# Modelling Physical Activity in Virtual Reality Games

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# Keywords

Virtual Reality; Head Mounted Display; Exercise; Exertion; Games; User Model; Personalisation; Personal Informatics; Long-term Data; Physical Activity; Physical Activity Tracker; Exergame.

# Abstract

This thesis was inspired by the possibility that virtual reality (VR) games, which are designed primarily to be fun, could also provide exercise. It aimed to gain insights about this by exploring whether people can gain beneficial levels of exercise while playing VR games and how they might use VR games for exercise over several weeks. Furthermore, this work also focuses on how the level of physical activity that can be captured during gameplay and how a long-term user model can be created for individual players, as a foundation for supporting the user in gaining personal informatics insights about their exertion as well as being used for personalisation and external recommendation for VR games.

The key contributions of this research are:

- The first study of a diverse set of commercial VR games to gain insights about the level of actual and perceived exertion players have.
- The first long-term study of VR games in a sedentary workplace to gain insights about the ways people utilise it and the levels of exertion they gain.
- Based on reflections on the above studies, this thesis presents a framework and guidelines for designing physical activity VR games.
- The systematic creation of a user model for representing a person's long-term fitness and their VR gameplay, exertion and preferences.
- A study of the ways that people can scrutinise their long-term personal informatics user model of exertion from VR game play and incidental walking.

These contributions provide a foundation for future researchers and industry practitioners to design VR games that provide beneficial levels of exertion and allow people to gain insights into the relative contribution of the exercise from gameplay.

# Contents

# Statement of originality

This is to certify that to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes. I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

Signature: Soojeong Yoo

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Name: Soojeong Yoo

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Date: 17 January 2020

# List of Publications

The following publications were achieved during my PhD candidature. Publications marked with an asterisk are included as chapters in this thesis.

**Conference Papers**

* Soojeong Yoo, Phil Gough, and Judy Kay (2020). 'Embedding a VR Game Studio in a Sedentary Workplace - Use, Experience and Exercise Benefits'. In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM

* Soojeong Yoo, Jisu Jung, Cécile Paris, Bob Kummerfeld, and Judy Kay (2019). 'Exermodel: A User Model for Scrutinising Long-term Models of Physical Activity from Multiple Sensors'. In: *Adjunct Publication of the 27th Conference on User Modeling, Adaptation and Personalization, UMAP 2019, Larnaca, Cyprus, June 09-12, 2019*, pp. 99–104

Soojeong Yoo, Phillip Gough, and Judy Kay (2018b). 'VRFit: an interactive dashboard for visualising of virtual reality exercise and daily step data'. In: *Proceedings of the 30th Australian Conference on Computer-Human Interaction*. ACM, pp. 229–233

* Soojeong Yoo, Marcus Carter, and Judy Kay (2018a). 'VRmove: Design Framework for Balancing Enjoyment, Movement and Exertion in VR Games'. In: *Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts*. ACM, pp. 295–307

* Soojeong Yoo, Tristan Heywood, Lie Ming Tang, Bob Kummerfeld, and Judy Kay (2017b). 'Towards a Long Term Model of Virtual Reality Exergame Exertion'. In: *Proceedings of the 25th Conference on User Modeling, Adaptation and Personalization*. ACM, pp. 247–255

* Soojeong Yoo, Christopher Ackad, Tristan Heywood, and Judy Kay (2017a). 'Evaluating the Actual and Perceived Exertion Provided by Virtual Reality Games'. In: *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. ACM, pp. 3050–3057

Soojeong Yoo and Judy Kay (2017). 'Body-map: visualising exertion in virtual reality games'. In: *Proceedings of the 29th Australian Conference on Computer-Human Interaction*. ACM, pp. 523–527

Soojeong Yoo and Judy Kay (2016). 'VRun: running-in-place virtual reality exergame'. In: *Proceedings of the 28th Australian Conference on Computer-Human Interaction*. ACM, pp. 562–566

Soojeong Yoo, Callum Parker, Judy Kay, and Martin Tomitsch (2015). 'To Dwell or Not to Dwell: An Evaluation of Mid-Air Gestures for Large Information Displays'. In: *Proceedings of the Annual Meeting of the Australian Special Interest Group for Computer Human Interaction*. ACM, pp. 187–191

**Workshop Proceedings**

Callum Parker, Waldemar Jenek, Soojeong Yoo, and Youngho Lee (2018). 'Augmenting Cities and Architecture with Immersive Technologies'. In: *Proceedings of the 4th Media Architecture Biennale Conference*. ACM, pp. 174–177

Soojeong Yoo, Lichen Xue, and Judy Kay (2017d). 'HappyFit: Time-aware Visualization for Daily Physical Activity and Virtual Reality Games'. In: *Adjunct Publication of the 25th Conference on User Modeling, Adaptation and Personalization*. ACM, pp. 391–394

Soojeong Yoo, Callum Parker, and Judy Kay (2017c). 'Designing a Personalized VR Exergame'. In: *Adjunct Publication of the 25th Conference on User Modeling, Adaptation and Personalization*. ACM, pp. 431–435

Callum Parker, Joel Fredericks, Martin Tomitsch, and Soojeong Yoo (2017). 'Towards Adaptive Height-Aware Public Interactive Displays'. In: *Adjunct Publication of the 25th Conference on User Modeling, Adaptation and Personalization*. ACM, pp. 257–260

**Posters**

Soojeong Yoo, Callum Parker, and Judy Kay (2018c). 'Adapting Data from Physical Activity Sensors for Visualising Exertion in Virtual Reality Games'. In: *Proceedings of the 2018 ACM International Joint Conference and 2018 International Symposium on Pervasive and Ubiquitous Computing and Wearable Computers*. ACM, pp. 307–310

Soojeong Yoo and Callum Parker (2015). 'Controller-less interaction methods for Google cardboard'. In: *Proceedings of the 3rd ACM Symposium on Spatial User Interaction*. ACM, pp. 127–127

**Doctoral Consortium**

Soojeong Yoo (2017). 'Harnessing Virtual Reality Exergames and Physical Fitness Sensing to Create a Personalised Game and Dashboard'. In: *Proceedings of the 25th Conference on User Modeling, Adaptation and Personalization*. ACM, pp. 339–342

# Authorship Attribution Statement

The publications listed below have been included in this thesis as separate chapters each presenting their own unique insights, and synthesis of research findings and results. The following authorship attribution statements are included for each respective publication. Affiliations are based on the positions the co-authors held at the time of writing the papers.

***Chapter 3***
*Soojeong Yoo, Christopher Ackad, Tristan Heywood, and Judy Kay (2017a). 'Evaluating the Actual and Perceived Exertion Provided by Virtual Reality Games'. In:* Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems. *ACM, pp. 3050–3057*

This chapter was co-authored as a Late Breaking work paper with Christopher Ackad, Tristan Heywood, and Professor Judy Kay from the Computer Human Adapted Interaction Lab, School of Computer Science, The University of Sydney.

The paper details a lab study I conducted with four commercial VR games from Steam VR. The main contribution of this paper was the finding that exertion from playing commercial VR games for short periods can provide beneficial level of physical activity. I conducted the lab study, analysed the collected data from the study, and contributed towards the main body of work for the whole paper. Chris helped with setting up the VR lab for user study. Tristan contributed towards the interpretation of the results and proof-reading. Judy was involved in the design of the user study and supported the editing of the paper.

This paper was presented as a poster at the International Conference on Human Factors in Computing Systems (CHI) in Denver, USA, in May 2017. The paper was subsequently published as a late-breaking work and included as part of the extended abstract proceedings in the ACM Digital Library.

***Chapter 4***
*Soojeong Yoo, Phil Gough, and Judy Kay (2020). 'Embedding a VR Game Studio in a Sedentary Workplace - Use, Experience and Exercise Benefits'. In:* Proceedings of the

2020 CHI Conference on Human Factors in Computing Systems. *ACM* This chapter have accepted at the CHI2020. This chapter co-authored as a full conference paper with Dr Phil Gough from the Design Lab, Sydney School of Architecture, Design and Planning, The University of Sydney; and, Professor Judy Kay from the Computer Human Adapted Interaction Lab, School of Computer Science, The University of Sydney.

The study discussed in this chapter builds on the study presented in Chapter 4 by testing five commercial VR games and the exertion they provide over multiple sessions (8 weeks) in a workplace environment. I conducted the study, analysed the collected data from the study, and contributed towards the main body of work for the whole paper. Phil contributed towards the interpretation of the results and proof-reading. Judy was involved in the design of the user study and supported the editing of the paper.

This chapter is unpublished. We plan to submit the work to a conference venue in future.

***Chapter 5***
*Soojeong Yoo, Marcus Carter, and Judy Kay (2018a). 'VRmove: Design Framework for Balancing Enjoyment, Movement and Exertion in VR Games'. In:* Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts. *ACM, pp. 295–307*

This chapter was co-authored as a spotlight paper with Dr Marcus Carter from Faculty of Arts and Social Sciences, The University of Sydney; and, Professor Judy Kay from the Computer Human Adapted Interaction Lab, School of Computer Science, The University of Sydney.

In this chapter the results from a previous study (Chapter 4) are discussed and brought them together to create a framework which aims to help game designers and researchers strike a balance between enjoyment, movement, and exertion in VR games to ensure the players have a positive experience while also gaining beneficial levels of exercise. We also created a new VR game to test this framework. I contributed to the main body of work for the whole paper, including the analysis of the previous user study data. Marcus gave feedback on the paper structure in the early stages and supported editing the paper. Judy was involved in the design of the user study and guide me to create VRmove framework, and supported the editing of the paper.

The paper was presented at the Annual Symposium on Computer-Human Interaction in Play (CHIPLAY) 2018 conference in Melbourne, Australia. The paper was published as part of the extended abstracts proceedings in the ACM Digital Library.

***Chapter 6***

*Soojeong Yoo, Tristan Heywood, Lie Ming Tang, Bob Kummerfeld, and Judy Kay (2017b). 'Towards a Long Term Model of Virtual Reality Exergame Exertion'. In:* Proceedings of the 25th Conference on User Modeling, Adaptation and Personalization*. ACM, pp. 247–255*

This chapter was co-authored as a full conference paper with Tristan Heywood, Lie Ming Tang, Associate Professor Bob Kummerfeld and Professor Judy Kay from the Computer Human Adapted Interaction Lab, School of Computer Science, The University of Sydney.

In this paper, the results from Chapter 3 are utilised to design a user model for VR exercise games (VREX) based on physical activity in VR games, such as heart-rate, and the attributes of VR games, such as score. We designed this model for three main roles - (1) recommending games to play based on individual preferences; (2) personalising the experience within the VR games; and (3) enabling people to review their long-term exercise and their preferences from VR game sessions. I conducted the user study, analysed the collected data from the study, and contributed towards the main body of work for the whole paper. Tristan contributed towards the interpretation of the results and proof-reading. Lie Ming contributed towards the open learner model part in the discussion section. Bob proof-read the paper. Judy was involved in the design of the user study and supported the editing of the paper.

This paper was presented at the 25th Conference on User Modeling, Adaptation and Personalization (UMAP) 2017 conference in Bratislava, Slovakia. The paper was subsequently published as part of the full conference proceedings in the ACM Digital Library.

***Chapter 7***

*Soojeong Yoo, Jisu Jung, Cécile Paris, Bob Kummerfeld, and Judy Kay (2019). 'Exermodel: A User Model for Scrutinising Long-term Models of Physical Activity from Multiple Sensors'. In:* Adjunct Publication of the 27th Conference on User Modeling, Adaptation and Personalization, UMAP 2019, Larnaca, Cyprus, June 09-12, 2019*, pp. 99–104*

This chapter was a co-authored journal paper with Jisu Jung, Associate Professor Bob Kummerfeld and Professor Judy Kay from the Computer Human Adapted Interaction

Lab, School of Computer Science, The University of Sydney; and, Cecille Paris from Commonwealth Scientific and Industrial Research Organisation (CSIRO) Data61.

This chapter discusses how a user model can be harnessed in a graphical interface to enable people to review their own long-term physical activity data from playing VR games and incidental activity outside VR gameplay. The main contribution of this work are the insight into how physical activity data from both VR games and daily physical activities, such as walking, can be reviewed by individuals as well as gaining insights into how people would use the data. I conducted the user study, analysed the collected data from the study, and contributed towards the main body of work for the whole paper. Jisu helped run an initial user study and built the user interface. Bob contributed the backend work for the interface and added the data into the user model server. Cecille proof read the paper. Judy was involved in the design of the user study and supported the editing of the paper.

This paper was presented at the 27th Conference on User Modeling, Adaptation and Personalization (UMAP) 2019 conference in Larnaca, Cyprus. The paper was subsequently published as part of the extended abstract proceedings in the ACM Digital Library.

# Human Ethics

The user studies presented in this thesis were conducted under human ethics project number 2016/089, approved by The University of Sydney Human Research Ethics Committee. All of the documents given to participants (e.g. information sheets and consent forms) are included as Appendices.

# Acknowledgements

Over the past three years, I had the privilege of meeting and working with a number of outstanding people. They all contributed to this thesis in their own way, like motivating me to keep going, helping with edits, and giving advice or feedback on certain aspects of this work.

First and foremost I would like to express my sincere gratitude to my supervisor Prof. Judy Kay for her continuous support throughout my PhD research. I sincerely appreciate her guidance both inside and outside of my research since I started this journey and I feel very fortunate and honoured to supervised by her.

I am also very grateful to my co-authors of the research papers written during my PhD candidature, A/Prof. Bob Kummerfeld, A/Prof. Martin Tomitsch, Dr. Phil Gough, Dr. Marcus Carter, Dr. Chris Ackad, Tristan Heywood, Lichen Xue, Jisu Jung, Lie Ming Tang.

Also, thank you for my research colleagues, office mates, and friends, Dr. Naseem Ahmadpour, Dr. Winyu Chinthammit, Dr. Joel Fredericks, Prof. Youngho Lee, Prof. Marcus Foth, Marius Hoggenmueller, Rohann Dorabjee, Dawei Zhou, Karen Cochrane, Louis Chew, Sakib Jalil, Drew Cosgrove, Claudio Esteban Diaz, Augusto Dias, Farahnaz Yekeh and Nick Brown. Thank you all for motivating me, providing emotional support, and contributing towards my research. Thank you also goes out to everyone that participated in my user studies over the years.

Thank you to the Australian Department of Defence and School of Psychology at the University of Sydney for the HTC Vive for the user studies. Also, thank you to Evelyn Riegler from the School of Computer Science in Faculty of Engineering & Information Technologies for her assistance with obtaining funding for the presentation of my papers in conferences outside Australia, and therefore their eventual publication.

Thanks also goes to my family for all their support over the years. Thank you Mum (강아지), Dad (곰도리) and my brother Wonjae Yoo. Thank you also to Callum's family.

Finally, I would like to special thank my partner & best ever friend Dr Callum Parker for his unconditional support and love to help me through this long journey, it wouldn't be possible without you.

# 1 Introduction

This doctoral thesis aims to gain understanding on how to harness commercial virtual reality (VR) games as a new way for people to gain beneficial levels of exercise. To achieve this, we set out two specific goals:

- **Goal 1.** Explore the exertion provided by commercially available VR games both in lab and authentic settings.
- **Goal 2.** Understand how to use data from VR gameplay to create a long-term user model to support personal informatics.

The motivation of the aim and its goals are explained further below.

Regular exercise can provide many health benefits, both physical and cognitive. Authoritative national guidelines (Health.gov, 2008; Guide, 2014) recommend exercise at least 2.5 to 5 hours of physical activity per week. However, for many people, there are barriers to getting regular exercise (Herazo-Beltrán et al., 2017; Cerin et al., 2010; Alharbi et al., 2017; Salmon et al., 2003), such as lack of time, motivation, or a job that requires a lot of sitting for computer-based work (Smith et al., 2015; Niven and Hu, 2018). Such sedentary behaviour can lead to negative health consequences (Salmon et al., 2011; Biswas et al., 2015; Van der Ploeg et al., 2012).

Exergames offer a way to overcome this, as they can motivate people through exerting and engaging gameplay. The term, exergame, was created to describe the combination of physical exercise and video games (Rizzo et al., 2011). The reason for this combination is that video games are usually designed with enjoyable and addictive elements, which can lead people to playing them for long periods of time (Wood, 2008; Pontes, 2018; Triberti et al., 2018). Exergames often require players to physically move their body to interact, tracking them through cameras and sensors (Rizzo et al., 2011; Chatta et al., 2015). A notable example of a popular commercial exergame is Wii Sports, created for the Nintendo Wii[1], which enabled players to physically play virtual sports such as tennis, baseball, and bowling.

[1]Nintendo Wii - `https://en.wikipedia.org/wiki/Wii`

Building on the success of exergames making people more active (Peng et al., 2011; Douris et al., 2012; Laufer et al., 2014), VR is an important platform for exergaming because of its ability to provide immersive and engaging experiences. VR is a term used for computer systems which utilise various displays and interfaces that aim to provide the user with the feeling of immersion (Pan et al., 2006). In the context of this thesis, the term VR refers to experiences where the player needs to wear a Head mounted display (HMD).

Since VR is an immersive platform, we expect that the more fun and compelling a VR exergame is, the less the player is aware of the exercise they are doing. Additionally, some VR platforms such as the HTC Vive[2] are particularly well suited for exergaming due to their ability to provide 'room scale' experiences. Many VR games created for the Vive require the player to engage their whole body and move around the room as they play. This full body movement means a game can give players significant exertion, even when it was not explicitly designed for exercise. The availability and fast dropping cost of emerging VR hardware such as the HTC Vive has the potential to allow the general public access to the benefits of VR exergaming. This physical movement can vary between different games as shown in Figure 1.1, where the game on the left requires the player to swipe their arm to slash virtual fruit while the game on the right requires little physical movement as it relies on a teleportation mechanic for movement around the virtual environment.

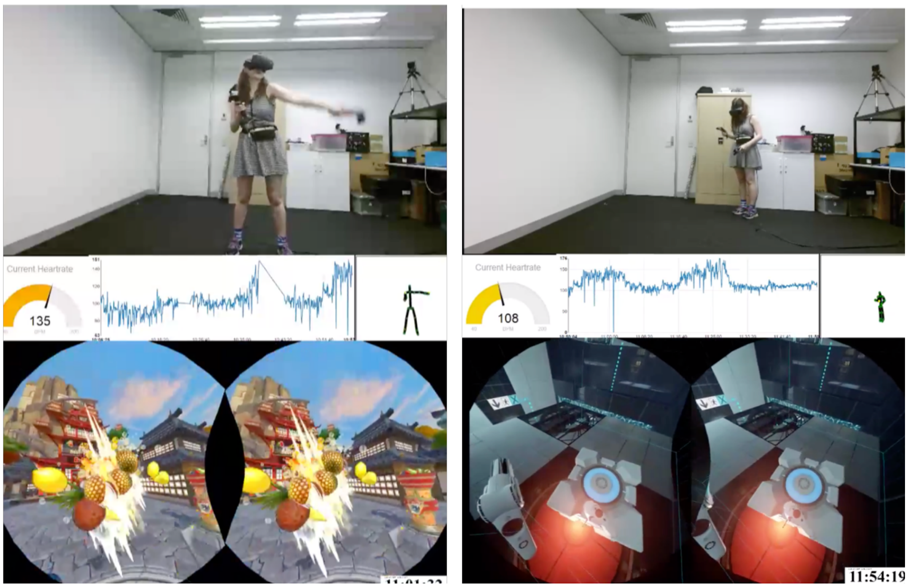



**Fig. 1.1.:** Commercial VR games: (Left) Fruit Ninja, which requires a lot of physical arm movements; and (Right) Portal stories VR, where little physical movement is required due to the ability to teleport around the environment.

[2]HTC Vive – https://www.vive.com/au/

Overall, the key benefit of playing VR games over standard exergames is that players are fully-immersed in the virtual world due to them wearing a head mounted display (HMD). Therefore, we wanted to gain insights into the *actual* and *perceived* exertion someone can experience while playing commercial VR games, both short and long-term. To achieve this, **Goal 1** seeks to gain understanding around the actual exertion people get when they play commercial VR games.

While VR games have potential for getting people active, each player is different and has their own reasons for playing such games. Currently, VR games do not take into account the combination of physical characteristics and game preferences of individual players. Without tailored workouts for individual players, their exercise outcomes are limited (McClaran, 2003). There is also the potential for overexertion, which poses significant health risks such as musculoskeletal injury (Haskell et al., 2007).

Both personalised game recommendation and within-game personalisation could be a way to overcome these problems. They could make VR games more effective in providing beneficial exercise while being enjoyable – such as giving VR games the ability to deliver appropriate levels of exercise to individuals and be progressively more challenging to keep people engaged (Hagen et al., 2016). To support this type of personalisation over the long-term a user model is required (Kay, 1990; Kay, 1994), which represents key aspects of the user, such as their preferences, goals, and previous playthroughs of particular games over a long period of time. Data from emerging consumer devices for sensing heart-rate (HR) can then be used to model exertion (Nes et al., 2013), which can be used to find out an individual's progress towards their long-term personal fitness goals.

Apart from personalisation, a personal informatics user model containing physical activity data could also be particularly useful for making VR game players aware of how much exercise they performed in-game combined with the exercise they gained incidentally during the day, such as walking, in relation to their health goals (Barua et al., 2014). This information could be displayed and reviewed in dashboards, such as the one shown in Figure 1.2; where users could compare and make sense of different types of activity data such as heart-rate and steps over a period of time. A dashboard like this creates new ways for people to get insights about their physical activity.

Therefore to gain more understanding around long-term personal informatics user models, **Goal 2** leads this research towards the development of our own user model using data from people who participated in multiple VR gaming sessions.


**Fig. 1.2.:** Dashboard for comparing active minutes as measured by two devices that a person used. The blue is the exertion from playing VR games measured by a heart-rate monitor (ActiveMinsHR). The figure also shows active minutes from incidental steps measured by a wearable step counting device (ActiveMinsStep). In our actual studies we had to use different devices for these contexts as explained in Chapter 7.

## 1.1 Research Approach

To address the aims of this doctoral research, this thesis contains five core chapters which follow an exploratory, iterative approach. Each chapter is connected, with the results informing the next. The structure of relationships between these studies and the goal they address is depicted in Figure 1.3. As these chapters are taken directly from published papers, there is some repetition as the same study design applied to (1) Chapters 3, 5 (Section 5.1), and 6; and (2) Chapter 4 and 7.

