatar speed and timing [46].

7.4.3 Physiological Measurement
Measurement of people’s heart rate is necessary for the heart rate balancing technique. Unfortunately, heart rate monitors can be unreliable, and designers need to be aware of potential problems. For example, during the experiments presented in chapters 5 and 6, the Polar heart rate monitors occasionally failed to initially register players’ heart rates. This was a result of poor contact between the sensor and a person’s skin. Moistening the sensors solved this issue. Additionally, chest-worn monitors are prone to shifting during physical activity, which can lead to lost heart rate readings. Other types of heart rate monitors exist and may address some of these problems, such as the wrist-worn ePulse2 from Impact Sports Technologies. Exergame designers should consider which heart rate monitoring equipment will work best with their games.

When configuring heart rate balancing, a measure of a player’s resting heart rate is required. Exergame developers should explicitly remind players that they need to be sufficiently rested before measuring their resting heart rate. Otherwise, target heart rate may be over-estimated making it hard for players to reach the target heart rate without over-exerting themselves.
CHAPTER 7. DISCUSSION

7.5 Summary

This chapter summarized the results and analysis of testing the heart rate balancing algorithm. The general findings are that heart rate balancing improves competition in multiplayer exergames and the transparency of the technique varies depending on game type, but exergames remain playable. Additionally, factors regarding the portability and the exploitability of heart rate balancing are considered in section 7.3.

Experiences with heart rate balancing lead to three main guidelines for exergame designers, as discussed in section 7.4. First, designers should consider exergame type when applying heart rate balancing. Second, several parameters of the heart rate balancing algorithm can be adjusted and verified using player testing. Third, it is important to use reliable heart rate sensors in order for the balancing technique to work effectively.

The following chapter summarizes the contributions and limitations of this thesis. Future areas of investigation are also presented.
Chapter 8

Conclusion and Future Work

8.1 Thesis Summary

Multiplayer exergames take advantage of the motivating aspects of group activity by allowing two or more people to play and exercise together. However, it is difficult for people of varying fitness levels to exercise together. The solution explored in this thesis better supports group activity by basing peoples’ in-game performance on estimated effort rather than raw physical output. Heart rate balancing bases performance relative to how closely a person is adhering to her target heart rate.

Heart rate balancing was tested in two separate studies. The first showed that the technique provides more balanced competition between players as opposed to standard exergame input. Additionally, a strong correlation was found between players’ perceived effort and their in-game performance when using heart rate balancing. The second experiment showed that the transparency of heart rate balancing varies depending on the type of game; it is less noticeable in high-intensity low-precision games compared to low-intensity high-precision games. Despite this difference, heart rate balancing did not interfere with peoples’ ability to play the exergames.

Over all, this research demonstrates that heart rate balancing is feasible and useful in multiplayer exergames. The improvements provided by the technique can allow for engaging experiences between people of varying physical abilities.
CHAPTER 8. CONCLUSION AND FUTURE WORK

8.2 Contributions
The main contribution of this thesis is the derivation and testing of the heart rate balancing algorithm. Empirical evidence shows that heart rate balancing improves competition in exergames, provides a better measure of effort, and does not impact people’s ability to play. The feasibility of heart rate balancing was confirmed by implementing the technique into three exergames.

A secondary contribution of this thesis is the proposed metrics for evaluating player balancing in exergames: balance, enjoyment, transparency, exploitability, and portability. Prior to this research, it was unclear how to determine the effectiveness of player balancing techniques. These metrics allow designers to evaluate balancing mechanisms across several important criteria.

Additional contributions include the design and development of three power-based exergames: Heart Race, Cow Crossing, and Dust Buster. The games were developed to test the heart rate balancing technique. Finally, this thesis provides a better understanding of player balancing in multiplayer exergames.

8.3 Limitations
Heart rate balancing is designed to set in-game performance based on heart rate. However, a measure of peoples’ raw physical output is still needed in order to make controls feel natural. This can be difficult to measure in some games. For example, the Pulsemasters Biathlon exergame only uses heart rate and keyboard input [84]. The nimbleness factor of the algorithm can be omitted, removing the need to measure physical output [20]. By doing so, players may
CHAPTER 8. CONCLUSION AND FUTURE WORK

more easily notice a disconnect between changes in exertion and changes in in-game performance.

Heart rate balancing assumes that heart rate behaviour during physical activity is similar for all players. Although the algorithm was derived from observed and accepted properties of heart rate, it does not account for potential outliers. For instance, tachycardia is a rapid resting heart rate greater than 100bpm. This rapid heart rate typically persists during exercise, and can include a rapid response at the outset of physical activity [14]. Alternatively, bradycardia is a resting heart rate less than 60bpm [14]. This can be a result of physiology or athletic conditioning. The heart rate balancing technique was not tested for these extreme heart rate behaviours, and may give some players an unfair advantage or disadvantage.

Unlike some dynamic difficulty balancing techniques, heart rate balancing requires player information prior to the start of a game. Because of this, users need to provide their age and resting heart rate before they are able to play.

Heart rate balancing was designed to balance competition between players in exergames. As such, it was only tested in one competitive multiplayer game and two single-player games. It is unclear whether heart rate balancing has any advantages in cooperative exergames. Currently a player with the poorest fitness level limits the performance of her team in cooperative games. Heart rate balancing may help to address this problem, but it has not been evaluated in such scenarios.
CHAPTER 8. CONCLUSION AND FUTURE WORK

8.4 Future Work

The initial investigation into the feasibility and effectiveness of heart rate balancing leads to a series of open questions. Areas requiring further research are presented in the sections below.

8.4.1 Future Studies

The user experiments presented in this thesis were limited in game setup, participant population, and study design. These factors can be explored in more detail in future studies.

The three exergames used to test heart rate balancing use recumbent exercise bikes as input devices. It is unclear how heart rate balancing performs using different peripherals such as treadmills and rowing machines. The exergames are all five minutes in duration. Thus, the effectiveness of heart rate balancing has not been tested in longer game sessions. Additionally, Heart Racer is a two-player distributed exergame. Further experiments are needed to determine how heart rate balancing scales to three or more players or in co-located settings.

The studies presented in chapters 5 and 6 involved participants from the university community. As such, participants tended to be young and physically fit. Pilot studies found that heart rate balancing best improves competition when players are of significantly different fitness levels. However, future studies are required to test the technique between considerably different player populations (e.g., young/fit versus older/unfit).

The user experiments only compared heart rate balancing to standard exergame input. It is unknown how the performance of heart rate balancing compares to other player balancing techniques. Additionally, the long-term effects of heart rate balancing need to be explored.
CHAPTER 8. CONCLUSION AND FUTURE WORK

8.4.2 Algorithm Improvement
The heart rate balancing algorithm presented in chapter 4 could be improved in several ways. For instance, the algorithm does not account for people who have abnormally low or high heart rates. Tailoring heart rate balancing for each player may improve the performance of the technique. One way to achieve this is to keep a profile of people’s heart rates and exercise behaviours over time. With this information the target heart rate band, ramp-up window, and nimbleness factor could all be customized to best fit each player. Tailoring the algorithm would allow for a more precise estimate of effort.

8.4.3 Simplified Deployment
Heart rate balancing was manually implemented into the three example systems used in this research. A heart rate balancing toolkit would allow developers to more easily integrate the technique into exergames. This was demonstrated with a simplified heart rate input technique in the GAIM toolkit [21]. However, the heart rate balancing algorithm presented in this thesis has not been released as a toolkit.

A set of design guidelines for tuning the parameters of heart rate balancing would be valuable to game designers. It is unclear how the constant variables in the algorithm should be adjusted for different types of exergames. For instance, the size of the ramp-up window could vary depending on the intensity of an exergame. Low-intensity games may require a longer ramp-up window for players to reach their target heart rate. It is also unclear what the value of the nimbleness constant should be for different types of input such as treadmills or rowing machines.
CHAPTER 8. CONCLUSION AND FUTURE WORK

8.5 Summary
Heart rate balancing provides an effective approach for balancing competition in multiplayer exergames. The techniques allows people of varying physical abilities to play together by basing in-game performance on effort relative to fitness levels. This leads to more enjoyable and engaging experiences, potentially improving people’s motivation to participate in physical activity. Refining the technique and integrating it into commercial multiplayer exergames might be the first steps towards increasing people’s physical activity, leading to improved health and fitness.
References


REFERENCES


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REFERENCES


REFERENCES


REFERENCES


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REFERENCES


REFERENCES


REFERENCES


REFERENCES


137
REFERENCES


REFERENCES


[103] A. Sall, and R. Grinter. Let’s get physical! In, out and around the gaming circle of physical gaming at home. In *Computer Supported Cooperative Work*, 16(1-2), 199-229, 2007


REFERENCES


REFERENCES


REFERENCES

Appendix A

Experiment 1 Measures
APPENDIX A. EXPERIMENT 1 MEASURES

**Personal Information Questionnaire**

1. Age: __________

2. Gender: M / F

3. How often do you play video games:

<table>
<thead>
<tr>
<th>Everyday, or almost everyday</th>
<th>A few times a week</th>
<th>A few times a month</th>
<th>Less often</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. Over a typical week, how many times do you engage in physical activity that is sufficiently prolonged and intense to cause sweating and rapid heart beat?