**Goal 1: Explore the exertion provided by commercially available virtual reality games both in lab and authentic settings**

To achieve this goal, three studies were conducted (Chapters 3 to 5). The first study in Chapter 3 studied 10 people who played each of the four commercial VR games in a single session. The results from that study highlighted that commercial VR games can provide high levels of exertion.

Building on that study, the next study in Chapter 4 focused on how much physical activity people can gain from VR gameplay when a VR game studio was available at their sedentary workplace, over multiple sessions spanning 8 weeks. During this study, 11 people participated and played 5 commercial VR games in the VR studio. Participants could schedule a time to come and were able to freely choose their own games and playtime.

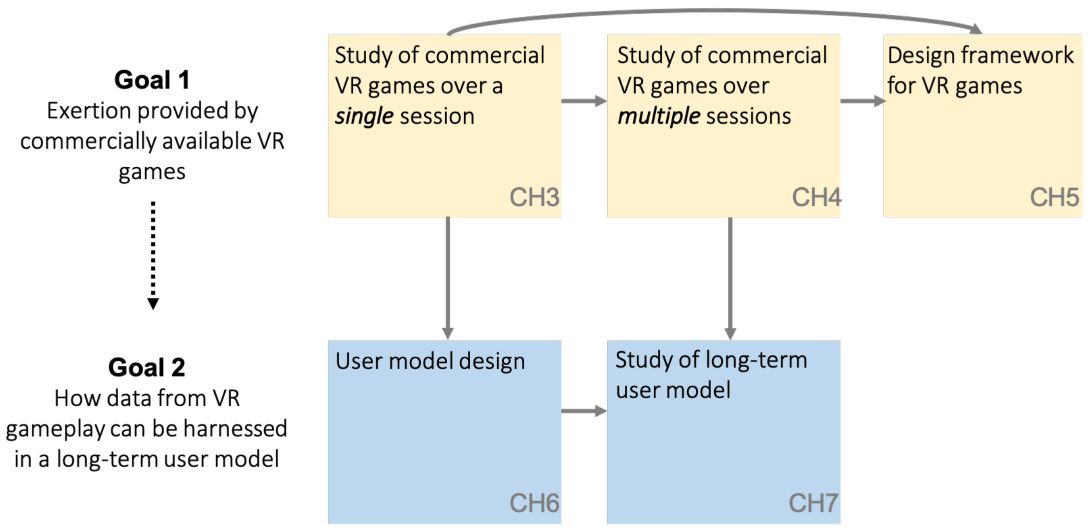



**Fig. 1.3.:** Structure of the relationships between the studies.

The single and multiple session studies with VR games are then reflected upon in the last chapter of this part (Chapter 5). This chapter discusses the insights from the studies and synthesised these, leading to a framework that future VR game designers and developers can use to strike a balance between game enjoyment and exertion in their VR games as well as motivate people to play longer. This framework was tested by applying it to the design and development of a VR game called Snowballz, intended to be both fun and exerting.

**Goal 2: Understand how to use data from virtual reality gameplay to create a long-term user model to support personal informatics**

This goal builds on one of the key findings found from the studies in **Goal 1** where participants had different preferences and play styles affecting the physical activity experienced when they played VR games. For instance, some participants wanted to play VR games for physical activity, while others just wanted to have fun and not experience too much physical activity. To further investigate how VR games can be designed to accommodate different preferences, Chapter 6 responds to the findings from the studies in **Goal 1** studies by defining a user model, which could be used to help support players review their post game session data and personalise VR games or exercise schedules. The study reported in Chapter 7 builds on the user model defined in the previous chapter to include multiple session (long-term) data and then tests the model with participants, getting them to review their data. This study delivered insights into how people's long-term activity data should be represented.

## 1.2 Thesis Contributions

This thesis makes the following contributions.

- The first study of a diverse set of commercial VR games to gain insights about the level of actual and perceived exertion players have.
- The first long-term study of VR games in a sedentary workplace to gain insights about the ways people utilise it and the levels of exertion they gain.
- Based on reflections on the above studies, this thesis presents a framework and guidelines for designing physical activity VR games.
- The systematic creation of a user model for representing a person's long-term fitness and their VR gameplay, exertion and preferences.
- A study of the ways that people can scrutinise their long-term personal informatics user model of exertion from VR game play and incidental walking.

These five contributions map to Chapters 3 to 7 of the thesis. Each of these chapters is based on a paper. For this thesis, the content of the introduction and related work sections of those papers appears in Chapter 2, which provides the background to the thesis work. Therefore, to link Chapter 3 to 7, we rewrote parts of their introduction sections, so they act as preambles and clearly define how they connect to the other chapters and our broader aim and goals.

# Background

# 2

This section discusses previous research in relation to the aim of this doctoral thesis, which is to gain understanding on **how to harness commercial virtual reality (VR) games as a new way for people to gain beneficial levels of exercise**.

The purpose of this chapter is not to provide an exhaustive account of all the work in the field, but to gain an initial overview of the related work that gives grounding to later chapters. Additionally, the work covered in this section does not cover the work on rehabilitation, as the research in this thesis only focuses on the exertion healthy adults could get from playing commercial VR games. This chapter was written using the background and related work sections originally included in the papers featured in **Parts I** and **II** of this thesis. However, the work has been significantly altered to expand on discussions and to include work that has occurred since those papers were written.

Therefore, this chapter is made up of four main themes: (1) Exergaming; (2) Exercising with VR games; (3) Measuring exertion; and (4) User modelling for long-term personal informatics. At the end of this section, the key knowledge gaps from the reviewed work are summarised.

## 2.1 Exergaming

Playing video games can be a fun pastime for all ages. Certain video games can provide benefits beyond entertainment, such as enhancing perceptual and cognitive skills (Eichenbaum et al., 2014) as well as the social benefits provided by multiplayer games (Granic et al., 2014). Video games are typically sedentary and do not require the player to move their body, which can potentially result in players being seated for long periods of time particularly when they are engaged in the game.

An alternative to sedentary video games are exergames, which combine the engaging elements of traditional video games while the input requires the player to perform some type of exercise (Marshall and Linehan, 2017; Huang et al., 2017); combining two activities that were long considered polar opposites: exercise and the traditionally sedentary computer gaming. The digital game elements, such as addictive mechanics and immersion can augment traditional exercise by motivating players to workout harder and longer.

Exergames are compatible with sports-HCI research (Mueller and Young, 2018), which introduced 10 lenses to support designers and researchers of exertion experiences. The lenses highlight that exertion experiences can support personal growth through learning how to appreciate a void (Reverie), find pleasure in exertion (Pleasure), become humble (Humility), enjoy the stimulation that comes from fear (Sublime), be more aware of one's own body (Oneness), value sacrifice as a chance for a simpler existence (Sacrifice), bring beauty into the world through movement (Beauty), see benefit in pain (Pain), foster consistency for life (Consistency) and welcome patience (Perseverance). These virtues can also exist in exergames, for instance a good exergame may help players see the pleasure of pain while rewarding perseverance.

Like traditional video games, exergames often need a controller that players can use to interact with the virtual environment. This is usually in the form of depth sensing cameras, dance mats, and hand-held controllers (Rizzo et al., 2011; Chatta et al., 2015; Yim and Graham, 2007). While the production of the Nintendo Wii was discontinued after newer console generations were released, it is a popular example of an exergaming system. Research on the Wii's effectiveness at providing exercise found that people can gain significant amounts of exercise from playing games on the Wii, making it an alternative to traditional forms of exercise (Barkely and Penko, 2009; Peng et al., 2011; Douris et al., 2012; Daley, 2009; Park et al., 2014). Furthermore, work by Barkely and Penko (2009) studied 12 healthy adults who each completed three 10 minute exercise conditions with a five-minute rest period between each. The exercises were: treadmill walking; traditional sedentary video game play (Nintendo Punchout!); and the Nintendo Wii Sports Boxing game. The findings showed that playing exergames such as Wii Sports Boxing was a well-liked activity capable of eliciting a physical challenge greater than both the sedentary and treadmill conditions.

Although discontinued, like the Wii, the Microsoft Kinect was a popular interface for commercial exergames (Boulos, 2012; Wu et al., 2015) for the Xbox 360 Xbox One consoles. It was designed to track players' bodies and recognise certain gestures, such as a swinging arm motion. A number of fitness related games have been released on Xbox consoles that specifically take advantage of this camera, simulating a diverse range of sports. Work by F. X. Chen et al. (2014) explored using intentional priming and health feedback with a commercial Kinect exergame called Dance Central (Figure 2.1). They tested the game with 44 participants and found that the game provided moderate intensity activity. Their results also suggested that by priming participants by telling them to exercise with the game before they started playing increased duration of use. Additionally, health feedback (calories burned and time spent) during the session increased positive feedback. The core findings from this work emphasised the need for “healthifying” engaging games rather than “gamifying” health games.

**Fig. 2.1.:** Player engaging with the exergame, Dance Central detected through the Microsoft Kinect sensor. *Figure from [Chen et al., 2014], included with permission from the author(s).*

Exergames have also gained popularity outside of the home. For instance, due to the high cost of greens fees and of travel to outdoor golf courses in South Korea, playing simulated golf on screens at golf cafés is popular (Han et al., 2014). There is an estimated 5,000 screen golf cafés and 175 physical golf courses. Screen golf is played indoors, in private rooms on large projected screens with a simulated golf course displayed. Players use real golf clubs and balls, aiming at the screen. The balls are tracked, and the speed, impact and orientation determines where the ball will land in the virtual world.

## 2.2 Exercising with Virtual Reality Games

Due to advances in tracking technologies, VR can accept whole body physical movement for interaction, which has resulted in research investigating its efficacy for being used as a form of exercise. Unlike many previous exergames, VR exergames provide fully-immersive virtual worlds through head mounted displays (HMD) that

| Study | Equipment | N | study sessions | Game Type | HMD | Measurement |
|---|---|---|---|---|---|---|
| Bolton et al., 2014 | Exercise bike | 0 | 0 | Custom | Oculus Rift | None |
| Shaw et al., 2016 | Exercise bike | 6 | 1 | Custom | Oculus Rift | Heart-rate |
| Tuveri et al., 2016 | Exercise bike | 19 | 1 | Custom | Oculus Rift | None |
| Barathi et al., 2018 | Exercise bike | 48 | 1 | Custom | HTC Vive | Heart-rate |
| Löchtefeld et al., 2016 | Exercise bike | 16 | 1 | Custom | Oculus Rift | None |
| Arndt et al., 2018 | Rowing machine | 16 | 1 | Custom | HTC Vive | None |
| Tiator et al., 2017 | Trampoline | 38 | 1 | Custom | Samsung GearVR | None |
| Rabbi et al., 2018 | Gym equipment | 15 | 1 | Custom | Smartphone VR | None |
| Tregillus & Folmer, 2016 | None | 18 | 1 | Custom | Smartphone | None |
| Yoo and Kay, 2016 | None | 18 | 1 | Custom | Google Cardboard | None |
| Ioannout et al,. 2019 | None | 15 | 1 | Custom | HTC Vive | None |
| Study for Chapter 3 | None | 18 | 1 | Commercial | HTC Vive | Heart-rate |
| Study for Chapter 4 | None | 11 | multiple | Commercial | HTC Vive | Heart-rate |
| Study for Chapter 5 | None | 9 | 1 | Commercial + Custom | HTC Vive | Heart-rate |

Tab. 2.1.: An overview of the key work on using VR games for exercise. It contains a citation of the study; whether the featured prototype required external equipment to play the exergame; number of participants (N); number of study sessions – meaning the number of times participants came for the study; game types; HMD types; and how they measured the exertion for their study.

have the potential to not only make exercise fun, but to also distract the player from the exercise itself. Table 2.1 provides an overview of the key work in this area, containing the citation of the study; whether the featured prototype required external equipment to play the exergame; number of participants; number of sessions; game types; HMD types; and how they measured the exertion for their study. The 11 studies contained in the white part of the table were chosen based on their focus towards using VR games for physical activity with young adults. The studies in the blue part of the table feature studies conducted for this doctoral research. They were included to compare with previous work. The key work from the table is now discussed further below.

Much of the work to date that has focused on using VR for exercise is equipment assisted, often utilising exercycles to travel through the virtual worlds. For example, Figure 2.2 simulated a newspaper run called PaperDude (Bolton et al., 2014). The player sat on the exercycle and peddled to move while wearing a VR HMD. The player's body was tracked using a Microsoft Kinect so the player could perform throwing motions with their arms to physically throw virtual newspapers in the virtual world. Since this demo, other studies followed up on the exercycle concept to evaluate how effective such systems are for exercise.

Work by Shaw et al. (2016) presented an exergame prototype that had a procedurally generated virtual environment. The prototype was tested with 6 participants using an exercycle under three different conditions: (1) exercising without the game; (2) exercising with the game displayed on a monitor; and (3) exercising with an Oculus Rift HMD. Exertion was measured through data collected by a heart-rate monitor. The findings from this study showed that each condition had a mean exertion of moderate to high heart-rate for 80% of the time. Furthermore, while the exergame itself can increase performance over just using an exercycle, the exergame in combination with the VR HMD can further increase motivation and enjoyment.

Similarly, work by Tuveri et al. (2016) described the results from a study of a VR prototype called Rift-a-bike, a VR exercycle game for the Oculus Rift. Their study tested different gamification techniques, such as challenges, levels, points, and rewards. This study was conducted with 19 participants, where each participant trialled the Rift-a-bike under two conditions: (1) Baseline virtual environment without gamification; and (2) same virtual environment with gamification. Additionally, the focus of this work was primarily on participant engagement, as the work did not report on any measures of exertion. The findings from the study showed that the gamification techniques can be effective at increasing participant enjoyment during VR gaming sessions.

**Fig. 2.2.:** Playing a VR exergame using an exercise bike - this example simulates a newspaper run. *Figure from [Bolton et al,. 2014], included with permission from the author(s).*

Building on from this previous work, Barathi et al. (2018) used a custom HTC Vive exercycle VR game to test a method for improving performance while maintaining intrinsic motivation in high intensity VR exergaming. This was tested with 48 participants in a single session for each. During the session, participants trialled the system multiple times, competing against themselves through a self model that was generated throughout their play session. Exertion was measured based on the participant's heart-rate using a Polar H10 chest strap sensor. The results of this study reported that players can be continuously motivated through an interactive feedforward technique, being a viable replacement for competition with other players.

Other research investigated how player performance can be increased by making cycling more realistic through speed deception (Löchtefeld et al., 2016). A custom prototype was created for the Oculus Rift DK2 HMD that allowed the researchers to manipulate the player's speed perception using visual and haptic cues. To test the prototype, a user study was conducted over a single session with 16 participants. The results from this study showed that a player's speed can be increased by 15.2% during gameplay without them noticing. In this work, there was no report of exertion measures being used.

Similar to the examples shown using exercycles, work has successfully simulated rowing in VR by linking custom rowing machines (Figure 2.3). Work by Arndt et al. (2018) tested this setup in a user study, trialling their VR rowing machine prototype for the HTC Vive HMD with 16 participants, each in a single session. The results indicated that participants in the VR condition had improved performance and experience compared to the non-VR condition. There was also some indication that VR helped players keep a rhythmic motion, which is important for performance in exercises like rowing.


**Fig. 2.3.:** Rowing machine VR exergame
*Figure from [Arndt et al,. 2018], included with permission from the author(s).*

Another interesting interaction shown in Figure 2.4A is the use of a trampoline in a custom virtual jump game called Jump 'N' Run for the Samsung Gear VR (Tiator et al., 2017). The findings from a single session user study with 38 participants found that the game was engaging and despite the rapid jumping, participants did not experience any motion sickness, which could be due to the precise OptiTrack system used to track the player's movement and position.

Finally, while not necessarily a game, work by Rabbi et al. (2018) presented JARVIS, a virtual exercise assistant based on a miniature IoT sensing device and a mobile VR HMD to enable immersive and interactive gym exercise experiences (Figure

2.4B). The system can retrieve information about the exercises performed by the user on exercise machines in real-time. JARVIS achieves this by attaching an IoT sensing device on exercise machines that use sensor signal processing algorithms to recognise exercise type and track exercise progress. Based on the exercise information collected from the sensors, JARVIS creates an immersive and interactive gym exercise experience that gives users real-time feedback while they are exercising.

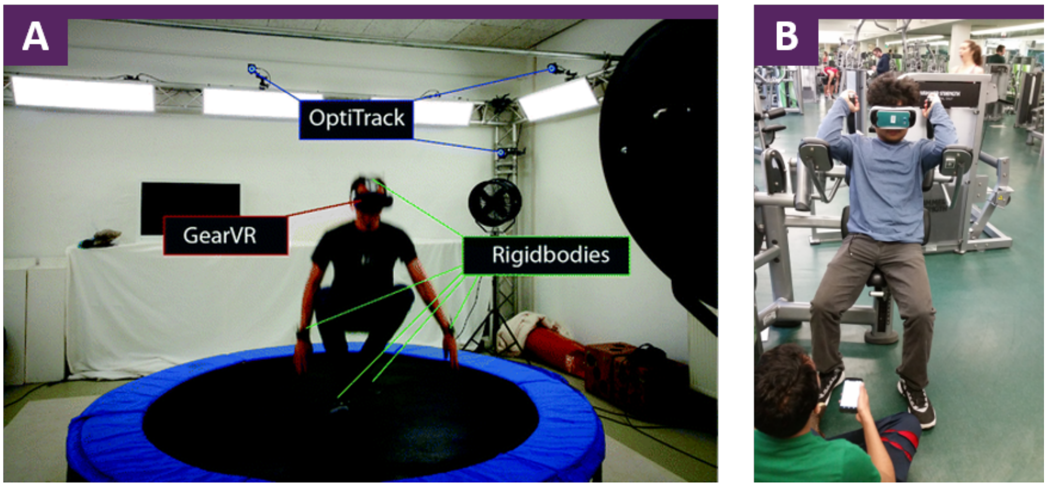



**Fig. 2.4.:** Playing VR game using trampoline playing Jump 'N" Run game through Samsung Gear VR (A) and exercise using both gym equipment and smartphone VR (B) *Figure from [Tiator et al,. 2017], [Rabbi et al,. 2018], included with permission from the author(s).*

However, VR exergames do not necessarily need to use large and expensive equipment. Research by Tregillus and Folmer (Tregillus and Folmer, 2016) presented VR-STEP, a custom walking-in-place (WIP) prototype for smartphone VR. The prototype utilises the smartphone's accelerometer sensor to detect steps through a detection algorithm. VR-STEP was tested in a user study with 18 participants over a single session, where it was compared with an auto-walk navigation method. Their findings showed no signicant difference between the two in relation towards performance or reliability. Despite this, their work demonstrated that sensing steps using an accelerometer brings the cost down for VR experiences while enabling portability.

A similar study by Yoo and Kay (Yoo and Kay, 2016) explored a prototype running-in-place VR exergame made for the Google Cardboard, called VRun. The work explored its potential as a portable VR exergame experience.The game required the user to physically run in-place to move through the virtual world, with activity detected through the smartphone's accelerometer (Figure 2.5). To evaluate the game, it was trialled in three different immersion conditions (VR, large wall display, and a baseline laptop) with 18 participants in a single session. This is the first evaluation of a running-in-place VR exergame. The results point to the potential for fully-immersive VR games like VRun to engage people, particularly those who cannot visit the gym regularly, allowing them to perform the exercise anywhere.

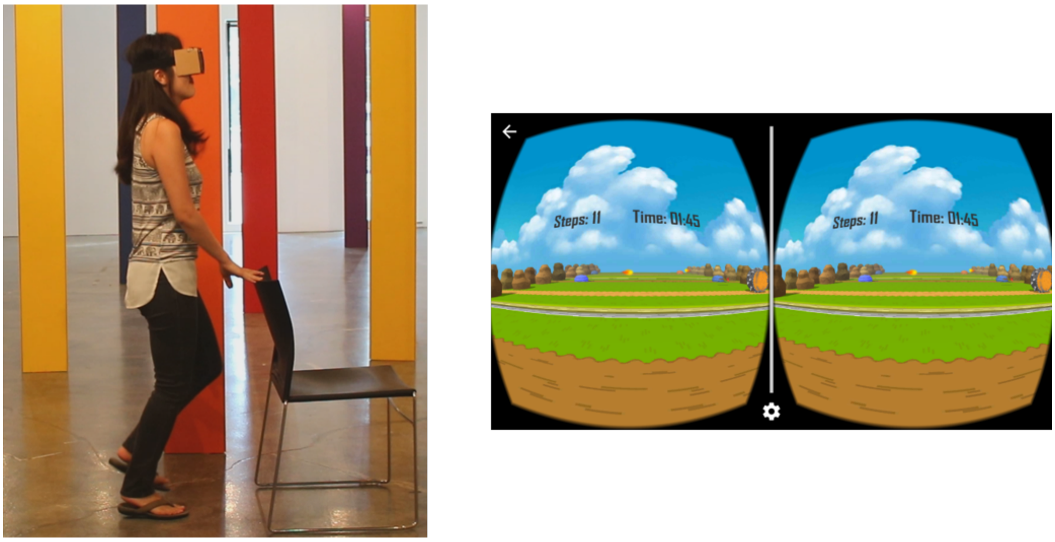



**Fig. 2.5.:** Running on spot in VR : (Left) user engaging with the VRun game; (Right) screen shot of the gameplay [Yoo and Kay 2016]

Building on these studies, work by Ioannou et al. (2019) investigated virtual performance augmentation using VR to provide the illusion of superhuman abilities, such as augmented running and jumping. They created a custom VR game for the HTC Vive which allowed players to run and jump in-place. The results of the study found that in-place running and jumping in VR games can provide medium to high physical exertion while being immersive.