<table>
<thead>
<tr>
<th>At least three times</th>
<th>Normally once or twice</th>
<th>Rarely or never</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


APPENDIX A. EXPERIMENT 1 MEASURES

Borg CR10 Scale
Rating of Perceived Exertion

0  Nothing at all
0.5  Extremely weak
1  Very weak
2  Weak (light)
3  Moderate
4  Somewhat strong
5  Strong (heavy)
6
7  Very strong
8
9
10  Extremely strong (almost maximal)
•  Maximal
APPENDIX A. EXPERIMENT 1 MEASURES

Heart Racer: Post-Condition Questionnaire

Please answer the following questions based on the version of the Heart Racer game you just played.

1. I had fun playing this game:

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
</table>

2. I would play this game again:

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
</table>

3. I was good at playing the game:

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
</table>

4. I tried hard to win each stage of the game:

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
</table>

5. My opponent was good at playing the game:

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
</table>

6. If I was behind in the game, I felt like I had a chance of catching up:

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
</table>

7. If I was ahead in the game, I found it challenging to maintain my lead:

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
</table>
APPENDIX A. EXPERIMENT 1 MEASURES

8. I thought the other player had no chance of catching up:

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
</table>

9. If you **WON** any of the stages, was there a point during these stages where you reduced your pedaling because you were confident you were going to win?

<table>
<thead>
<tr>
<th>Yes</th>
<th>No</th>
<th>Does Not Apply</th>
</tr>
</thead>
</table>

10. If you **LOST** any of the stages, was there a point during these stages where you reduced your pedaling because you felt it was impossible to catch up?

<table>
<thead>
<tr>
<th>Yes</th>
<th>No</th>
<th>Does Not Apply</th>
</tr>
</thead>
</table>

11. The speed of my car matched the speed of my pedaling:

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
</table>

12. Any additional comments or suggestions:
APPENDIX A. EXPERIMENT 1 MEASURES

**Game Experience Questionnaire (GEQ)**

Please indicate how you felt while playing the game for each of the items, on the following scale:

<table>
<thead>
<tr>
<th>Item</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. I felt content</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>2. I felt skilful</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>3. I was interested in the game’s story</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>4. I could laugh about it</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>5. I felt completely absorbed</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>6. I felt happy</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>7. I felt tense</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>8. I felt that I was learning</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>9. I felt restless</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>10. I thought about other things</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>11. I found it tiresome</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>12. I felt strong</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>13. I thought it was hard</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>14. It was aesthetically pleasing</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>15. I forget everything around me</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>16. I felt good</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>17. I was good at it</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>18. I felt bored</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>19. I felt successful</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>20. I felt imaginative</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>21. I felt that I could explore things</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>22. I enjoyed it</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>23. I was fast at reaching the game’s targets</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>24. I felt annoyed</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>25. I was distracted</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>26. I felt stimulated</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>27. I felt irritable</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>28. I lost track of time</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>29. I felt challenged</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>30. I found it impressive</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>31. I was deeply concentrated in the game</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>32. I felt frustrated</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>33. It felt like a rich experience</td>
<td>0 1 2 3 4</td>
</tr>
</tbody>
</table>
### APPENDIX A. EXPERIMENT 1 MEASURES

<table>
<thead>
<tr>
<th>Question</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>34. I lost connection with the outside world</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35. I was bored by the story</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36. I had to put a lot of effort into it</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37. I felt time pressure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>38. It gave me a bad mood</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>39. I felt pressured</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40. I was fully occupied with the game</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>41. I thought it was fun</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>42. I felt competent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Heart Racer: Post-Experiment Questionnaire**

1. In which version of the *Heart Racer* game did you have the best chance of winning?

<table>
<thead>
<tr>
<th>First version</th>
<th>No difference</th>
<th>Second version</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. In which version of the game was competition between you and your opponent most equal?

<table>
<thead>
<tr>
<th>First version</th>
<th>No difference</th>
<th>Second version</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. Which version of the *Heart Racer* game had more responsive controls?

<table>
<thead>
<tr>
<th>First version</th>
<th>No difference</th>
<th>Second version</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. Which version of the game was more fun?

<table>
<thead>
<tr>
<th>First version</th>
<th>No difference</th>
<th>Second version</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5. Which version of the game did you prefer?

<table>
<thead>
<tr>
<th>First version</th>
<th>No difference</th>
<th>Second version</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Can you explain?