In summary of this section, what all these examples show is that VR can be utilised to simulate a range of existing exercises and activities, which can be augmented through gamification elements. Referring back to Table 2.1 that was first introduced at the beginning of this section, majority of the prototypes featured in work from the white part of the table utilise either the Oculus Rift or HTC Vive. This could be due to players having more freedom to physically move around as the HMDs use positional tracking - 6 Degrees of Freedom (DoF)[1]. The studies also only focused on young healthy adults. The most interesting aspect from the collection of studies in the white part of the table is that, they were tested with custom created games by the researchers over a single session. While testing custom VR games can reveal some

[1] Six degrees of freedom (6DoF) describes the amount of free movement in a three-dimensional space and rotation around each dimensional axis.

valuable insights into ideas for VR exergames with unique interactions, no work has focused on existing commercial VR games from Steam or the Oculus online game stores. As these games require players to physically move around, they have the potential to provide physical exertion even though they are not explicitly designed for exercise. Understanding the exertion provided by these commercial VR games is important as VR becomes increasingly adopted. Therefore, Chapters 3 - 5 focus on comparing existing commercial VR games. Chapter 5 also discusses the design and development of a custom VR game that was based on the findings from the studies on commercial VR games.

## 2.3 Measuring Exertion

In the previous sections exergaming and using VR games for exercise were discussed in relation to the health benefits they provide. This section builds on from these to discuss how exertion VR games provide can be measured, identifying measures of exertion and the devices that can collect the information needed for the measurements. It is important to measure exertion from VR gameplay sessions to compare against the player's personal goals and whether they have met health recommendations, such as 30 minutes of moderate daily activity, or half that time for intense activity (Pate et al., 1995; Haskell et al., 2007).

The ability to accurately quantify physical exertion in VR is essential in assessing the efficacy of VR games in improving health outcomes compared to conventional exercise methods such as walking or weight-lifting. Collecting data regarding a wide variety of physical health parameters (such as cardiovascular) before, during and after a game to determine intensity of physical activity and, over extended use, might allow monitoring of improvements in cardiovascular function and strength. This data might be combined with that obtained from wearable devices, such as FitBits, which continuously make measurements during daily life, to produce individual activity profiles that allow personalisation of exercise prescriptions. Analysis and interpretation of raw data is dependent upon reliable, valid and accurate markers of physical fitness and exertion levels.

Currently the gold standard for measuring both exertion and physical fitness is $VO^2max$ (Thin and Poole, 2010; Noah et al., 2011; Godin, Shephard, et al., 1985). However, obtaining the $VO^2max$ requires the user to wear an oxygen mask, which can potentially be cumbersome when already wearing a VR HMD. The level of accuracy provided by $VO^2max$ is also unnecessary; consumer devices that measure heart-rate give quite a useful measure that we now describe.

There are two main units for measuring exertion that are widely used in health recommendations: active and vigorous minutes. The general recommendation is 150 active minutes per week, achieved by 30 moderate minutes on most days of the week (with vigorous activity, half this number of minutes meets the recommendation) (Haskell et al., 2007).

For daily life this is easily calculated with a personal activity tracker, such as the Fitbit or Pebble watch, with a minute judged as active when there are 100+ steps (Pedišić and Bauman, 2014). However, these activity trackers are not always effective for measuring exertion in VR games, as the player might be only moving parts of their body and not physically moving around the room. Therefore, an alternative measure is through wearable heart-rate sensors (Gao and Mandryk, 2012; Hagen et al., 2016), such as a consumer grade Polar chest strap heart-rate monitor[2]. The Polar heart-rate monitor takes account of the user's age (220-age), therefore the heart-rate can be converted to moderate (50%) and vigorous (70%) minutes (Mesquita et al., 1996). Together, these enable the number of active minutes a person gains in VR gameplay to be calculated and compared with the active minutes of the person's daily life.

Exertion itself can be felt in two different ways: there is the actual exertion the body experiences and the exertion a person feels. These are explained in more detail in the following sections.

### 2.3.1 Actual Exertion

There is a correlation between a person's heart-rate as a percentage of their maximum heart-rate, and the intensity of the exercise they are engaged in (Karvonen and Vuorimaa, 1988). As a result government guidelines label exercise that produces a heart-rate between 50% and 70% of the individual's maximum as moderate exercise. Vigorous exercise raises the individual's heart-rate beyond this (Channel, 2017). The recommended amount of exercise is then stated in terms of minutes of moderate or vigorous exercise. A simple but widely used estimate of maximum heart-rate uses the formula 220 - user's age (Mesquita et al., 1996). Using this, and measuring heart-rate in each minute, provides an estimate of how many minutes of moderate and vigorous exercise a person has achieved.

[2]https://www.polar.com/

### 2.3.2 Perceived Exertion

A common measurement for perceived exertion is the Borg measure of perceived exertion. This is measured through a Borg questionnaire which is filled out after exercise (Borg, 1998). The individual taking the questionnaire should choose a number between 6 and 20 (6 means "no exertion" and 20 means "maximum exertion") which best fits the exertion they experienced during their exercise. Table 2.2 shows the mapping of Borg scores to heart-rate (Borg, 1982).

| Intensity | Max HR (%) | Borg score (RPE) |
|---|---|---|
| No exertion | 20 - 39 | 6 - 7 |
| Very light | 40 - 59 | 8 - 10 |
| Light | 60 - 69 | 11 - 12 |
| Moderate | 70 - 79 | 13 - 14 |
| Heavy | 80 - 89 | 15 - 16 |
| Very Heavy | 90 - 99 | 17 - 18 |
| Maximum | 100 | 19 - 20 |

**Tab. 2.2.:** Mapping exercise intensity heart-rate with Borg score (RPE).

### 2.3.3 Measures of Fitness

It may also be important to measure an individual's fitness over time. This is commonly achieved by measuring an individual's *resting heart-rate* which tends to be inversely related to physical fitness and low values are associated with lower mortality (Jensen et al., 2013). It is also relatively easy to measure, either by taking manual measurement or with smart watches and fitness devices. This makes resting heart-rate one useful indicator of fitness over the long term. Another fitness measure is *heart-rate recovery*, how quickly a person's heart-rate returns to their rest heart-rate following intense exercise. A faster recovery rate is associated with increased fitness (Ostojic et al., 2011). There are protocols for measuring it, such as the change from the peak heart-rate after set exercise, to that measured 2 minutes later (Cole et al., 2000). It is possible to get an estimate of this, by measuring the heart-rate decrease over 2 minutes after playing an exergame.

## 2.4 User Modelling for Long-term Personal Informatics

This thesis focuses on a particular form of long-term personal user model that can support personal informatics. This section introduces key aspects from previous research that are relevant to this thesis: (1) First, we review work that has points to the potential value of long-term user modelling of exertion, based on sensor data from wearables such as a smart-watch and HR monitor; (2) We then introduce the Personis platform that we used to build such long-term user models, which could personalise the game itself and drive personalised recommendations; and (3) We focus on a third use, which is to support personal informatics via an interface that enables the user to gain insights about their long-term physical activity and the benefits of the exercise gained from playing VR games.

### 2.4.1 The Need for Mechanisms for People to Manage their Long-term Physical Activity Data

There is a substantial and growing body of research into the ways that people make use of wearable physical activity trackers (such as Fitbits) and the ways that they *use the data*, as well as the ways that they *would like to be able to use the data*. One stream of this work has emphasised that people's initial reasons for wearing a tracker may change over time (Niess and Woźniak, 2018). Considerable work has reported abandonment and lapses in the use of worn trackers (Fritz et al., 2014; Lazar et al., 2015; Kim et al., 2016; Epstein et al., 2016a; Epstein et al., 2016b), which causes long-term data sets to have breaks. Other studies have highlighted the various stages in tracking and reasons for doing it (Fritz et al., 2014; Lazar et al., 2015; Kim et al., 2016; Epstein et al., 2016a). In one of these studies (Lazar et al., 2015), 17 participants were funded to buy smart devices they considered would help them reach a goal they valued. When interviewed after 2 months, 80% had stopped using the sensors because they considered the data was not useful to them. Some explained that it was unprocessed and they did not know what to do with the data. Notably, some continued wearing them, explaining that they hoped that "*current capabilities of devices would be extended someday with new ways to process recorded data*". This resonates with the study of people who were asked about the ways that they would manage and use long-term data from sensors for physical activity, weight and inactivity (Barua et al., 2013). The common response was they wanted to be able to keep the data in a store that they controlled and even when they could not propose the ways they wanted to use such data, they wanted the long-term data available for future use. This is also consistent with the picture that people value and are interested in their long-term data (Choe et al., 2014; Epstein et al., 2015; Epstein et al., 2016b; Li et al., 2012). Studies of long-term users of worn trackers have emphasised that people currently make little use of long-term data from worn sensors (Fritz et al., 2014; Meyer et al., 2017; Tang and Kay, 2017). The key reason is due to the difficulty of exploring and managing the data, in terms of being able to access and manipulate the data to see different models, understanding the meaning of the data, and bringing different streams together.

Long-term data from users can be stored and scrutinised in a user model, which contains a conceptual understanding of the user. An important aspect of managing user model data is the ontology (Sosnovsky and Dicheva, 2010; Heckmann et al., 2005; Golemati et al., 2007). This refers to the naming and overall structure of the user model. There has been research on ontologies for user models, notably important early work by Heckermann (Heckmann et al., 2005) explored the potential for a general and reusable ontology. A comprehensive review of user model interoperability (Carmagnola et al., 2011) highlighted the many challenges of such reusable user models. There has also been some work on designing a user model ontology for integrating multiple sensors in the context of ubiquitous computing (Kuflik et al., 2012) and also supporting explanations (Niu and Kay, 2010).

For our work, the design of the ontology also has a key role for the user who needs to be able to understand the model as they explore it.

### 2.4.2 Personis Long-term User Modelling System

The Personis user modelling system is a database of information relating to the user (Assad et al., 2007; Kay and Kummerfeld, 2012). This data is structured into relevant components, where the data can be resolved with resolver functions. Due to Personis' rule system, certain actions can be triggered based on new or changed data. Actions could start an internal or external service.

The prototype discussed in Chapter 7 of this thesis makes use of the Personis user modelling shell (from a long-term research project[3]) to store user model data. A user modelling shell is a system that can manage user data independent of any particular application. This thesis is concerned with the particular form of user modelling system that can store and reason about long-term user data (Kay, 1990). This allows information about the user to be accumulated over a period longer than a single session and also enables comparisons of the exertion gained from different games, comparison of exertion from daily step activity, and gameplay.

The raw data in a Personis model is stored as *evidence* items in a *component* of the model. Components are organised in *contexts* that are arranged in a simple hierarchy.

[3]Created by Jisu "Joseph" Jung – `https://github.com/jbu/personis`

Each component can have a set of associated *resolvers* which interpret the evidence in the component to return a value.

In our work, this model was tested in an interface for users to gain a view of their long-term data. The next section discusses previous work on user model interfaces that were precursors of the one used in Chapter 7.

### 2.4.3 User Interfaces onto User Models

This section introduces previous work that has reported on user interfaces that enable the user to explore the ontology of a user model. This is critical if people are to be able to harness a long-term general user model to explore the ways that they gain exercise from VR gameplay and other activities, such as daily walking. The ontology and structure of the user model is the focus of Chapter 6 of this thesis and the study of people's exploration of their user model is the focus of Chapter 7. The key insights from this section are from two main areas of research that informed our work: (1) Open Learner Modelling which has reported many studies of learners exploring their learner models through an interface; and (2) work on an interface onto physical activity data with opportunities for multiple interpretations of the data.

In the literature, interfaces that allow exploration of a learner model are referred to as an open learner model. There has been considerable work on open learner models, recently reviewed in Bull and Kay (2016). These interfaces can serve various goals, including enabling users to answer important questions about their learning. The design of a learner model's ontology is driven by the particular role of the learner model. In the context of this thesis, the user can be considered as a lifelong learner who wants to be able to reflect on their physical activity, in particular how much exercise they get from playing VR games and how that relates to other sources of exertion.

For example, one of the earlier examples is the ELM-ART tutoring system which teaches LISP and tracks the student's demonstrated knowledge. The interface it provides shows which presents the key learning objectives (Brusilovsky et al., 1996). This serves a valuable role in advising students about navigation to learning topics, based on whether the user model indicates they are ready to tackle them. There has been far less work in the creation of user models and associated interfaces that allow the user to scrutinise their own user model, exploring what is modelled, the inferred values of aspects modelled and the underlying evidence and processes.

Another early example did this in a learning context (Cook and Kay, 1994). Their work introduced the first viewer interface for user models, giving users access to the system's model of them. The user model in the interface is presented to users as a hierarchical tree. Figure 2.6A shows the overview part of the interface. It uses different shapes to represent the component type. Squares are used to represent knowledge components. Diamonds for user beliefs. The crosses represent user characteristics and other properties. Figure 2.6B provides a view of the interface, showing leaves with information about the user regarding the aforementioned component types. The key finding from this work is these interfaces which enable users to gain an overview of their knowledge and to then drill down to scrutinise the details, including the actual evidence and how it was used to reason about whether the user knew a topic of not.

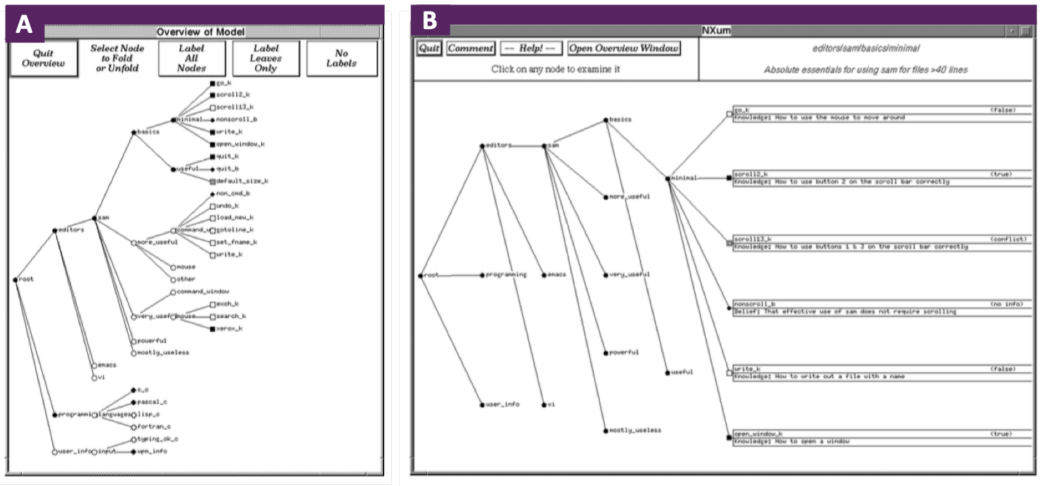



**Fig. 2.6.:** Screenshots from the model viewer interface. (A) An overview of the tree hierarchy; and (B) Detailed leaf view of the tree. *Figure from [Cook and Kay, 1994],included with permission from the author(s).*

Other work has explored scrutable adaptive hypertext with an interface called Tutor/ADAPT (Czarkowski and Kay, 2002). This system was used to make recommendations for holidays and for teaching. Importantly, it invited the user to explore their user model and to update it. Its user model was based on both the user profile visible in Figure 2.7A and the parts of the user model that were created by the system. For example, in the teaching instance shown, the students did quizzes and the scores on these were used to model their knowledge (Figure 2.7B). This was used to personalise the hypertext and colour code the course map to indicate the topics the student has completed – those they are ready to read and the ones they are not ready to read (see the course map in Figure 2.7C).

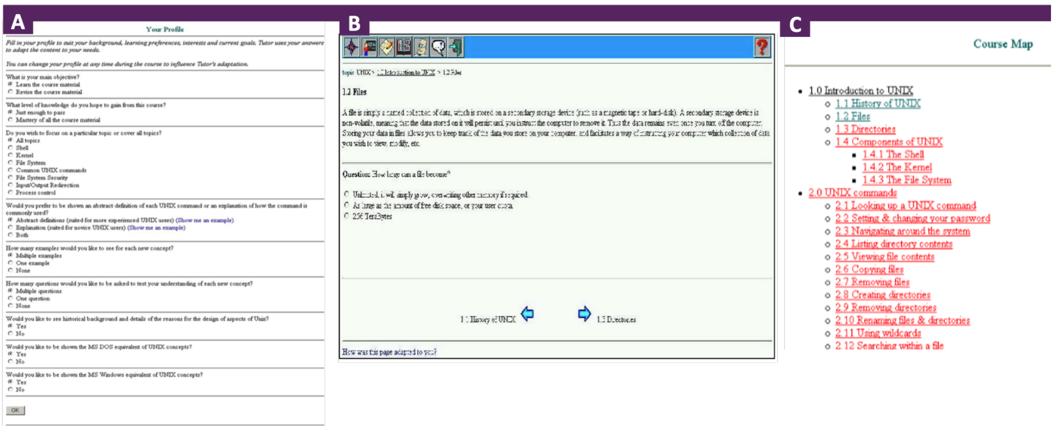


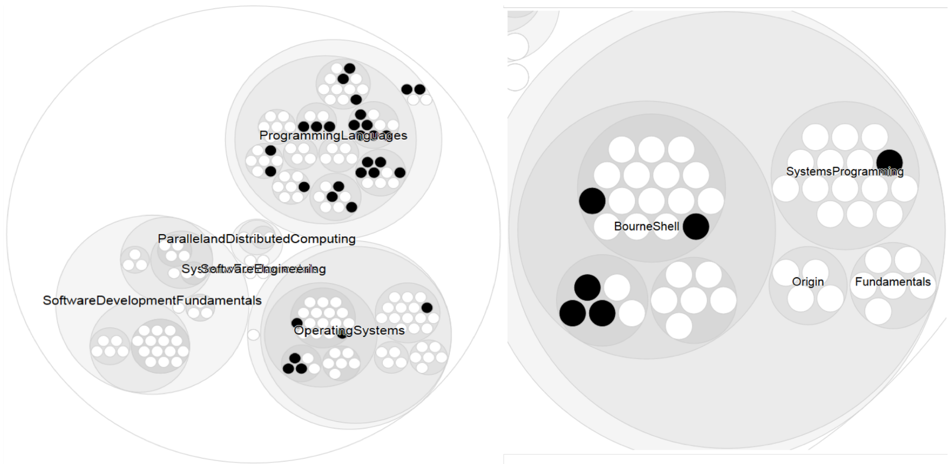

**Fig. 2.7.:** Screenshots from the Tutor/ADAPT interface. (A) User profile that is accessible by users and can be tweaked anytime; (B) User view of a lesson where this particular user has opted to not see examples; and (C) Course map with topics colour coded based on what they student is ready or not ready to read. *Figure from [Czarkowski and Kay, 2002],included with permission from the author(s).*

Work by Cook et al. (2015) presented an OLM interface which enables a learner or teacher to gain an overview of their progress, view the learning objectives achieved to date and what they need to catch up on, the progress status on particular class activities, and finally how a student can act on these. The framework and its interface was validated through the implementation of a learner model. It was tested with a computer science small private online course (SPOC) at the University of Sydney, which had 345 students enrolled.

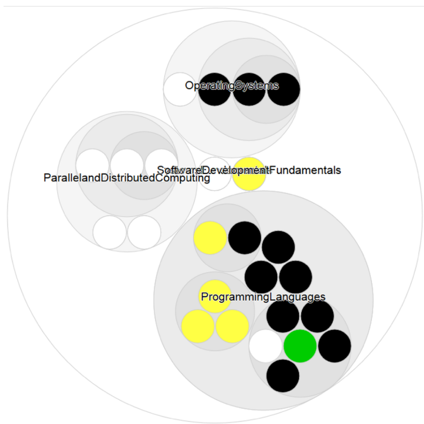
Figure 2.8a (Left) shows a simple overview of the interface that is representing one of the users. The dots are contexts of components in the Personis user model. Black dots mean that the evidence available about the learner indicates they know a component – or all the components within a context. White dots mean the evidence indicates they do not know the knowledge component or set of these that constitute a context. The interface can be zoomed in and out to move through the context hierarchy (Figure 2.8a Right).

Figure 2.8b shows how student knowledge can also be compared to a benchmark set by the teacher. This benchmark can vary over time. The figure specifically shows the benchmark compared against student performance in week 4 of the semester. The yellow dots are items that the student does not know yet but is expected to know by now. Content that the student knows ahead of the current course material is represented as a green dot.

This work is relevant to the thesis in that it provided an interface for a user to explore the ontology of their own user model, just as Chapter 7 does. However, Work by Cook et al. (2015) presented an OLM interface, called Massively Open Online Course Learner Model(MOOClm) because it was designed a a learner model for a MOOC. This enables  to create an ontology from a standard international computer science curriculum. There is not similar ontology for modelling physical activity over long-term.




**(a)** **Black** = “Known” **White** = “Unknown” (Left) Simple view – core C programming and Unix; (Right) ZoomedView concepts




**(b)** Student progress against teacher’s ideal model for Week 4 - **Black**: Alice meets targets, **Green** = Alice is ahead, **Yellow** = Alice is behind, **White** = Alice has not mastered this. Teacher did not expect students to know it at Week 4 either.

Fig. 2.8.: Screenshots from the OLM interface for the MOOClm platform. *Figure from [Cook et al., 2015],included with permission from the author(s).*

There has also been some work for broader user models (Bakalov et al., 2010) where the authors explored an interface called IntrospectiveViews, which enables the user to edit and view their user model. Unlike the previous work which presented hierarchical interfaces, IntrospectiveViews differs by displaying user interests as labels on a circular surface with coloured rings (Figure 2.9A). The closer the label is to the centre (coloured red for high interest), the higher the degree of interest to the user. The size of the font represents the frequency of the label's term gained from the user's browsing history. Similar to the work by Cook et al. (2015), the interface can be zoomed in to gain a detailed view on labels in a certain area (Figure 2.9B). Label terms can be filtered by the user and clicking on a label provides more information about it (Figure 2.9C). To determine how much importance users actually put on certain features of a scrutable user model and whether the interface was considered successful, it was evaluated with 26 participants in a user study. The results showed that participants found the interface useful for viewing their interests.