150
Heart Racer: Post-Debriefing Questionnaire

In one condition of the Heart Racer game, the movement of each player’s car was controlled directly by the speed at which they pedaled on the bike. In the other condition, the speed of each player’s car was determined by how closely the player was to her target heart rate. In this case, the closer your heart rate was to its target, the faster your car would move. Changes in pedal speed were taken into account in order to make this input technique feel more natural.

Heart rate provides a more effective measure of a person’s physical effort compared to their pedal speed. Therefore, by using heart rate to adjusting peoples’ in-game performance, we hope to improve competition in exercise video games between people of different fitness levels.

Now that you are aware of the differences between the conditions of the Heart Racer game, please answer the following questions:

1. Do you think it is fair to try to balance the game by adjusting your performance on heart rate instead of your pedal speed?
   YES / NO
   Can you explain?

2. Do you think that balancing competition can make playing multiplayer exercise games more fun for all players?
   YES / NO
   Can you explain?

If your performance is based on heart rate instead of pedal speed, would you like to know about it?
YES / NO
Can you explain?
Appendix B

Experiment 2 Measures
APPENDIX B. EXPERIMENT 2 MEASURES

Personal Information Questionnaire

1. Age: __________

2. Gender:  M / F

3. How often do you play video games:

<table>
<thead>
<tr>
<th>Everyday, or almost everyday</th>
<th>A few times a week</th>
<th>A few times a month</th>
<th>Less often</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. Over a typical week, how many times do you engage in physical activity that is sufficiently prolonged and intense to cause sweating and rapid heart beat?

<table>
<thead>
<tr>
<th>At least three times</th>
<th>Normally once or twice</th>
<th>Rarely or never</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX B. EXPERIMENT 2 MEASURES

*Dust Buster: Post-Condition Questionnaire*

Please answer the following questions based on the version of the *Dust Buster* game you just played.

1. I had fun playing this game:

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
</table>

2. I would play this game again:

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
</table>

3. Any additional comments or suggestions:
**Dust Buster: Post-Experiment Questionnaire**

1. Which version of the *Dust Buster* game did you prefer?

| First version | No difference | Second version |

Can you explain?

2. Which version of the *Dust Buster* game had more responsive controls?

| First version | No difference | Second version |

Can you explain?
APPENDIX B. EXPERIMENT 2 MEASURES

**Cow Crossing: Post-Condition Questionnaire**

Please answer the following questions based on the version of the *Cow Crossing* game you just played.

1. I had fun playing this game:

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. I would play this game again:

<table>
<thead>
<tr>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Any additional comments or suggestions:
Cow Crossing: Post-Experiment Questionnaire

1. Which version of the Cow Crossing game did you prefer?

| First version | No difference | Second version |

Can you explain?

2. Which version of the Cow Crossing game had more responsive controls?

| First version | No difference | Second version |

Can you explain?
Game Experience Questionnaire (GEQ)

Please indicate how you felt while playing the game for each of the items, on the following scale:

<table>
<thead>
<tr>
<th>Item</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>43. I felt content</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>44. I felt skilful</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>45. I was interested in the game’s story</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>46. I could laugh about it</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>47. I felt completely absorbed</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>48. I felt happy</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>49. I felt tense</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>50. I felt that I was learning</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>51. I felt restless</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>52. I thought about other things</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>53. I found it tiresome</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>54. I felt strong</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>55. I thought it was hard</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>56. It was aesthetically pleasing</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>57. I forget everything around me</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>58. I felt good</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>59. I was good at it</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>60. I felt bored</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>61. I felt successful</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>62. I felt imaginative</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>63. I felt that I could explore things</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>64. I enjoyed it</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>65. I was fast at reaching the game’s targets</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>66. I felt annoyed</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>67. I was distracted</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>68. I felt stimulated</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>69. I felt irritable</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>70. I lost track of time</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>71. I felt challenged</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>72. I found it impressive</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>73. I was deeply concentrated in the game</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>74. I felt frustrated</td>
<td>0 1 2 3 4</td>
</tr>
<tr>
<td>75. It felt like a rich experience</td>
<td>0 1 2 3 4</td>
</tr>
</tbody>
</table>
### APPENDIX B. EXPERIMENT 2 MEASURES

<table>
<thead>
<tr>
<th></th>
<th>Question</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>76</td>
<td>I lost connection with the outside world</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>77</td>
<td>I was bored by the story</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>78</td>
<td>I had to put a lot of effort into it</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>79</td>
<td>I felt time pressure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>It gave me a bad mood</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>81</td>
<td>I felt pressured</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>82</td>
<td>I was fully occupied with the game</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>83</td>
<td>I thought it was fun</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>84</td>
<td>I felt competent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>