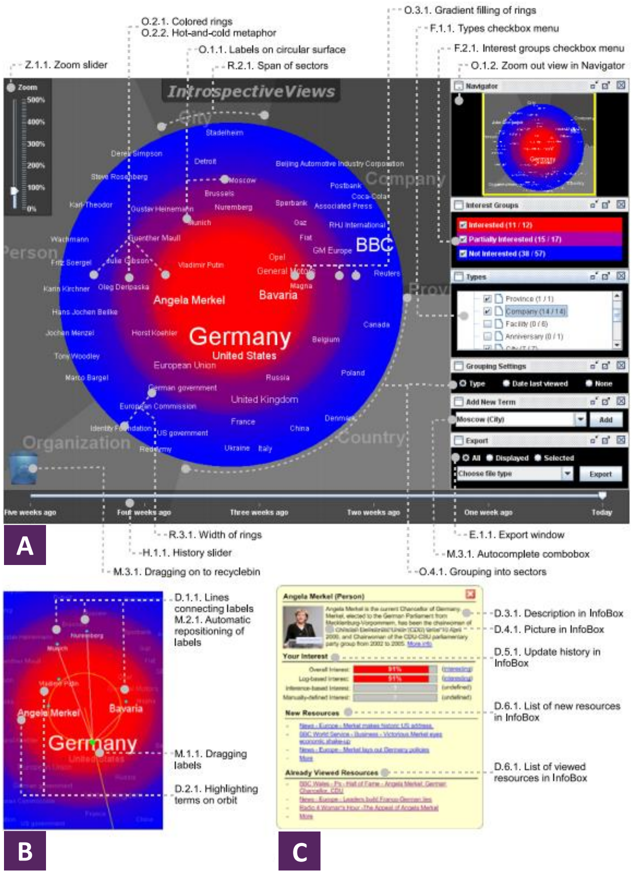



**Fig. 2.9.:** Screenshot from the IntrospectiveViews interface. (A) Main circular surface interface with labels representing user interests; (B) Zoomed in interface with a detailed view; and (C) Viewing more information about a label term.
*Figure from [Bakalov et al., 2010], included with permission from the author(s).*

Apart from interfaces that have been focused towards an education environment, there has been work that has focused on using similar systems for users to keep track of their physical activity. Work by Tang and Kay (2017) presented an interface for physical activity called iStuckWithIt (Figure 2.10). It visualises activity data collected from wearable FitBit devices in a custom calendar display, giving an overview of the years and their respective months and days. Figure 2.10A shows each day block as different colour shades based on the level of goal achievement. Users can add goals and see their current ones with questions (Figure 2.10B). As shown in Figure 2.10C, users can hover the cursor over a single day to see more information, such as total steps and hours of activity while wearing the activity tracker. A bar chart under each year gives an overview of the average hours per day that the user has worn the activity tracker (Figure 2.10D). The interface was evaluated with 21 Fitbit users with at least 6 months of data. After uploading their data they were asked to review it in the interface and were subsequently interviewed. The core findings from this work indicate that including adherence data into the design of interfaces for reviewing physical activity data can help people gain insights on their long-term physical activity even when data is incomplete.

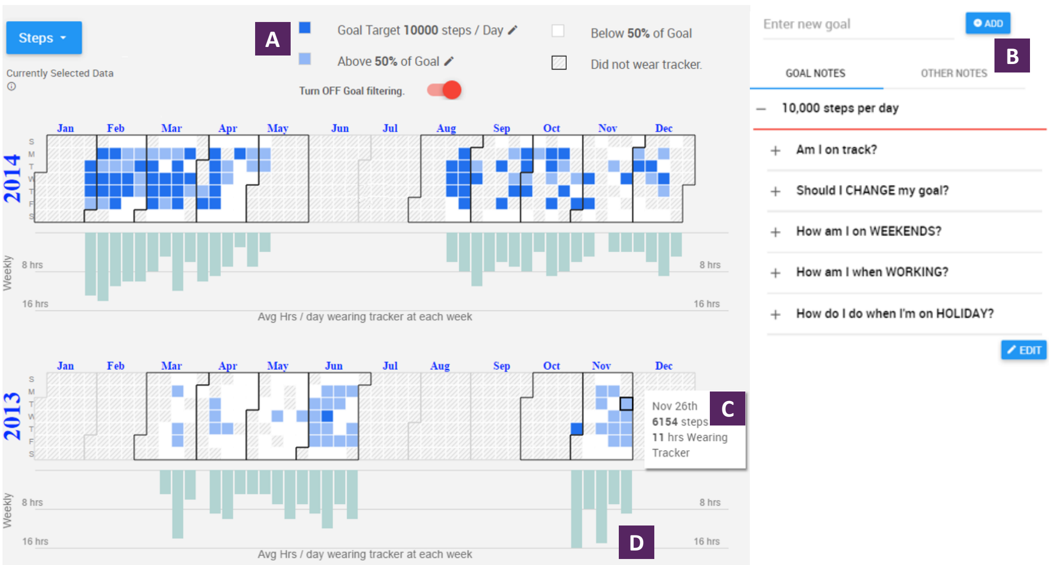



**Fig. 2.10.:** Screenshot of the iStuckWithIt model viewer interface. (A) shows the meaning of the colour shades which are used to indicate level of goal achievement for each day; (B) interface for the user to add a goal or view a current one with its associated questions; (C) hovering a cursor over single days can provide more information; and (D) bar chart of hours the user has worn the activity tracker. *Figure from [Tang and Kay, 2017], included with permission from the author(s).*

#### Summary

While the work discussed in this section is important, no work to date has explored allowing players to review their long-term data from playing VR games.

Related work on VR games and physical activity has been primarily focused towards making them more adaptive to players in order to deliver appropriate levels of exercise and be progressively more challenging to keep people engaged for longer (Hagen et al., 2016). Work by Sinclair et al. (2007) recommends taking account of both how attractive the user found the game as well as the player's physiological state, balancing the game challenge and exercise intensity. Other work by Hardy et al. (2012) used a similar model presented in a software API called Training Control. It allowed for adaptive adjustment of the training load of the exergames (time, power, heart-rate, speed, cadence) allowing the user to play at their own pre-defined level of exertion.

Additionally, playing VR games can result in different data, such as movement in the game (tracked by the VR system), gameplay elements (such as score, lives, etc), heart-rate (collected from worn activity trackers), and the player's perceived exertion. Such information could be of great interest to players so they can effectively track their progress towards their long-term fitness goals. No work to date has focused on how such data can be harnessed together in a scrutable user model for players to review.

### 2.4.4 User View of the Personis Interface

This section introduces the user view of the application used in Chapter 7. This application provides an interface for exploring Personis user models.

Similar to the interfaces discussed in the previous section, like the work by (Cook and Kay, 1994), this interface enables the user to traverse the Personis tree-hierarchy of *contexts* and *sub-contexts*, with the leaf contexts containing the user model *components*. Each component then holds the *evidence* about that component and it has *resolvers* which interpret the evidence to conclude the value of each component.

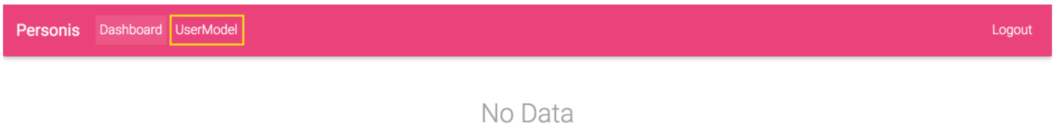
To use the interface, the user needs to first login (Figure 2.11a). They can then view their dashboard to scrutinise their long-term physical activity data.

The user can access folders (contexts) by clicking on the ones listed under the Folders heading. In Figure 2.11b, the user clicked on CARDIOPHYSICALEXERCISE context and then the VRMINUTES context within it. The user can then see the resulting screen depicted in the figure. While browsing through contexts, the user can see their depth at the top of the screen, which performs a similar function as an address bar, giving the user an idea of where they are in the model and quick access back to other context levels.

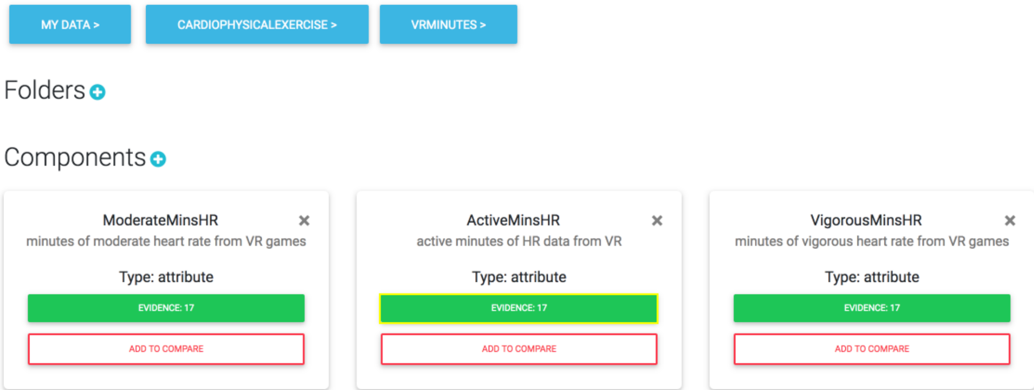
The user can view the components of the particular context below the Components heading. There the user can see brief information about the components. In Figure 2.11c, the user clicked on the green "EVIDENCE" button of the ActiveMinsHR component and can now see their active minutes in VR in the box on the right.

The interface enables users to compare the components of different contexts. The user first needs to navigate to the component they wish to compare. In the case of Figure 2.12a, the user has navigated to the DAILY context within the CARDIOPHYSICALEXERCISE context. This contains data of their daily active minute outside of VR gameplay – collected from a step counter. The figure shows a Component Comparison window popup with the ActiveMinsStep component added to the comparison. The user achieved this by clicking on the red "ADD TO COMPARE" button. The user can add their second component by repeating the above with a different component. In the case of Figure 2.12b, the user has navigated to the VRMINUTES context within CARDIOPHYSICALEXERCISE and added the ActiveMinsHR component. This appears within the Component Comparison popup along with ActiveMinsStep component. Once two components are added the user can then click GO TO DASHBOARD on the bottom of the popup. This takes them to another screen which displays a bar chart with the data from the two components they wished to compare (Figure 2.12c), ActiveMinsStep and ActiveMinsHR. This data is broken down into days to give the user a good overview of their activity over a period of time.

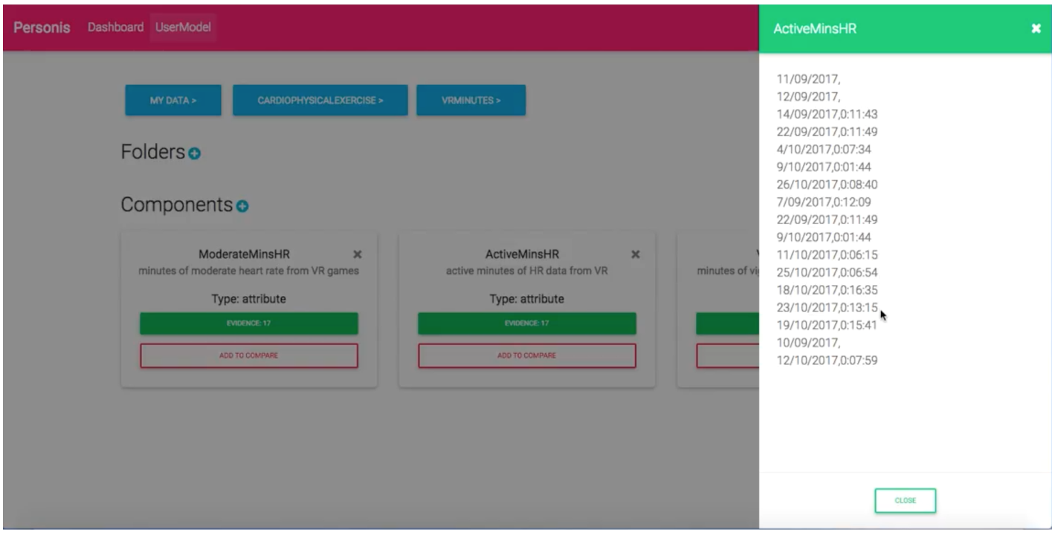
This section has given an overview of the Personis interface. The study in Chapter 7 made use of this interface, which intended to gain insights into the ways that people would and could explore their user model to answer important questions about their physical activity.




(a) Dashboard after logging in

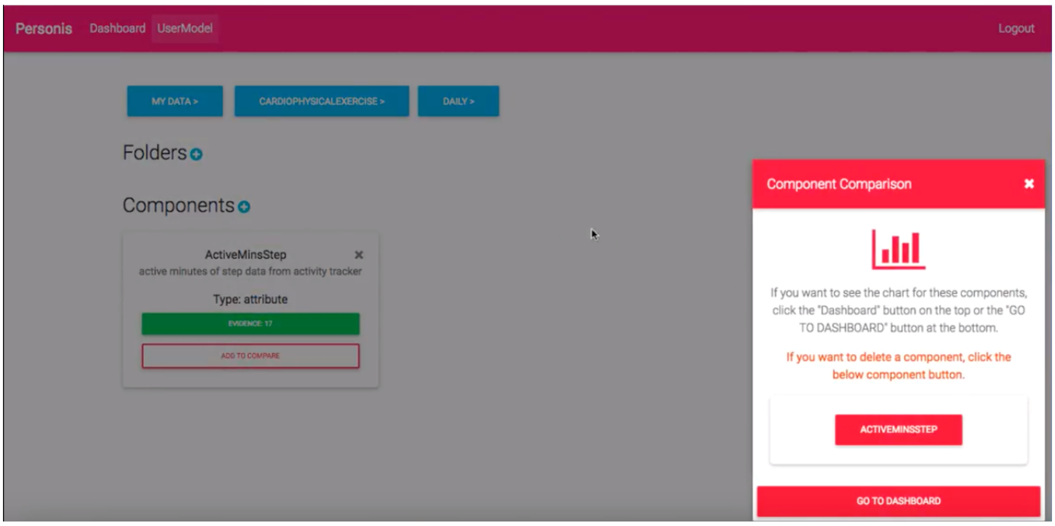



(b) Navigating contexts to find the active minutes for VR component

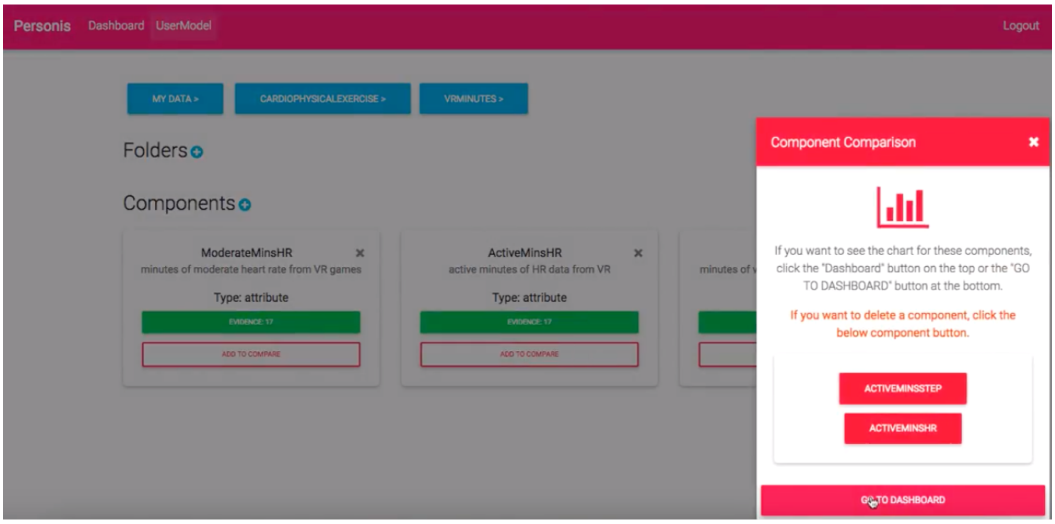



(c) Checking active minute data for VR

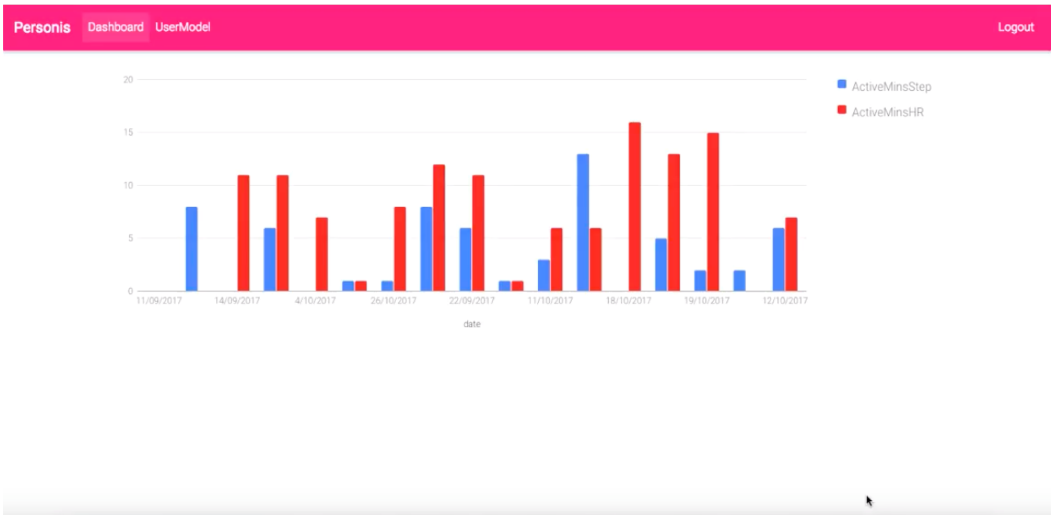
**Fig. 2.11.:** The steps the user took to explore their active minutes from playing VR games.




(a) Select the component for active minutes of incidental steps




(b) Select the component for active minutes of playing VR games




(c) Bar chart for comparing active minutes

Fig. 2.12.: Comparison of active minutes from the VR games with step active minutes; Blue: active minute step and Red: active minutes from playing VR games.

## 2.5 Summary

The work discussed in this sectionprovides a foundation for the opportunity of using VR as a tool for exercise and with that, VR experiences which aretailored to individual needs and abilities. Therefore this doctoral thesis sets out to gain further understanding of the following research gaps to answer the aim of this doctoral thesis, which is to gain understanding on how to harness commercial virtual reality (VR) games as a new way for people to gain beneficial levels of exercise.

**Understanding of how much exertion VR games can provide**
While work is starting to uncover the efficacy of VR games for exercise, more understanding is needed of the health benefits from playing VR games over short and long-term periods. There is also little work that has focused on the exertion provided by commercial VR games. The insights gained from this gap inform how people can gain beneficial levels of physical activity from playing commercial VR games.

**The need for a user model to track physical activity**
There has been little focus on giving players the ability to track the exertion gained from playing VR games to understand how much of the exertion gained contributes to their daily exertion in relation to other activities. This is important as VR games may not be their only source of exercise. Notably, there has been little work exploring how to create interfaces for users to scrutinise their own long-term user models. Particularly no work in the context of making sense of long-term physical activity data from multiple sensors such as heart-rate monitors and activity trackers for incidental steps. Additionally, no work has studied the challenges of designing user model ontologies that can enable people to scrutinise their user model to answer important questions about physical activity.

These gaps are addressed in the studies conducted for this doctoral thesis, detailed in parts I and II.

# Part I

## Exertion Provided by Commercially Available Virtual Reality Games

# 3 Evaluating the Actual and Perceived Exertion Provided by Virtual Reality Games

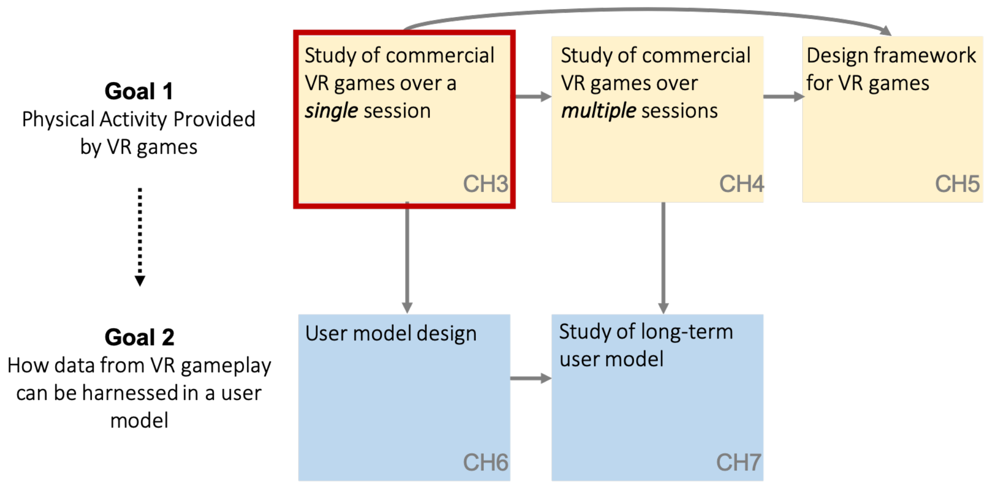



Fig. 3.1.: Structure of the relationships between this chapter (red outline) and others

This chapter[1] addresses **Goal 1** (*Explore the exertion provided by commercially available virtual reality games both in lab and authentic settings*) by exploring the perceived and actual exertion provided by four commercial VR games from Steam VR over a **single** session user study. This study collected data relating to each participant's experience and perceived exertion. Quantitative data relating to exertion was also collected, consisting of each participant's level of actual exertion, based on measures from worn heart-rate sensors. This data gave the first insights into using commercial VR games for exercise, demonstrating that they can provide beneficial levels of exertion.

[1] Following the University of Sydney's guidelines on a thesis by publication (`https://sydney.edu.au/students/hdr-research-skills/theses-including-publications.html`), a preliminary analysis documented in this chapter was published in: Soojeong Yoo, Christopher Ackad, Tristan Heywood, and Judy Kay (2017a). 'Evaluating the Actual and Perceived Exertion Provided by Virtual Reality Games'. In: *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. ACM, pp. 3050–3057

| Games | Arms | Legs | Steps |
|---|---|---|---|
| Fruit Ninja | ✓✓ | | |
| Hot Squat | | ✓✓✓ | |
| Holopoint | ✓✓ | ✓✓ | ✓✓ |
| Portal Stories:VR | ✓ | | |

Tab. 3.1.: Physical movement. ✓= Light use; ✓✓= Moderate use; ✓✓✓=Heavy use.

As shown in Figure 3.1, **Chapter 4**, builds on this one and explores commercial VR games over **multiple** sessions and branches out to discuss how VR games can be integrated into a workplace environment. **Chapter 5** utilises the data from this study to contribute a design framework for VR games to ensure they deliver just the right amount of exertion while still being enjoyable. Finally, the user model in **Chapter 6** harnesses the physical activity data from VR gameplay, collected in this study.

## 3.1 Study Design

For this study, we selected four existing VR games from the Steam VR store that supported the HTC Vive head mounted display (HMD). Three of the games, Fruit Ninja VR, Hot Squat, and Holopoint (shown in Figure 3.2) require considerable body movement. We chose each game to provide a different form of physical interaction.

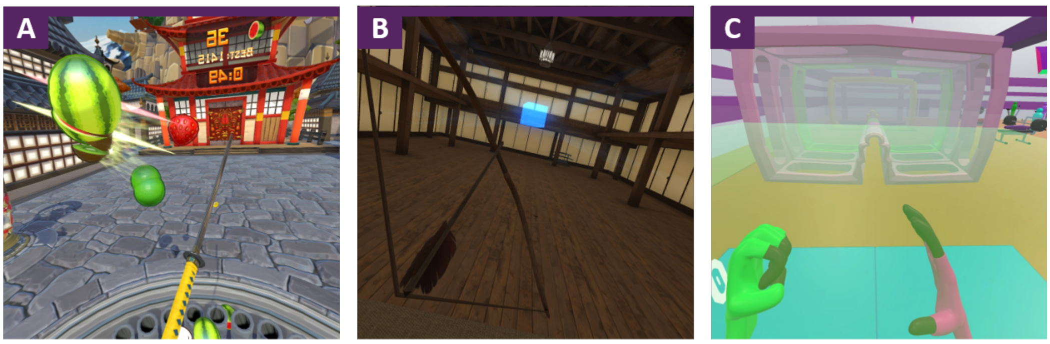



Fig. 3.2.: Screenshots of games: (A) Fruit Ninja, (B) Holopoint and (C) Hot Squat.

Table 3.1 shows this with the number of ticks indicating how much that part of the body is exerted. Broadly, Fruit Ninja involves just arms, Hot Squats, the large leg and gluteal muscles needed to squat and Holopoint has a mix. The fourth game, Portal Stories: VR, was our baseline low exertion condition; it was more of a puzzle game requiring little physical movement.

### Pre-study

We excluded participants with medical conditions that prohibit physical exertion. Participants completed a pre-study questionnaire which asked about physical health, susceptibility to motion sickness, if they do regular exercise and whether they have played exergames.

### Session

Each session ran up to one hour. Participants wore a chest strap heart-rate monitor and a HTC Vive HMD while holding the Vive controllers (Figure 3.3). Each session started with the Vive tutorial for 6.5 minutes, introducing them to VR. Then, each started their first game.

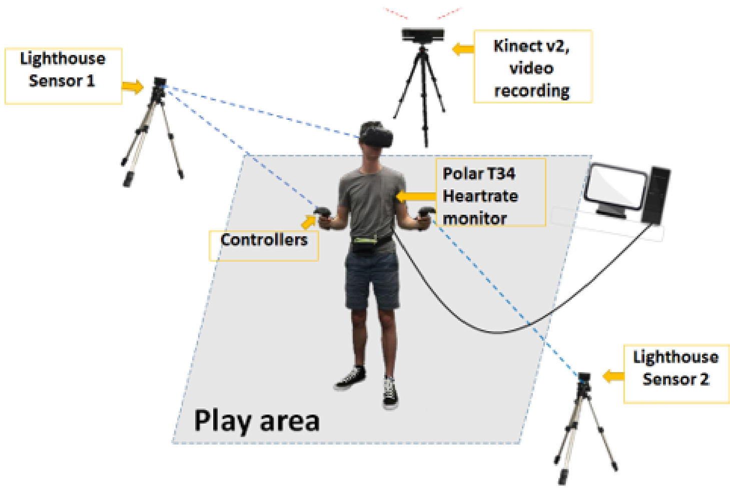



**Fig. 3.3.:** Study setup showing a person wearing the HTC Vive HMD while holding the Vive Controllers. The Kinect was used for video recording.

The order of the three exertion games (all but Portal Stories) was counter-balanced. Each game was played for at least five minutes to about ten. (We advised participants to stop if they became tired). After each game, there was a 2 to 10-minute break. In this time, participants did the Borg questionnaire(Borg, 1998; Borg, 1982) for perceived exertion then explained their score. For consistency and baseline purposes, the last game each participant played was Portal Stories: VR. At the end of the session, participants completed a questionnaire, rating their enjoyment of each game (Likert scale, from 1, very boring, to 7, high enjoyment).

| Game | Max HR % (SD) | Borg Score (SD) | Enjoyment (SD) | Time (SD) |
|---|---|---|---|---|
| **Fruit Ninja** | 66 (±7.01) | 10 (±2.99) | 5.5 (±0.97) | 10:12 (±0:16) |
| **Hot Squat** | 76 (±9) | 16 (±2.74) | 2.9 (±2.07) | 6:43 (±02:42) |
| **Holopoint** | 78 (±4.72) | 12 (±2.25) | 5.6 (±1.07) | 10:14 (±00:33) |
| **Portal Stories: VR** | 55 (±8.58) | 6 (±0.42) | 4.7 (±1.56) | 10:08 (±01:16) |

Tab. 3.2.: Physical, perceived exertion, enjoyment, and time for each game with the standard deviation (SD) in brackets. Red indicates the maximum per column.

## 3.2 Results

Our ten participants (3 females and 7 males) were aged between 18 to 37. Three exercise regularly, with others not exercising at all. Additionally, 5 had used VR before.

### Exertion

Table 3.2 summarises the exertion results, as an average from all the participants, and the standard deviation. The rst column shows the average heart-rate as a percentage of the maximum heart-rate (calculated by subtracting the participant's age from 220). We use this measure to make the heart-rate comparable across the participants. Next is the Borg average, followed by the average enjoyment rating, and finally the average time spent on each game.

Figure 3.4 shows the average individual data for each participant for each game. The y-axis shows the percentage of the maximum heart-rate in blue and the red line shows the corresponding mapping of the Borg score (Borg, 1998).

Fruit Ninja's Max heart-rate was equal to light exercise (Table 3.3), with the average Borg rating 10, indicating lower perceived than actual exertion. Figure 3.4 shows that this is accounted for by four participants (6, 7, 9, 10). Notably, P7 had the largest gap; they explained this rating as follows: "*Fruit Ninja did nothing on my arms*" and "*It provided no exertion at all as I did not have to utilise my whole arm*".

Hot Squat has a perceived heart-rate of 16, which is considered heavy (Table 3.3). Furthermore, Table 3.2 shows the heart-rate percentage was 76, which is moderate

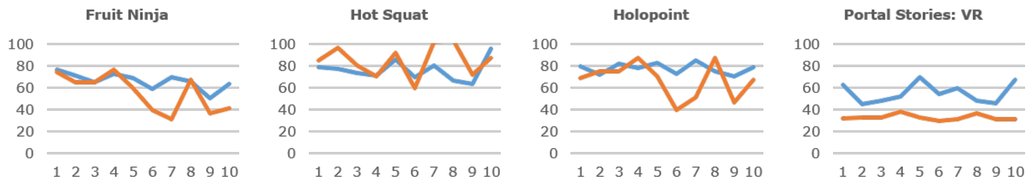



Fig. 3.4.: Heart-rate and Borg RPE data charts. Blue line = Heart-rate; Red line = Borg RPE. The reason that the Hot Squat results seems to be cut off is that the participant's perceived exertion was higher than their max heart-rate (P8

| Intensity | Max HR % | Borg Score |
|---|---|---|
| No exertion | 20 - 39 | 6 - 7 |
| Very light | 40 – 59 | 8 - 10 |
| Light | 60 – 69 | 11 - 12 |
| Moderate | 70 – 79 | 13 – 14 |
| Heavy | 80 – 89 | 15 - 16 |
| Very Heavy | 90 – 99 | 17 - 18 |
| Maximal | 100 | 19 - 20 |

Tab. 3.3.: Mapping of intensity classification to heart rate as %-age of maximum heart rate and Borg Score.

intensity (Table 3.3). This is the only game where participants stopped short of the 10 minutes. Table 3.2 shows that the average was just under 7 minutes. This is because they were tired. This was due to the particular muscles involved in doing squats, rather than cardio-vascular exertion our heart-rate measures. This is consistent with Figure 3.4 which shows that 8 participants rated the perceived exertion higher than the actual measure and P7 and P8 rated it over the 100% score (102%, 103%). Only P6 and 10 rated it lower; notably, they were two of just three participants who played the full 10 minutes in this game. Also, they stated that they thought the game was too simple and saw it as just exercise.

Holopoint's heart-rate measure of 78% is moderate intensity (Table 3.3) . However, the perceived intensity is only 12, which is light intensity, reflecting that this games' perceived intensity due to just the cardiovascular exertion measured by heart-rate. Additionally, the %-age of maximum heart-rate was quite similar to Hot Squat but Hot Squat's perceived exertion (Borg score) was higher. Furthermore, we observed that participants playing both Holopoint and Hot Squat breathed heavily and were visibly sweating.

Portal Stories had the lowest exertion measures, as expected. The heart-rate maps to very light activity (Table 3.3) and the Borg score to no exertion. The Figure 3.4 picture is strikingly different from the other games, with perceived exertion consistently below the actual heart-rate measure. Additionally, a t-test revealed that there is a significant difference.

### Enjoyment

We now consider the third column in Table 3.2. We asked about enjoyment of the games since this is important for interpreting perceived exertion. We expected that people will not perceive exertion as much if they are enjoying the game. All but Hot Squat have similar scores, around 5 on a scale of 7. Hot Squat scored lower, with the greatest standard deviation. One participant enjoyed Hot Squat because he found it good exercise. Another found it rather simple, not making good use of the VR platform. This reflects the fact that Hot Squat does not take advantage of the HTC Vive's advanced 'room scale' tracking as it is a simple game where the player needs only to stand in one position and duck (squat) under obstacles that come from one direction

By contrast, Holopoint was designed to use every direction of the space and utilized more of the body than the other games in our set. In addition, it provided a good experience with one participant comparing it to "*doing archery in real life but better because it required me to move around and shoot targets in 360 degrees, something that is not possible at a range*" and "*it made me feel like Legolas from Lord of the Rings*". Another participant explained that they preferred Holopoint over Hot Squat as it "*was more fun and felt like I was in the Matrix. Hot Squat on the other hand was boring*".

Fruit Ninja was rated highly in terms of enjoyment. Participants enjoyed Fruit Ninja as it had fine grain controls and "*it's got things people can relate to: Fruit Ninja aspect, as some people might think it's cool to be a ninja*". In addition, participants considered it one of the easiest games to play for someone who is not proficient at playing games.

Two participants (P7, P8) particularly enjoyed Portal Stories: VR for its storytelling and use of environment queues "*it was like the narrator knew exactly my physical presence no matter where I went*". Another participant commented that "*I think the teleportation thing is pretty awesome*".

### Post-study follow up results

The day after each session we collected feedback from participants by email. Every participant reported they had mild, delayed onset muscle soreness (DOMS), in their gluteal muscles and legs the next day, regardless of whether they regularly exercised. Additionally, all participants said that they enjoyed the experience overall, such as one participant who said that it "*encourages people like me to do some exercise*".

#### Gameplay

In Holopoint, every participant was bothered by the HMD cable, "*Holopoint was a fun game but the cables often got in my way*". This cable was also disconnected twice when participants became entangled. This was not a problem for Hot Squat, where the cable ran down the participant's back while they were squatting; some mentioned this, indicating it was as slightly distracting and affected the feeling of immersion.

#### Motion Sickness

Only one participant (P2) experienced motion sickness in each game. P2 had no VR experience. This did not impact the time they spent in each game, however he later mentioned he tend to suffer from claustrophobia. This suggests future studies should use this as an exclusion criterion.

## 3.3 Implications

There are three main implications from this work.

1. If VR games are engaging like Portal Stories VR, then the perceived exertion may be low compared with the actual exertion, and there is still some physical exercise benefit. This was true for both low exertion games, like Portal Stories VR and for the higher exertion games.
2. Existing VR games can provide enough exertion to be considered exercise, as Fruit Ninja's Borg score is comparable to walking, while Hot Squat's to running, and Holopoint to dancing (Borg, 1998).
3. It would be valuable to establish exercise ratings for VR games, based on studies like ours which used heartrate as an objective measure of cardiovascular exertion, along with coding the forms of exertion in terms of muscle groups, as we did in Table 3.1.

We note that these games could easily be made more challenging if people wore weights. It may also be valuable to use heart-rate measures to enable people to see their actual exertion levels. This is an interesting future direction to explore.

## 3.4 Conclusion and Future Work

In this chapter, we explored the potential of VR games for providing exercise. We conducted a laboratory study evaluating four existing HTC Vive games with 10 participants, measuring perceived and actual exertion levels. The results from this study point towards VR being able to deliver enough exertion to be considered exercise. In addition, we chose games with diverse exertion demands. This suggests that an important future direction is provide standardised exercise gradings for the growing body of VR games so people know what interactions and muscle groups are involved, how much exertion they can expect, and how make their games a valuable part of their broader physical activity.

The study is not without limitations. As it was a single session study, we could not gain an understanding of how these VR games affected individuals over a period of time. The small sample size, setup and games may not be fully representative. Therefore, future work should extend this work further with a larger scale, multiple session study.

# 4 Embedding a VR Game Studio in a Sedentary Workplace - Use, Experience and Exercise Benefits

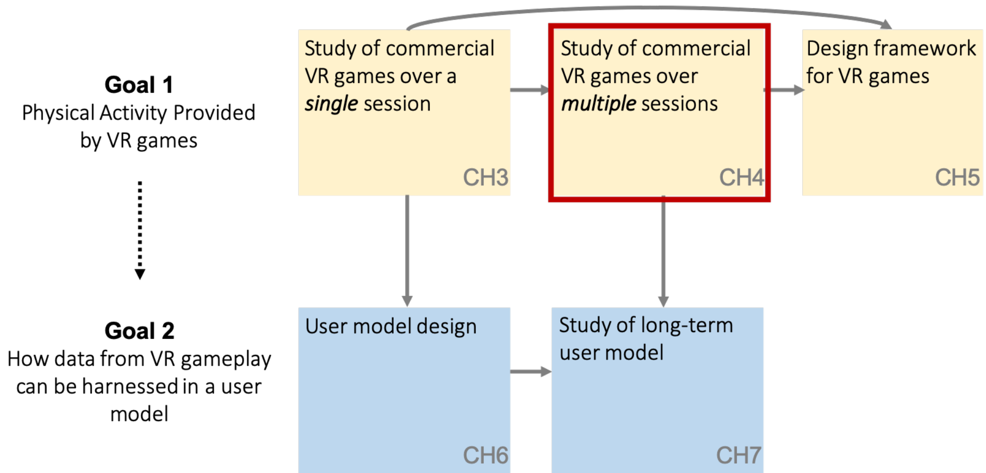



Fig. 4.1.: Structure of the relationships between this chapter (red outline) and others

The chapter[1] provides further insights towards **Goal 1** (*Explore the exertion provided by commercially available virtual reality games both in lab and authentic settings*). It explores the exertion and experience gained by playing current commercial VR games over **multiple** sessions, building on from the single session study presented in **Chapter 3**. This study was also theoretically motivated by the health risks facing workers who work within office environments (Owen et al., 2009; Biswas et al., 2015; Hamer and Stamatakis, 2014; Voss et al., 2014; Mouchacca et al., 2013; Hamer et al., 2014), which often require a lot of sitting due to computer-based work (Smith et al., 2015; Niven and Hu, 2018). To mitigate the risk of health problems caused by sedentary jobs, it is recommended that people take regular breaks from

[1]Following the University of Sydney's guidelines on a thesis by publication (`https://sydney.edu.au/students/hdr-research-skills/theses-including-publications.html`), a preliminary analysis documented in this chapter was accepted in: Soojeong Yoo, Phil Gough, and Judy Kay (2020). 'Embedding a VR Game Studio in a Sedentary Workplace - Use, Experience and Exercise Benefits'. In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM

sedentary activities (Healy et al., 2008). Fitting a physical, active break into the working day can also lead to more productive work, due to improved cognition (Coulson et al., 2008). Even when workers recognise this, many believe that they cannot find time for exercise without impacting their productivity (Niven and Hu, 2018). However, these breaks do not need to take a lot of time as research has shown that exercising for short bursts of as little as 10 minutes a day can have physical health benefits (Osei-Tutu and Campagna, 2005; DeBusk et al., 1990; Haskell et al., 2007). Exergames, which are designed to combine video games and exercise, have potential at being used for such short bursts of exercise, providing both physical and cognitive benefits (Gao and Mandryk, 2012). However, games do not necessarily need to be designed for exercise to provide beneficial levels of exertion. As shown in the previous chapter (Chapter 3), VR games can lead to players experiencing high levels of exertion while perceiving a much lower level due to being so fully immersed within the virtual world (Bolton et al., 2014; Yoo and Kay, 2016; Yoo et al., 2017a).

These results seem promising for helping people in sedentary workplaces gain valuable benefits from short periods of playing VR games, by taking work breaks. However, this has not been previously explored. Therefore, we set up a VR game studio in a sedentary workplace and designed a study to gain insights into the ways people use it and the physical exertion that they gain. We aimed to answer the following two research questions:

1. *What health benefits do participants gain from VR game studio sessions?*
2. *What motivates participants to use the VR game studio and how to they use it*

Our VR game studio was equipped with an HTC-Vive VR system. Over 8 weeks, 11 participants used it to play commercial VR games, from the Steam platform. For RQ1, we asked participants to rate their *perceived* mental and physical fatigue before and after each session and we measured *actual* exertion (based on heart-rate) and compared this with their step count activity measured by a smartwatch activity tracker that they wore for 8 weeks. For RQ2, for each VR game studio visit, we asked participants to tell us why they came. We tracked the details of the games played and analysed the changes over 8 weeks.

The data from this study, gained from physical activity sensors (such as a smartwatch for incidental daily steps and heart-rate monitor for gaining heart-rate during VR gameplay), informs **Chapter 7**; which uses the data from this study to design and build a user model that harnesses physical activity data from multiple VR gameplay sessions and other incidental sources, such as walking.

## 4.1 Study design

This section first describes the set up of the VR game studio, including how we chose the games. Next is the design of the overall study with data sources that we collected. This study was undertaken under ethical approval (ID 2016/089).

### 4.1.1 VR Game Studio Setup

Fig. 4.2.: VR game studio room set up with a play area of 2.5 x 3.5 metres, marked with yellow tape.

We made use of a dedicated room (Figure 4.2) approximately 2.5 x 3.5 metres. We mounted two base station sensors on tripods at opposite corners of the room, approximately 2 metres from the floor. These sensors tracked the user's position in the physical space. In all sessions, users wore the Polar H7 heart-rate monitor and we calculated their level of activity (light, moderate, vigorous) based on the actual heart-rate as a percentage of theoretical maximum, accounting for age. This is widely used in informal testing outside academia (Stanton, 2016; Nafarrete, 2016) and has been validated against medical-grade devices (Cheatham et al., 2015; Plews et al., 2017).

### 4.1.2 Game Choice

We short listed five commercial VR games for the HTC Vive HMD from Steam. Several factors informed their selection. Firstly, we chose three games (Hot Squat, Fruit

Ninja and Holopoint) based on previous research that demonstrated they enabled people to gain relatively high *actual exertion* compared with their *perceived exertion* (Yoo et al., 2017a). We then selected two more, Holoball and Longbow, based on analysis of online discussion boards and recommendations to identify popular and appealing games. We also trialled games to make this selection. To meet the goals for exercise, we selected games with diversity in the level and form of exertion in terms of the main muscle groups used. Table 4.1 characterises the games in terms of how much they exert the upper body exertion and the larger lower body muscles that generally give higher levels of exertion. The table shows the level of exertion we would anticipate each game to be. For example, Hot Squat involves just squats, making heavy use of the large lower body muscles and so requires high exertion. In addition, we chose 5 games so that participants had some choice but also to have a small set of games so that we could more readily compare participants' choices. We also chose games that are quick to learn. We now briefly describe the games.

| Game | Upper | Lower | Anticipated Exertion |
|---|---|---|---|
| Hot Squat | | ✓✓✓ | High |
| Fruit Ninja | ✓✓ | | Low |
| Holopoint | ✓✓ | ✓✓ | Between Moderate and High |
| Holoball | ✓✓ | ✓✓ | Moderate |
| Longbow | ✓✓✓ | | Low |

Tab. 4.1.: Level of physical movement for upper and lower body (✓= Light; ✓✓= Moderate; ✓✓✓= Heavy) and a summary of the anticipated exertion based on the number of checkmarks

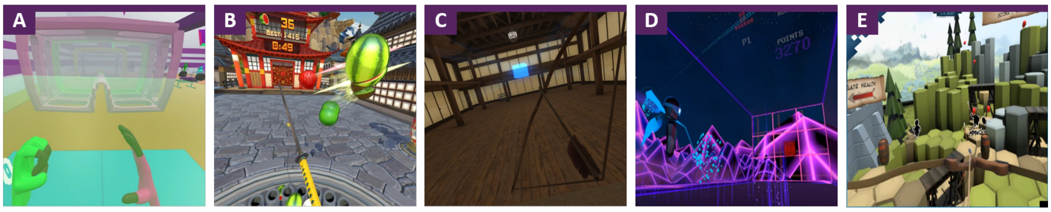



Fig. 4.3.: Screenshots of the VR games used in this study: (A) Hot Squat, (B) Fruit Ninja, (C) Holopoint, (D) Holoball, and (E) Longbow.

***Hot Squat (Figure 4.3A).*** The player **stands still** while a series of barriers move towards them. Players must **squat** to duck under the barriers and must then stand up again between barriers. As the game progresses, the barriers move faster and the distance between them decreases, forcing the player to squat faster. Playing for 10 minutes gives a similar level of exertion as *running* (Yoo et al., 2017a).

***Fruit Ninja VR (Figure 4.3B).*** This game involved mainly **arm movement**. The player holds a virtual samurai sword in each hand. Fruit flies into the air in front of the player, who must slice as much fruit as possible. Playing for 10 minutes gives a *walking* exercise level (Yoo et al., 2017a).

***Holopoint (Figure 4.3C).*** The player **holds** a virtual bow in one hand while the other hand draws arrows from behind the player's head. Enemies appear all around the player. The enemies must be shot with the bow and arrow and upon being hit will launch a projectile at the player, which the player must either **side-step** or **duck under** to avoid being hit and losing the game. Playing for 10 minutes provides similar exertion to *dancing* (Yoo et al., 2017a).

***Holoball (Figure 4.3D).*** Holoball is a sports game, similar to tennis or squash. Players use their paddles to hit, smash and curve the Holoball past the AI's shield to increase their score. This game involves **arm movement** to hit the ball and **leg movement** as the player need to move sideways.

***Longbow (Figure 4.3E).*** This is one of the demonstration games from Valve for the HTC Vive. The player must defend their castle gate, using a bow and arrows, as a horde of cartoon attackers appear at the gate at an increasing rate. This requires a lot of **arm movement** especially as the game levels increase, meaning the player has solid use of their arms.

### 4.1.3 Study Procedure and Data Collection

Figure 4.4 summarises the elements and timeline of the study and what data have collection methods. We now describe the design of each of these.

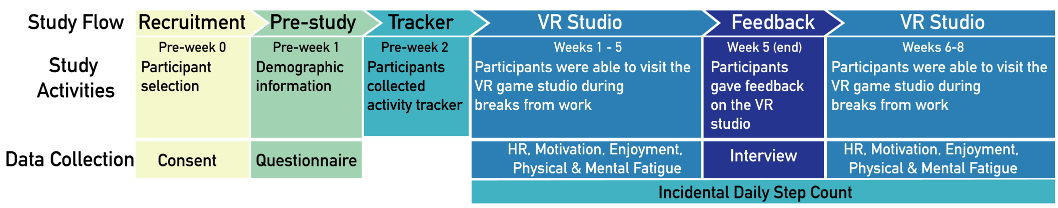



**Fig. 4.4.:** Study flow for the study and data collection methods.

#### Recruitment

We sent an email invitation to University mailing lists to recruit potential participants. To be eligible, participants needed to have a sedentary job at a workplace and their workplace had to be in walking distance from the VR game studio. This meant they worked in the same building as the studio or in a nearby building. We recruited 11 participants, all with highly sedentary occupations. The number was restricted so as to ensure that the VR game studio could be scheduled to fit participants' preferences and availability.

### Pre-study and screening

Those willing to participate were sent a questionnaire and a Participant Information Statement, explaining the study, including its duration, that participants would be asked to wear an activity tracker and they should want to come to the studio and play games as a work break. We suggested that they should want to come at least once a week over the 8 weeks of game play.

Potential participants then completed a questionnaire about gender and a set of screening questions on: age group (18-29, 30-49, and over 50); physical health; and susceptibility to motion sickness, claustrophobia, vertigo, epilepsy, and seizures. We only accepted those under 50 (to avoid any potential risks associated with age) and free of health problems and the other aspects that may have caused them to be unwell during VR gameplay.

### Activity tracker

After the pre-study and screening, we invited eligible participants to meet the researcher in VR game studio to collect their activity tracker. We offered each a Pebble Watch 2[2]. Of the participants, nine agreed to wear use this. The researcher showed them how to send their step-data to the server with our custom Pebble Watch app (pre-installed on each watch). Two participants preferred to use their own Fitbit Charge 2[3] and they sent us their data manually. Both devices recorded participants' steps at 1-minute accuracy. We needed this to calculate the number of moderately active minutes as those with at least 100 steps per minute. We needed this to calculate the number of moderately active minutes (100 steps per minute) and vigorous minutes (120 steps per minutes) **haskell2007physicalA**.

Next, we introduced the VR games explaining what part of the body each game most works out. Participants were also advised to wear comfortable shoes, ideally ones that for sports or exercise. This was also a requirement of our ethics approval but it was in line with typical dress in this workplace. Also, we asked them to avoid

[2]https://www.pebble.com/pebble-2-smartwatch-features
[3]https://www.fitbit.com/charge2

eating a heavy meal or drinking for at least an hour before coming into the VR game studio.

### Scheduling

To schedule the studio, we created a shared Google spreadsheet. This meant participants could book their sessions in advance, in one-hour blocks between 9am and 7pm on workdays. Participants were invited to book any free slot up to an hour beforehand. This approach meant participants could get an overview of the times available and have flexible options to schedule their slots to fit in with their work (Olsen et al., 2018).

### VR game studio session (week 1-5)

Our ethics approval required that the researcher be present for all times participants used the studio. This was to ensure that help was available if any participant became unwell. Each session began with the participant putting on the Polar chest heart-rate monitor. They then sat for a minimum of two minutes so that we could measure their resting heart-rate (Haskell et al., 2007). We used this to assess changes in heart-rate with exertion. In this time, the researcher asked each participant:

- to rate how mentally and physical fatigued they felt on a scale of 1 to 7 – where 7 is extremely tired (see Appendix A.7 for interview questions that were adapted from Barte et al. (2017) and Beurskens et al. (2000));
- to answer an open question about what motivated them to come for that session;
- what game they wanted to play and an open question about why they chose that game.

Each participant played their chosen game until they wanted to stop. Then, they sat down and answered questions:

- to again rate how mentally and physically *fatigued* they felt on the same 7-point scale as earlier;
- to rate their *enjoyment* of the game on a scale of 1 to 7 (7 is high enjoyment);
- an open invitation for free comments.

Since the questions at the start and end of sessions were asked at each session, we kept them minimalist so they were quick and easy to answer but also allowed participants to make any comments they wished to.

#### Feedback

After the first five weeks, we asked participants for feedback on any aspect that they felt would give them a better experience. One of the most common requests was to see how they were performing compared to the other participants with a leader board as is typical in game contexts. Other comments included a room to change clothes, a hygiene mask for the HTC Vive HMD, and refreshments to eat after playing. We acted on each of these for the remaining 3 weeks.

#### VR game studio session (week 6-8)

The main change for this period was the introduction of a *leaderboard*. This was on a whiteboard showing the top 3 players in each game, manually written and updated by the researchers. We also provided water, chocolate for refreshment and alcohol to wash the mask after each use.

## 4.2 Results

This section first presents participant background information. Then we present analyses, starting with those for exertion, then the motivations to come and use of the studio, followed by other benefits.

### 4.2.1 Participants

Table 4.2 shows the participant demographics. Our workplace is a University and all participants had sedentary jobs: 2 University employees (E); 6 full-time postgraduate research (PG) students; and 3 final-year undergraduate thesis students (UG). Each worked within 5 minutes walk of the VR game studio. Participants were all healthy and most were young, aged $22 - 46$ (mean 29.3). There were 2 women and 9 men, in line with the gender balance in our workplace. Some participants already knew each other (P1, P3, P4, and P7) but most had not met before the study. Five participants did no regular exercise. The other 6 reported exercising at least once

| | Age | Occupation | Gender | Exercise (# times per week) | VR experience |
|---|---|---|---|---|---|
| **P1** | 46 | E | M | Soccer (1) | ✓ |
| **P2** | 23 | UG | M | No | No |
| **P3** | 37 | PG | M | No | ✓ |
| **P4** | 34 | PG | M | Dance (1) | ✓ |
| **P5** | 26 | PG | M | No | ✓ |
| **P6** | 37 | PG | M | Gym (2) | ✓ |
| **P7** | 36 | PG | M | No | ✓ |
| **P8** | 22 | UG | F | Run(1) | No |
| **P9** | 32 | E | M | No | ✓ |
| **P10** | 32 | PG | M | Commuting by bicycle (5) | No |
| **P11** | 22 | UG | F | Run (1) | ✓ |

Tab. 4.2.: Participant background information - age, occupation (E= employees, PG= postgraduate research students, UG= undergraduate thesis students), gender, regular exercise per week, and VR experience.

a week, with activities such as soccer, dancing, gym workouts, running, or riding a bicycle to work. Eight participants had experience with VR, either for watching videos or playing games; the other three had never used it before.

Most participants tended to book the studio at similar times for each visit: 2 favoured early visits, usually 9-11am; 2 at lunchtimes; and 4 mainly came after 3pm. The other 3 came at varying times of day.

### 4.2.2 Physical Activity

We now summarise the physical activity participants did in the game studio and how much this contributed to their activity measured by the step tracker.

#### Physical activity from playing VR games

We calculated active minutes from the participants daily steps, combined with the active minute from the heart-rate date from VR studio. We used the different tools for measuring physical activity as measuring HR in the studio indicated various devices were not as accurate as the chest strap.

Figure 4.5 summarises the exertion from each game. The heart-rate measurements indicate that the VR gameplay contributed valuable levels of exertion towards the recommended 30 minutes of moderate activity most days (or 15 minutes of vigorous activity) (Haskell et al., 2007)). Vigorous activity is described as activities like jogging at 9.5 km/h (6mph) where moderate activity is a brisk walk (Harvard School of Public Health, 2018).

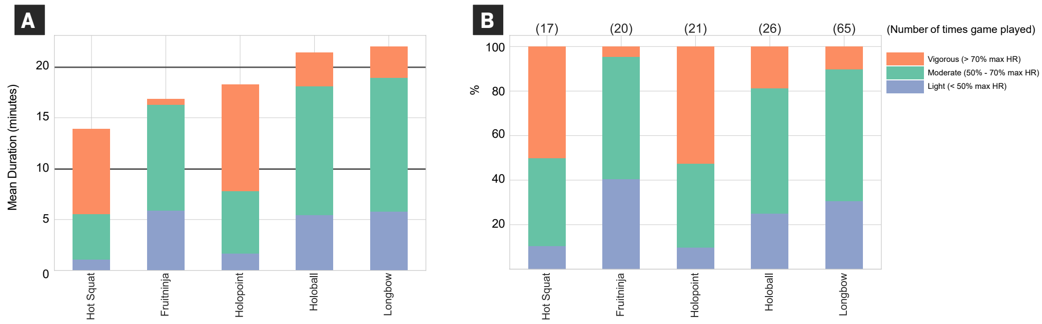



**Fig. 4.5.:** Mean exertion levels for each game: Vigorous (red), moderate (green) and light activity (blue). **A**: mean number of minutes at each activity level for each game; **B**: the same data, now as proportions of the total play time (number of times each game was played at top)

Figure 4.5A shows the average time people played each game, with the average Hot Squat game lasting 13.9 minutes. Each bar is coded to show the split of light physical activity (blue) moderate (green) and vigorous (red) minutes. All the games provided enough physical activity to elevate the participant's heart rate to achieve moderate (between 50% and 70% of theoretical maximum) and vigorous (> 70% of theoretical maximum) exercise (Haskell et al., 2007). In fact, the figure shows clearly that for all games, the play time was dominated by the green and red of moderate or vigorous activity.

Figure 4.5B shows the same data, now normalised to make it easier to compare the proportion of game time at each level. Hot Squat and Holopoint stand out as giving the highest proportion of vigorous activity. This figure shows that all games provide a quite efficient use of time to get valuable levels of exercise. All games had a large proportion of play time giving at least moderate activity. Even the least efficient, Fruit Ninja in the second bar, had 65% of the time giving at least moderate exertion.

The standard deviations for total duration of the games was high, at 9 minutes for Hot Squat and 10 minutes for Longbow. This is notable, particularly for Hot Squat, as the maximum duration for a participant to play Hot Squat was 37 minutes and 45 seconds (P11): for a person to do squats for this amount of time is quite remarkable. Participants did not re-play Hot Squat on visits on consecutive days. We focus on cardiovascular exercise (measured by increased heart rate), but extensive playing of Hot Squat would provide strength-building benefits that were out of the scope of our study.

### Contribution of VR exertion to overall exercise

The number of active minutes is calculated from recorded data: moderate activity (100+ steps per minute from watch, or heart rate over 50% of theoretical maximum during VR session) is one active minute; and vigorous activity (120+ steps per minute from watch, or heart rate over 70% of theoretical maximum during VR session) counts as two active minutes. Table 4.3 shows the VR activity and steps activity. The green background is participants who gained more than half their active minutes from the VR game studio. The green text is the 4 participants pushed above 30 minutes of moderate physical activity on the days that they visited the VR studio.

| | Moderate Activity Equivalent (average number of minutes) | | | | |
|---|---|---|---|---|---|
| Participant | VR | Steps | Total | From VR | Incidental Steps |
| P1 | 16 | 25 | 41 | 39% | 10559 |
| P2 | 25 | 39 | 64 | 39% | 7598 |
| P3 | 28 | 4 | 32 | 88% | 4260 |
| P4 | 10 | 3 | 13 | 77% | 5884 |
| P5 | 5 | 20 | 25 | 20% | 5557 |
| P6 | 20 | 46 | 66 | 30% | 10874 |
| P7 | 40 | 13 | 53 | 75% | 6062 |
| P8 | 39 | 29 | 68 | 57% | 9914 |
| P9 | 27 | 22 | 49 | 55% | 7783 |
| P10 | 13 | 9 | 22 | 59% | 6039 |
| P11 | 20 | 27 | 47 | 43% | 7512 |

Tab. 4.3.: Summary of the contribution of the exertion in the VR lab, compared with activity measured by the step counter. Coloured highlighting indicates participants with more than half the total from VR gameplay. Red text marks participants whose step activity put them below 30 minutes moderate activity but the VR game activity took them above it.

It is clear that several participants (P3, P4 and P10) get low levels of moderate activity from incidental activity. However, as noted in Table 4.2, walking and VR studios were not the sole sources of activity; as for with P10, who commutes by bicycle. We do note that our data does not take account of activity not detected by the step counter. Only 2 of our participants (18%) average 30 active minutes a day without the VR studio (P2 and P6), with another three coming close (P1, P8 and P11), at 25 minutes on more, a total of 45%.

Figure 4.6 shows another analysis in terms of the number of days a week participants achieved 30 minutes of activity. At the left, we use the step data only and this shows that 5 participants averaged 0 days a week and 4 more averaged only 1 day a week. At the right we show the impact of the VR lab with green dots showing people who changed up a category. Now, only 1 participant has 0 days a week, 4 have moved up to once a week, 4 more to twice week and one has moved to 3+ per week. This is still short of the recommendation to get 30 minutes most days to make a total of 150 minutes, but shows potential for another source of physical activity.

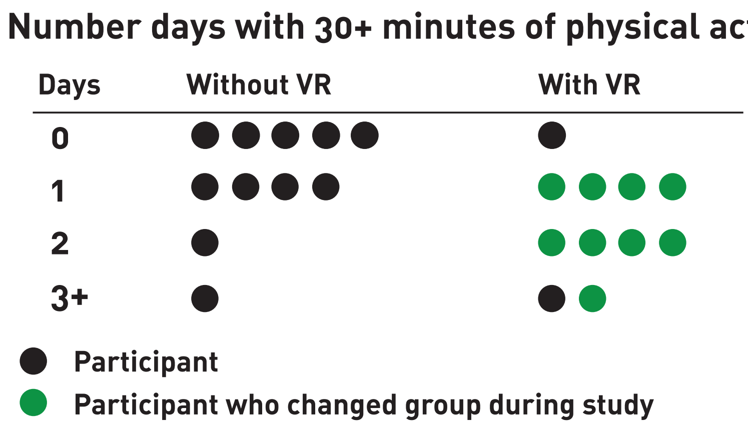



**Fig. 4.6.:** Change in the number of days per week that participants achieved at least 30 minutes of physical activity.

Figure 4.7 demonstrates that, from incidental steps, only two participants averaged 30 minutes of physical activity, but four participants (P3, 7, 9 and 11, as shown in green text in Table 4.3) achieved the 30-minute threshold on days when they came to the VR studio. Figure 4.7 also shows that of those who achieved more than 30 minutes of exercise on days when they came to the VR studio (VR + Steps), half achieved more than 50% of their active minutes from the VR games for that day.

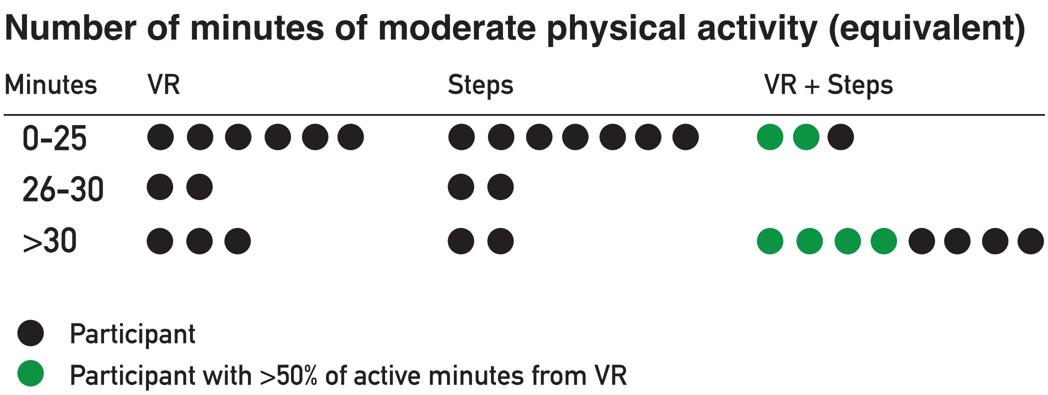



**Fig. 4.7.:** The number of active minutes from VR, incidental steps and combined

### Summary

Our analysis indicates that the VR game studio provided a time-efficient way to get at least moderate levels of exercise. Our comparisons of the exertion from the VR game studio with that from daily step counts indicates that the VR game studio makes a valuable contribution for most participants. It can provide a substantial proportion of moderate activity, which is a valuable contribution towards meeting the recommended levels people should aim to achieve on most days.

## 4.2.3 Motivation to Visit to the VR Game Studio

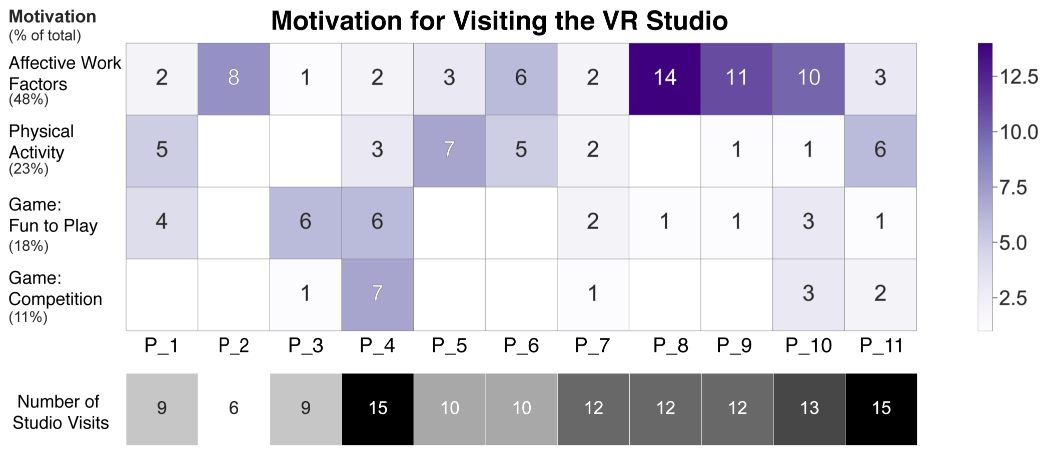



**Fig. 4.8.:** Summary of the main reported motivation for coming to each VR game studio session (purple). Total sessions are (grey) are the bottom row. Some participants gave multiple motivations in a single visit. The very infrequent responses are not included

We wanted to understand why participants came for each lab visit and asked about this at the start of each session. This resulted in 141 responses, which were collected on post-it notes. One researcher then clustered these in an affinity diagram (Holtzblatt et al., 2005), grouping them to identify key themes. These were reviewed by two other researchers in the team to reach a consensus on the grouping and theme identification.

Table 4.8 shows the results. The labels at the left show the four main themes that emerged. We describe them as (1) Affective Work Factors, (2) Physical Activity, (3) Game: Fun and Play, and (4) Game: Competition. The first column of the table shows the number of comments in each of these.

The bottom row of the table shows the number of visits for each participant. Six participants attended the studio more than 10 times (P4, P7, P8, P9, P10 and P11). P2 attended only six sessions, as their plans changed towards their deadline.

The strongest motivation was clearly the *Affective Work Factors* (62 responses), with sub-categories in order of frequency being: to take a break from the work (31); for relaxation (18) gaining motivation to work (13). Somewhat surprisingly, these *Affective Work Factors* were far more important than either the game aspects or physical activity. It seems that the VR game studio primarily provided participants a welcome break from work, with participant comments like: *“it was good to come and have a break”* and *“I found that after the study that I can focus on my work better.”* Figure 4.8 shows that the *Affective Work Factors* are the only motivations mentioned by every participant, with all but P9 mentioning it at least twice.

Notably, five participants came for *Affective Work Factors* at least 6 times (P2, P6, P8, P9, P10), with P8 mentioning it 14 times (including multiple sub-categories at the same session). Also notable is P2, had had this category as their only responses - twice as "break from work", twice as "relaxation", and twice as both "relax" *and* "break from work".

The two next most common themes were *Physical Activity* (23%) and *Game:Fun to Play* (18%). These were mentioned by 8 participants, with 5 of them mentioning both. *Physical Activity* was mentioned at least 5 times by P1, P5, P6, and P11. The most common comments were about gaining exercise with the P6 stating they came to warm up and wake up, involving both this factor and a *Affective Work Factors*. The *Game: Fun to Play* had at least 4 mentions for P1, P3, and P4. The comments that we have received in this cluster were to "play game" and "to have fun".

The remaining category is *Game: Competition* (11%). The comments included competing against a previous personal score or to improve my own game level (2), to beat the highest score of other participants (2) and, interestingly, beating the high score on leader board (10) was the most popular responses in this category, even though it was only for the 3 weeks with the leader board which we adopted after feedback on week 5. Competition seemed particularly important for P4, who also had the equal highest number of attend the sessions.

#### Game Choice

Longbow was the stand out as the most popular game. All the other games have similar counts, 21 - 26, about one-third of the Longbow count. Figure 4.9 shows the per-participant spread of games played by total playtime for each games. Every participant played Longbow at least twice and P7 played Longbow almost exclusively (also trying out Holoball once). Five participants (P3, P5, P6, P7 and P9) played Longbow for more than 100 minutes. Beyond this, we see considerable individual differences. With the exception of Fruit Ninja, all the other games had at least one participant who particularly favoured the game eg P1 and P11 for Hot Squat, P4 for Holoball, and P8 for Holopoint.

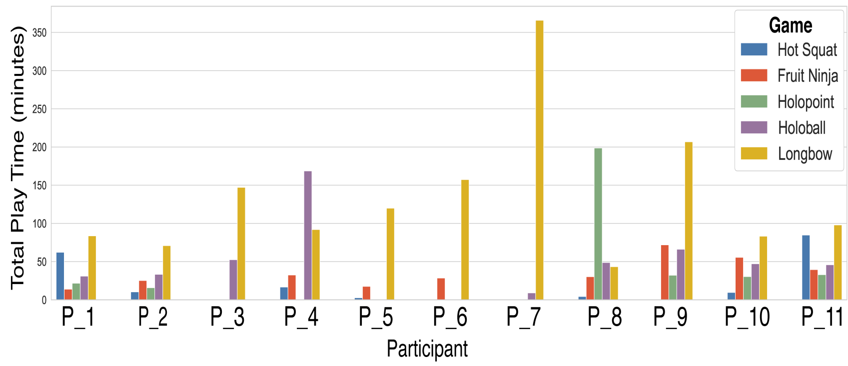



**Fig. 4.9.:** Duration (minutes) that each game was played by each participant.

***Summary.*** Most participant comments covered multiple themes. Six mentioned at least 4 of the 5 themes. About quarter of the participants mentioned multiple themes at similar levels (P1, P4, P6, and P7) while the other 7 participants seemed most motivated by a single theme: P2, P3, P5, P8, P9, P10 and P11 had one theme in more than half their comments. Four key themes arose as motivations for coming to the studio, with the *Affective Work Factors* being most common in aggregate counts, and also being mentioned by all participants. At the next level, similar numbers of comments were made about the *Physical Activity* and the *Game:Fun to Play*.

### Other Benefits

We now move to three potential benefits, (1) perceived mental fatigue, (2) perceived physical fatigue and (3) enjoyment of the games.

We compared the effect of each VR session by looking at the means of *perceived mental fatigue* values before and after the VR session using a paired-sample t-test and found that the difference was not significant ($t(4) = 2.480, p = 0.068, n = 123$). The same test for *perceived physical fatigue* was significant ($t(4) = -4.859, p = 0.008, n = 123$).

All games show an increase in physical fatigue after playing, as seen in Figure 4.10B. This was expected, since we have seen that some games require substantial physical exertion. It follows that Holopoint, shown in Figure **??**B to provide the greatest amount of physical activity, had the steepest increase in physical fatigue (Figure 4.10B). The average increase in physical fatigue was 1.49 on a 7-point Likert scale: $M_{before} = 2.29, \sigma = 0.46$; $M_{after} = 3.78, \sigma = 0.33$; $M_{change} = 1.49, \sigma = 0.69$.

All games except Hot Squat provided some positive effect on average on the participant's reported level of mental fatigue (Figure 4.10A). This was explained by comments made by some participants after their sessions, stating "*I feel much better, refreshed*", "*Feel like I woke up a little bit*", and "*I got this, I can do anything today.*" Hot Squat showed negligible change on the participant's mental state. However, one participant described it as a "*good fitness challenge*" that was able to give them a "*very good workout for a short time*". On average the change in mean reported levels of mental fatigue before and after was less than one point on a Likert Scale: $M_{before} = 2.74, \sigma = 0.29$; $M_{after} = 2.06, \sigma = 0.44$; $M_{change} = 0.67, \sigma = 0.61$. It is notable the average level of mental fatigue at the start of the session was fairly low (< 3.5), leaving little room for improvement in this score. The combination of the statistical tests show that while there is no stand-out improvement in people's mental state, there is certainly no negative effect on their mental fatigue. The positive comments from participants points towards this as an area for further, specific study.

### Enjoyment

The most enjoyed game was Longbow, with a mean score on a 7-point Likert scale $M = 6.1$ ($\sigma = 0.72$), marginally beating Holopoint ($M = 5.8, \sigma 1.46$) and Holoball ($M = 5.9, \sigma = 1.46$), and Fruit Ninja ($M = 5.4, \sigma 1.34$), which provide a similar range of enjoyment. Hot Squat received $M = 3.3$ enjoyment ($\sigma = 0.88$), much lower than other games. Participants chose Hot Squat for the exercise they believed it would provide, with one participant stating that they were going on a skiing holiday and wanted to train by playing Hot Squat. Only 2 of all participants mentioned that they choose Hot Squat for fun.

### Summary

Our participants enjoyed playing games in the VR game studio. As expected participants reported increased perceived physical fatigue at the end of sessions. There was significant change in the mental fatigue.

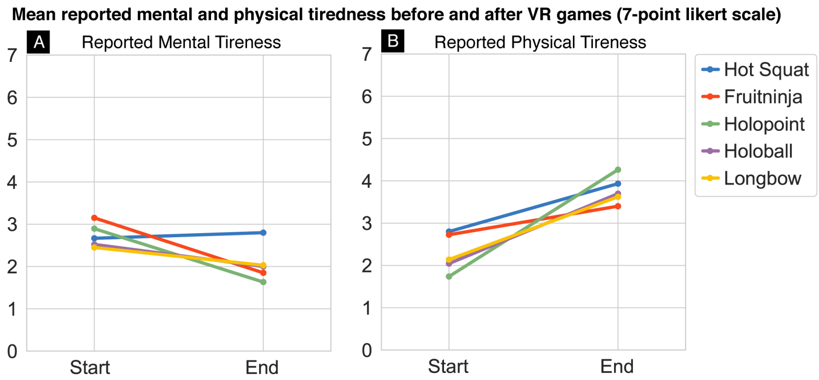



**Fig. 4.10.:** Mean change in perceived mental fatigue (A) and perceived physical fatigue (B) for each game (7-point Likert scale)).

## 4.3 Discussion

We now discuss the key insights form our work. We begin with the aspects related to our first research question which explored the health benefits of the VR games studio in a sedentary workplace. Then we move to the key insights from second research question about the participants' motivation for coming to the studio and the ways they used it.

### Participants gained valuable levels of physical activity

The VR games contributed an average of more than 22 active minutes to participants physical activity. While the context of our work was a sedentary workplace, there was considerable variability in the level of physical activity that was measured by the step tracker. In terms of the recommended target of 30 minutes of moderate activity a day, 2 participants achieved this just form their step tracker data (P2, P6) outside the studio and three more were closer, with at least 25 minutes (P1, P8 and P11). But all participants gained valuable levels of additional exertion on days they used the VR game studio. Six of our 11 participants gained at least half their moderate activity minutes from the VR game play and 4 participants who had previously been below 30 minutes were able to achieve it. Overall, these results are very promising in terms of the relative contribution of the VR game play.

If we consider the large population of people who sit for extended periods of time to play desktop games, a VR game studio like ours might enable them to swap sedentary time for valuable exertion that is also fun. If some of that game-play is at work, our studio could provide a way alternative with health benefits at no extra time cost to the worker who is already on a break. Our analyses also show that the VR game play was an efficient source of moderate+ minutes of physical activity. Overall, our results demonstrate that the VR game studio contributes meaningful levels of physical activity.

#### Diversity in the ways that people used the VR game studio

It was striking that the participants made very different uses of the studio in terms of their choice of games, the length of game play and their main reasons for coming to the studio. We now discuss some notable groups. There was a complex interplay between several factors, particularly participants' motivations for using the studio and the impact of competition.

One distinctive group was the *Hot Squatters*, particularly P1 and P11. This game is hard physical work as it involves the large lower body muscles. It is remarkable that these two participants played this game almost as long as they played Longbow, the game that was so popular across participants. The mean play time for Hot Squat was 13:55, a very long time to do squats. These participants chose it because they wanted to get exercise and they did so well that they eventually earned a place on the Steam Global Leaderboard.

Another important group is the *Longbowers* (P3, P5, P6, P7, and P9). In the week 5 interview, we learnt that some of them were already comparing their scores on Longbow and that they were motivated to compete on this game. This was before we introduced the leaderboard and they valued it when it was available. There was a social dimension in their friendly competition. It is also worth noting that though this game was rated as the most fun, from this group only P3 identified a game-related motivation as the reason to come to the studio.

Finally, *testers*, P1, P2, P8, P10 and P11, played all games at least once. They were not motivated to visit the studio primarily to play games. Most of these participants generally had a lower level of total playtime than participants who preferred a single game. It seems that a single game of interest plays some role of how much time the participants spent in the game studio.

As previously noted, some of our participants had very low levels of incidental activity during the whole day, but achieved a remarkable proportion of their activity from the VR game studio. Particularly, P3 and P7, two of the *longbowers*, achieved 88% 75% of their average physical activity from the VR game studio respectively, each of them only reaching their goal for active minutes per day due to the VR game studio. This shows that some people who do not get a lot of activity may greatly benefit from its implementation. Of course it is not a panacea, as we can also see that with P4 and P10, who were also generally inactive and received large *proportions* of physical activity from the VR game studio, did not reach their recommended 30 minutes.

### Leaderboard effects and social dimension

We introduced the leader board at the request of 5 participants from week 5 feedback. This was a whiteboard showing the names and scores for the top players of each game. The leader board motivated 4 participants to come to the studio. Interestingly, these participants all tried Hot Squat game just once, and this was after the leaderboard appeared (P2, P4, P8 and P10).

Surprisingly, after the leader board was introduced, average play time fell by 3:50, but the average number of active minutes also increased by 4:55, with all participants, except P5, increasing their count of active minutes per session by 3 minutes on average. P2 and P11 more than doubled their number of active minutes per game. There is a substantial body of knowledge about the leaderboard as a motivator and in line with this, 3 participants (P4, P10 and P11) mentioned it as part of their reason for coming to the studio. However, this is the first study to measure an effect that the leader board may have on the intensity of gameplay in VR, which has lead to a measurable change of physical activity for our participants.

### Affective Work Factors were the dominant motivators

Although we might have expected the appeal of the games to be more important, it is surprising that work affective factors were so broadly important motivators for our participants, who felt the need for a break from work, some relaxation or a way to motivate work. Every participant made such comments, accounting for almost half of all comments (48%). It was the most important reason for 5 participants. This highlights the fit of the VR game studio in this sedentary workplace.

While all participants mentioned *Affective Work Factors*, there is considerable diversity for the other factors. It is somewhat surprising that non-game factors dominated the stated motivations for coming to the studio. *Affective Work Factors* and *Physical Activity* account for 71% of comments. For 3 participants, *Physical Activity* was their most common motivator. In contrast, 3 participants never mentioned it.

Game aspects were important for some participants. Affective Game Factors and Competition together account for 29% of stated reasons to visit the VR game studio and they were the top motivations for two participants.

### 4.3.1 Implications and Future Direction for VR Game Studios

Consumer VR systems are continuing to fall in price and increase in quality. Some recent significant improvements in the hardware capability and price include the release of the Oculus Rift S and the un-tethered Oculus Quest.

Some of the surprising findings of our work are that even a game like Fruit Ninja, that involves only the upper body, still gives some valuable levels of exertion. A game like Longbow was more compelling and became the focus of competition and it was an even better source of exercise. This suggests that there is a quite broad range of games that can be well suited to a fun work break and they will give valuable exercise benefits. They may well give the cognitive benefits reported in other work (Coulson et al., 2008).

As noted in the related work, other workplace interventions have reported the struggle in motivating workers to take breaks, with the need for active reminders to exercise (F. X. Chen et al., 2014), or direct interventions in the work space during productive time (Commissaris et al., 2016). Our study demonstrated that, for the population we recruited, the motivation to play the games was enough to motivate them to come at least once a week. However, it should be noted that workplace culture will also play a significant part in the effective uptake of physical activity during breaks through any workplace intervention.

One key problem for making a VR game studio a most valuable is that people get sweaty, a problem that comes with the level of exertion, but is exacerbated by the Head Mounted Display. Another key problem for creating such as studio is the need for scheduling it. Multi-user games could reduce this effect and introduce new social dimensions that might well contribute to the level and duration of game play.

Our work suggests that creating such a space in a sedentary workplace could be valuable for helping workers take the breaks and get valuable levels of exercise. In spite of wide publicity about recommendations for physical activity, it is not easy for people to achieve it with a 20-minute break from work. Our study demonstrates that a VR game studio may be a valuable way to help workers do that.

### 4.3.2 Limitations

Any study design requires constraints, compromises and limitations. We were restricted to a single VR game studio, located in a computer science building with an architecture and design school building nearby. This constrained the potential participant population, giving mostly people working in computer science (9) and design (2), mostly men (9 of 11), most had VR experience (8) and most were rather inactive, falling below the recommended 30 minutes of moderate activity a day on most days (see Figure 4.6. Our ethics approval required strict supervision of participants; this limited the hours the studio was available and so we only recruited 11 participants as we wanted to be sure that they could find convenient times to use the studio. Participants may have appreciated more flexible hours, including early mornings and later evenings. Ethics approval also limited recruitment to healthy people unlikely to have problems such as motion sickness using VR. We recruited participants who would commit to coming consistently over the 8 weeks and all but one of them did so.

We used smartwatches that tracked steps through the day but in the lab we used a chest-strap based heart-rate monitor. Both of these can be used to calculate active minutes. It would be better to use a device that measures heart rate accurately and could also track cycling activity. We asked participants to wear the watch at all times but we had no control over this and our soccer player may have taken it off for their weekly game. We note that heart may increase by about 10-20 BPM as effect of excitement of the games rather than physical exercise (Barlett et al., 2008; H. Chen et al., 2017; Borusiak et al., 2008). This was far less than the overall increase in heart rate that we recorded. Sweat was a problem with our equipment, particularly the close fitting HMD, and it is also a problem with high levels of exertion. This posed problems for some. We asked participants to wear comfortable clothes and some could have changed these. The building has showers but our participants did not use them.

Another key study design decision was the selection of a small set of games that provided diverse levels of activity. our study design involved a mid-point survey about changes participants wanted. An important change after that was the introduction of a leader board.

We now consider the implications of these limitations. Our work shows enough promise that it should be replicated in other settings to gain insights about the health benefits (RQ1) we well as what motivates use and how it is used (RQ2). In future studies, we would recommend exploration of the whole dimension of competition that comes with a leader board. There are also other potential social dimensions to explore, such as multi-user games. Our recruitment favoured people who are keen to play games and this certainly does not cover the whole population (although the gamer community is a very large proportion of the population.) We identified distinctive play behaviour even in our small group of participants. This points to the need for further work to explore the impact of such individual preferences for the design of a workplace VR game studio. While we ran the study for 8 weeks, we have not explore the critical aspect of long term sustainability that has been a short-coming of so many workplace studies (Commissaris et al., 2016; To et al., 2013). A key aspect to explore here is to give workers more choice in the games to play. The problem of sweat is also important as an issue to tackle if people are to get exercise at their workplace. It would be valuable for future work to compare the game studio with a more conventional gym to gain insights about the particular benefits of the VR game play. So at this point, we cannot generalise our work to broader populations and the important need for long term measures to improve health.

## 4.4 Conclusion

This work was motivated by the potential for VR games to be harnessed to benefit people in a sedentary workplace, particularly to gain valuable levels of exercise. We created a VR game studio at a sedentary workplace and designed a study to gain insights about how even casual, commercial VR games are able to contribute important physical activity level to sedentary office workers and how this affect this would motivate their work at their workplace. We conducted an 8-week study where 11 participants could come and play any of our five VR games for the HTC Vive HMD. During this 8-week period, participants also wore a physical activity tracker to capture their step data. In each session, we measured *actual* exertion levels, based on heart rate. We compared the active minutes from incidental activity, against the active minutes in the VR sessions. This enabled us to assess the contribution of exercise in VR game play in our studio.

Our results point to multiple benefits of the VR game studio. One important benefit is the break from work, reported as valuable by the participants. This is accompanied by benefits the physical exertion, in terms of the active minutes gained. We demonstrated that the games are efficient sources of exertion, with 60% of game time being active minutes for all five VR games that we tested.

Importantly, this can contribute at a useful level towards the 30 moderately active minutes recommended for most days. For six participants with the lowest levels of incidental physical activity, the VR game studio made a substantial improvement to their number of active minutes and for four participants, the VR game studio days put them above the 30-minute target where they normally would not make it. This suggests that VR games may provide the allure to pull workers away from their desks in sedentary workplaces. It may substitute gamplay at desktops with a healthier and fun break. It may be a substitute for traditional exercise for people who may feel too time-poor to fit exercise into their work day.

# 5 VRmove: Design Framework for Balancing Enjoyment, Movement and Exertion in VR Games

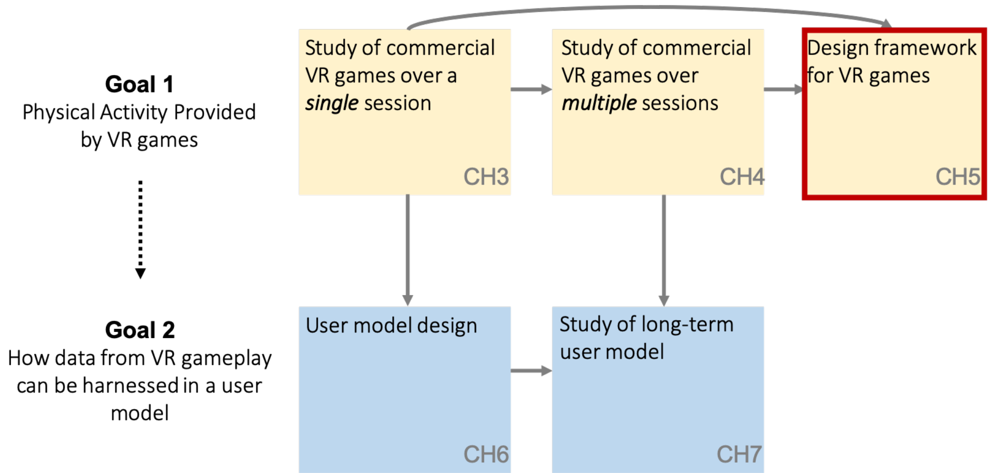



Fig. 5.1.: Structure of the relationships between this chapter (red outline) and others

The work previously discussed in **Chapter 3** focused on the exertion people gained from playing commercial VR games for single and multiple sessions respectively. The studies from that chapter showed that VR games can immerse players to a level where they are distracted from the actual exertion experienced (Yoo et al., 2017a). This could potentially lead to players working out for long periods of time if they are immersed in the virtual world (Bolton et al., 2014; Yoo and Kay, 2016). However, despite the demonstrated effectiveness of VR games providing beneficial levels of exertion, there is currently little in the way of guidelines or principles for the design of VR games that promote stand-alone cardio exercises. Therefore, this chapter[1] (Figure 5.1) contributes to **Goal 1** (*Explore the exertion provided by*

[1] Following the University of Sydney's guidelines on a thesis by publication (`https://sydney.edu.au/students/hdr-research-skills/theses-including-publications.html`), a preliminary analysis documented in this chapter was published in: Soojeong Yoo, Marcus Carter, and Judy Kay (2018a). 'VRmove: Design Framework for Balancing Enjoyment, Movement and Exertion in VR

*commercially available virtual reality games both in lab and authentic settings*) by bringing the data from the study discussed in **Chapter 3** together with a new study to identify key elements for exertion and enjoyment: actual and perceived exertion – being key for representing the gain from the fun disguising the effort and the multi-factorial element of movement involved. This led to us creating a framework called VRmove which aims to help game designers and researchers strike a balance between enjoyment, movement, and exertion in VR games to ensure the players have a positive experience while also gaining beneficial levels of exercise. The framework was validated by demonstrating its application to the design of a VR exergame we developed. After reflecting on this analysis, we present 4 design guidelines for future work on using VR games for exercise.

## 5.1 Study 1 - Commercial VR Games

We conducted studies on four popular commercial VR games from Steam for the HTC Vive head mounted display (HMD). The focus of that work was to explore whether players gained significant levels of exertion in these games, which were not explicitly designed as exergames, and to interrogate the fun and playful experience of them.

| **Game** | **Arms** | **Legs** | **Steps** |
|---|---|---|---|
| Holopoint | ✓✓ | ✓✓ | ✓✓ |
| Fruit Ninja | ✓✓ | | |
| Hot Squat | | ✓✓✓ | |
| Portal Stories: VR | ✓ | | |

**Tab. 5.1.:** Physical movement. ✓ = Light use; ✓✓ = Moderate use; ✓✓✓ = Heavy use.

The four commercial VR games were: Fruit Ninja, Hot Squat, Holopoint, and Portal Stories: VR. The VR games were selected based on their popularity and to represent three main body parts being utilised for the interactions: arms, legs, and steps (Table 6.2). Figure 5.2 shows screen-shots and indications of the body movement for the selected VR games. Importantly, while these games were not designed as exergames, they are designed so that players need to stand and physically move around during gameplay – making VR games very different from traditional sedentary games. At the very least, the player is standing and this has significant cardiovascular benefits (Healy et al., 2008; Owen et al., 2009; Chau et al., 2013).

Games'. In: *Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts*. ACM, pp. 295–307

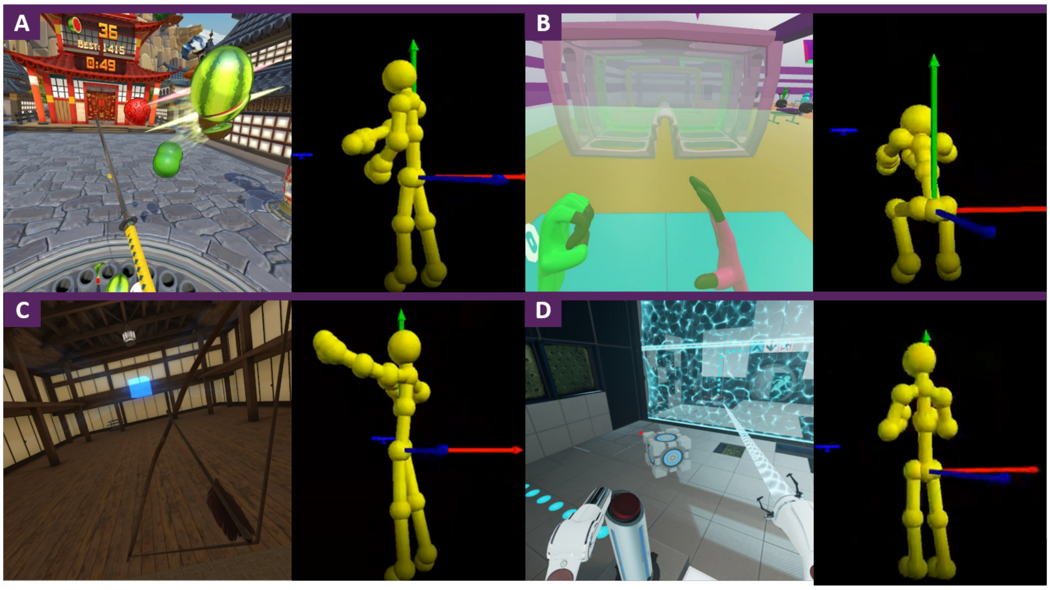



**Fig. 5.2.:** Screenshots and characterisation of the body movement for the 4 games (A) Fruit Ninja - uses arms; (B) Hot Squat - squats; (C) Holopoint - mainly arms and some ducking and weaving; and (D) Portal stories: VR - a baseline of very low movement.

In this study, we tested four VR games with 18 participants (female: 5, male: 13), aged between 18 and 36 (mean: 27) in a single session. Three participants had prior experience with VR gaming. Participants were asked to play each VR game for 10 minutes, however they could stop earlier if needed. While playing the VR games, participants were asked to wear a Polar chest heart-rate monitor to measure their actual exertion. After completing each game, the researcher would ask participants to rate their perceived exertion using the Borg scale (Borg, 1982; Borg, 1998) and enjoyment of the game (Likert scale, from 1, very boring to 7, high enjoyment). Only seven participants played all the games for 10 minutes.

We used the heart-rate measure for two key reasons:

1. It is adequate for a broad classification of exertion, as moderate or vigorous (Canning et al., 2014).
2. It is widely used on gym equipment and personal tracking by runners assessing their exertion (ie wearables like Fitbit, Pebble, and Polar), fitting our broader goals of sharing exertion measures with users.

**Fruit Ninja** (Figure 5.2A) This game involves a lot of ***arm movement*** and is played ***standing in one spot***. The player holds a virtual samurai sword in each hand. Fruit is thrown into the air in front of the player, who must slice as much fruit as possible

| Name | Interaction | Movement | Actual Exertion | Perceived Exertion | Enjoyment (SD) | Play Angle |
|---|---|---|---|---|---|---|
| Fruit Ninja | Slice and Cut | Stand on spot, Steps | Light | Very light | 5.5 (±1.12) | 180 |
| Hot Squat | Squatting | Sit up and down | Moderate | Heavy | 2.8 (±1.74) | 180 |
| Holopoint | Archery | Dodging, Step side and Spin | Moderate | Light | 5.8 (±0.92) | 360 |
| Portal Stories: VR | Teleporting | Stand on spot & Steps | Very light | No exertion | 4.2 (±1.75) | 360 |

Tab. 5.2.: Game description with game type, interaction methods, actual and perceived exertion (reference from Table 1), enjoyment with stand deviation (Likert scale, from 1, very boring to 7, high enjoyment), and play angle in virtual space.

for around one minute; this is repeated for 10 minutes. For the trials with this game, we used the *arcade* mode to ensure all participants played the game at the same difficulty.

**Hot Squat** (Figure 5.2B) Players need to ***stand in one spot*** and duck under incoming barriers by ***squatting*** and ***standing back up*** in between each barrier. As the game progresses, the barriers move faster and the distance between them decreases, gradually forcing players to squat at a faster rate.

**Holopoint** (Figure 5.2C) This game involves ***arm movements*** as well as sudden physical whole body movements, like ***ducking or moving fast***, to avoid being hit by an enemy projectile. The player holds a virtual bow in one hand while the other hand draws arrows from behind the player's head. Enemies appear all around the player, making it necessary to continuously turn around to check for enemies behind. The enemies must be shot with the bow and arrow and upon being hit will launch a projectile at the player, which the player must either side-step or duck under to avoid being hit and killed. The enemies appear in waves, which become progressively faster and harder. The goal of the game is to get to the highest wave possible.

**Portal Stories: VR** (Figure 5.2D) This is a puzzle game, requiring ***very little physical movement*** as players can teleport to move around the virtual world. The player moves through different rooms, each with their own puzzle. In one hand, the player holds a virtual device which allows them to teleport to any horizontal surface in their line of sight. In the other they hold a device which acts as a 'tractor beam', allowing the player to pull certain objects towards them.

## 5.2 Finding a Factor with Enjoyment

Table 5.2 shows the summary of each VR game. For each game the dimensions of the analysis were the name of the game, interaction method to play, movement in virtual space, actual and perceived exertion (described in Table 5.3), enjoyment

| Intensity | Max HR % | Borg Score |
|---|---|---|
| No exertion | 20 - 39 | 6 - 7 |
| Very light | 40 – 59 | 8 - 10 |
| Light | 60 – 69 | 11 - 12 |
| Moderate | 70 – 79 | 13 – 14 |
| Heavy | 80 – 89 | 15 - 16 |
| Very Heavy | 90 – 99 | 17 - 18 |
| Maximal | 100 | 19 - 20 |

**Tab. 5.3.:** Mapping exercise intensity, heart-rate, Borg intensity, and heart-rate

with standard deviation, and the degrees of view in the virtual space. Now, we will discuss details on what factors could affect the game enjoyment.

### Interaction, Movement and Play Angle

We now report on what the analysis revealed about the interaction types and actual movement by players. All but *Hot Squat* involved at least two different types of movement. While Fruit Ninja ostensibly is about arm movement alone, in practice, the study indicates that people actually stepped back and forth. *Portal stories: VR* was designed to use teleportation to move around the virtual environment. However, most participants (13 of the 18) preferred to walk instead. Interview comments indicate they found walking more natural. This indicated that stand on spot and use teleporting as a interaction methods or single repeated movement might lead to the game enjoyment.

The last column indicates the range of play in terms of player orientation in the virtual space. Fruit Ninja and Hot squat used 180 degrees – easily seen without actually walking or spinning around. By contrast, *Holopoint* and *Portal Stories: VR* used the full 360 degrees. This is important because, the study used a tethered HTC Vive HMD with a *cable*. For 360 degree play, this posed problems, with the cable becoming tangled and getting in the participants' way. This meant that players of *Holopoint* and *Portal Stories: VR* needed to be conscious of the cable and this was a particular problem for *Holopoint* dodging to avoid incoming enemy projectiles and spinning to keep track the enemy location. This problem was different for *Portal Stories: VR* as participants tried to physically walk rather than teleport to solve the puzzle around the virtual space.

### Actual and Perceived Exertion

Table 5.2 shows the actual maximum average exertion experienced by participants in each game. Bearing this in mind, perceived exertion was less than actual exertion (HR) for all but *Hot Squat* which was the opposite, with perceived exertion at heavy and actual exertion as moderate. Meaning the perceived exertion was higher than the actual exertion felt. This game involved only unremitting strength work which has a complex relationship with heart-rate.

Notably participants played all but Hot Squat for their full 10 minutes: only 7 (2 females and 5 males) managed to complete the full 10 minutes for Hot Squat. The participants who played Hot Squat for less than 10 minutes explained their reasons for stopping, which was mainly due to fatigue but also low enjoyment.

Holopoint and Fruit Ninja both had a percentage of actual exertion between light and moderate intensity level while their perceived was lower between very light and light intensity. Portal Stories: VR on the other hand, provided very light actual exertion with participants' not feeling any perceived exertion during the gameplay (grey). Lastly, Hot Squat (grey), people felt more exertion than their actual exertion.

The highest enjoyment score was for Holopoint (5.5) and lowest was Hot Squat (2.8) on the 7 Likert scale (1 - very boring and 7 - high enjoyment). Although this is a small set of games, it is striking that game enjoyment was higher for games with the very light to light *perceived exertion*. We describe this as the Goldilocks effect, where VR games that provide just the right amount of exertion, that is not too little and not too much. The games with between 60% - 79% actual exertion and 8 - 12 Borg's perceived exertion were found to be more fun (Table 5.3). If the exertion is over or less than that it seems to affect the game enjoyment. Somewhat surprisingly, people seemed to actually like to experience a sense of effort from playing VR games.

## 5.3 VRmove Framework

Based on the results of our study, we define a framework called VRmove (Figure 5.3), which is made up of three different factors which can affect a player's enjoyment while they play VR games: movement, actual, and perceived exertion. Additionally, movement and exertion factors can create a positive or negative effect on a player's enjoyment. For instance, if the game promotes a lot of movement it can distract the player, however, if the focus is on a single movement, players can become bored due to repetitiveness. On the other hand, a lot or heavy movement will only detract from the player's enjoyment as it can cause the player to sweat or become tangled in the cable (if it exists), thus creating a feeling of discomfort.

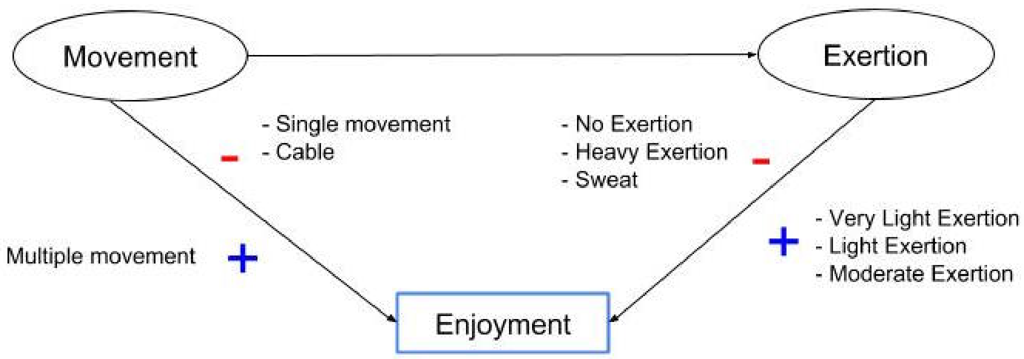



**Fig. 5.3.:** How enjoyment links with the four factors of the VR move framework. Movement and exertion can both positively and negatively impact on enjoyment (+ & -).

### Movement

Cable length limits movement during the gameplay for high resolution HMDs that are currently available on the market, such as HTC Vive and Oculus Rift[2]. For the purpose of exercise, VR games released today usually require a lot of movement. In large play areas however, the player's movement is often constricted by being tethered to a computer via a long cable. The cable may not always be an issue for certain games but it could be a problem for safety and can reduce the immersion felt by players as they need to be aware of the cable. This problem may be mitigated in future as HMDs are starting to be released with wireless accessories for cable-free experiences.

Also, VR games with no variation in movements or constricting the player to one type of movement can increase the feeling of exertion and impact negatively on enjoyment. Unnatural movements, such as teleporting, also seem to reduce the feeling of enjoyment.

### Exertion

We found from our study of the four VR games that VR games with very light to light *perceived exertion* were the most enjoyed. To design VR games for exercise and fun

[2]https://www.oculus.com/

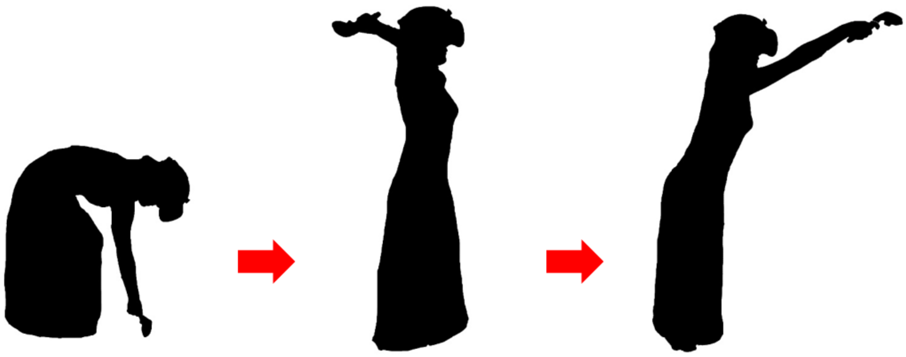


Fig. 5.4.: Interaction and movement in Snowballz, players need to pickup a snowball from the ground and throw them at incoming enemies.

purposes, they should provide between 60% - 79% actual exertion and 8 - 12 Borg's perceived exertion (Table 5.3). If it is over or less than that it can affect the game enjoyment. People actually like to get some real fatigue from playing VR games.

Game sweat was raised as one of the factor that affected the enjoyment of the participants in the study on commercial VR games. Sweat could affect enjoyment (-) if players get too sweaty as the lenses in the HMD become foggy. For hygiene it is better to use some sort of hygiene eye pad face mask for everyone or use alcohol to wipe the headset after each use. Alternatively, some VR HMD such as Google Daydream [3] can be washed in a washing machine after use.

## 5.4 Applying VRmove framework to the design of a VR game

In the previous section, we presented the VRmove framework to help inform the design of VR exergames with enjoyment. In this section, we will demonstrate the application of the VRmove framework and present our analysis of the VR game we designed and developed, called Snowballz. This game was created in Unity for the HTC Vive HMD.

[3] https://vr.google.com/daydream/


**Fig. 5.5.:** Overview of Snowballz' main level.

## 5.4.1 Design of Snowballz

Snowballz is an arcade-style VR game where the player's goal is to defend their camp-fire base for as long as possible against incoming enemies. To do this, players need to pickup snowballs from the ground and throw them at enemies (Figure 5.4). Each new wave brings more enemies that move slightly faster, with a boss enemy every ten waves. The game ends when five enemies make it to the camp-fire. Now, we will go through the design based on the four main factors from VRmove framework.

### Movement

The movement in Snowballz was informed by study 1, where we found that people enjoyed certain games more if there was more than a single movement required to play (For instance, Holopoint was enjoyed as its interaction consisted of multiple movements). Therefore, Snowballz had three main actions (Figure 5.4): pick up the snowball, stand up, and then throw it at the enemy. The interaction is open to different play styles by allowing players to throw snowballs in any way they prefer, such as underarm or overarm.

To mitigate problems with the cable, we created Snowballz to have a 180 degree play area. Figure 5.5 shows the overview of the game. The player location is in the centre of the game environment. Behind the player there is the camp-fire that they need to defend. Enemies only come from the marked yellow area and move towards the player's camp-fire.

### Exertion

The gameplay needed to be engaging in order to distract players from actual exertion experienced. Therefore, the game itself was designed so that the exercise would blend into the game seamlessly through the interactions required to achieve the game goals. At the same time, the play requirements need to be easy to understand and make sense (Sicart, 2008). For Snowballz, the design aimed to motivate players to do squats, which uses large muscles and requires exertion, but without making the game having a blatant focus on squats. Rather, squatting is a consequence of needing to pickup snowballs from the ground to throw at enemies.

To reduce the sweat problem, we designed Snowballz in a similar style to tower defence and arcade games, giving the player some respite in between waves. This also helps reduce the chance that the player becomes overexerted, which can potentially cause injury.

## 5.4.2 Study design

We evaluated Snowballz with 9 participants (3 females and 6 males), aged 21 to 37 (mean: 28). Five reported that they exercised regularly, which the others did not exercise at all. Four had played VR games before. We excluded participants with existing medical conditions that would prohibited them from performing physical activity (based on a pre-study screening questionnaire about susceptibility to motion sickness). The day before the experiment, we advised participants, by email, to avoid heavy eating or drinking an hour before study and to wear comfortable shoes, such as running shoes.

During the study, participants were asked to play for a minimum of ten minutes, but we advised them to stop anytime for any reason. A glass of water and a chair was provided in case anyone needed a break. While they were playing the games, participants wore a heart-rate monitor (Polar H7) so we could collect their heart-rate data, which was stored in an online Polar account. Immediately after finishing the game, participants completed two questionnaires. The first was a Borg scale questionnaire (Borg, 1982; Borg, 1998), which is the gold standard method for measuring *perceived exertion*. Secondly, participants rated their enjoyment of Snowballz on a Likert scale question, from 1 (very boring) to 7 (very fun). After the questionnaires, we interviewed participants to gain qualitative feedback about their experience with Snowballz. After the study the heart-rate data was downloaded from the Polar website as a csv file (minute by minute data) for us to analyse. We then calculated each participant's average Maximum heart-rate to compare against their Borg score.

### 5.4.3 Results

The average enjoyment of Snowballz was 4.4 on a Likert scale, which is higher than Portal Stories: VR (4.2) and Hot Squat (2.8).

In regard to the cable, no one raised this as an issue while they played Snowballz, but during the interview, participants suggested that it "*would be better if enemies came from different directions as it would promote whole body movement*".

Movement was quite simple, grab the snowball and throw at incoming enemies, however most participants stood on the spot to do both movements. Therefore even though we used multiple movements, it appears that Snowballz had a higher level of perceived exertion than actual, similar to Hot Squat. This was concurred by participants during the interviews with one suggesting that "*game interaction was very easy to understand but it is kind of boring to grab and throw. It would be much more fun if we needed to go somewhere to pick up the snowballs*".

The average Max heart-rate experienced in Snowballz was 69.61% which indicates *Light* intensity. Perceived Exertion was 13 which is considered *Moderate* intensity according to Table 3. While the game did not over-exert players, their perceived exertion was a lot higher than it actually was, meaning the game was not engaging enough to distract players from the exertion. Snowballz was in the same actual exertion category as Fruit Ninja (light), but perceived was even higher than Holopoint but less than Hot Squat (Moderate). This indicated that, if the perceived exertion is higher than actual exertion, it also could affect the game enjoyment, which is affected by the movement. This could be due to Snowballz having an 8 second pause between each wave, which we implemented with the intention of not overexerting players. However, the wait time was considered too long by most participants, with one commenting that there should be something players can do while they wait, such as "*objects like balloons to practice with, similar to the Longbow VR game*". Such an idea could be combined with power-ups when the player hits enemies, such as score multipliers, which could give players more motivation to keep active between waves.

## 5.5 Design Guidelines

The following is a series of design guidelines that were identified after synthesising the results from the two studies.

**Keeping the player engaged.** During the game, the player needs to be constantly engaged in order to maintain distraction from the actual exertion felt. Designers should aim to minimise downtime during gameplay, but ensure the player is not overexerted. Rest periods could be integrated into the game naturally by getting the player to do less exerting tasks, such as solving puzzles. This guideline is similar to therapy which utilises VR to distract patients from painful procedures, like bandage changing for burn victims (Carrougher et al., 2009; Hoffman et al., 2000).

**Exert the player just enough.** If it is the goal of the VR game to provide exercise, then the perceived exertion needs to be lower than the actual exertion. If the game provides too much actual exertion, it can impact on player experience - which is the most important factor in order to feel comfortable in the VR game environment. In the end, it all depends on the fitness goals of individual players.

**Be hygienic.** Playing HMD VR games can make players sweaty after long periods or if the actual exertion is high. To increase comfort and hygiene, players should wear a washable or disposable face mask which absorbs the sweat. This is particularly a problem with shared HMDs and is something that needs to be managed if VR will be incorporated into gym environments in the future.

Sweat could also be reduced by the game tracking the exertion of a player and responding by dynamically adjusting the difficulty or intensity of the game (Yoo et al., 2017c). This could be achieved through heart-rate or sensors.

**Make it varied.** To keep players engaged the interactions should be varied and enable different play-styles. The game environment itself should give players a sense of progression. Designers should avoid keeping players in the same spot. This could be achieved by giving players a reason to move around, such as collecting resources.

**Untethered experiences.** VR games that require the player to move around the space in 360 degrees can be affected by cables connected to the HMDs. While this is less of an issue for games that require players to stand in one spot and use only a play angle of 180 degrees, being tethered via a cable can have negative safety and comfort implications. It can also ruin the sense of immersion if the player needs to constantly be aware of a cable. For VR games to truly become a viable platform for exercise, HMDs need to be wireless.

## 5.6 Conclusion

In this work, we defined a design framework called VRmove for balancing exertion in VR games. The framework was derived from the analysis of data from the study of 18 players over four diverse commercial VR games. We validated this framework by applying it to the design and development of a VR game made for exercise. After testing this VR game in a formal user study, we make five design suggestions that can inform the design of future VR games to ensure they provide enough exercise while being fun and engaging.

This work particularly highlights the importance of the Goldilocks effect, where VR games that are made for exercise are designed so that they strike a balance between beneficial levels of exertion, while being engaging enough to distract players from actually feeling it.

## 5.7 Limitations and Future Work

The findings from this work are ultimately limited by the small number of VR games tested (4 commercial and 1 research) and using only the heart-rate measure. Future work will expand on this and test a larger range of VR games along with using a combination of exertion measures, such as breathing, steps, and heat expenditure. However, our work shows that VR designers need to consider not only enjoyment but also the exertion levels their games provide, even if they did not intend on creating an exergame, as this can affect a player's overall enjoyment and experience.

# Part II

## How Data from Virtual Reality Gameplay can be Harnessed in a Long-term User Model

# 6 Towards a Long Term Model of Virtual Reality Exergame Exertion

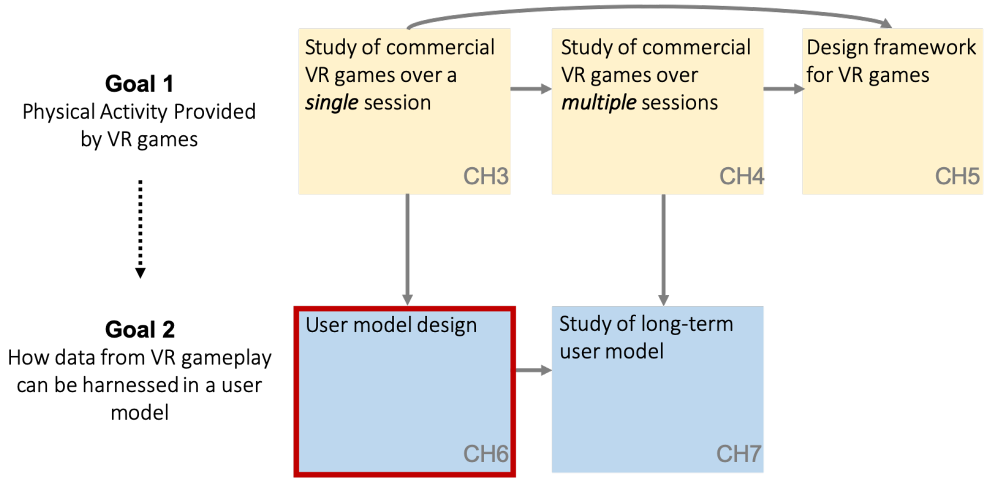



**Fig. 6.1.:** Structure of the relationships between this chapter (red outline) and others

The work in **Chapter 3** focused on measuring physical activity gained from playing VR games over a single session. This chapter[1] disseminates the data gained from people participating in the study from **Chapter 3** to design a user model that stores physical activity data, such as heart-rate, and the attributes of the VR gameplay session, such as the score. Specifically, the work in this chapter addresses **Goal 2** (*Understand how to use data from virtual reality gameplay to create a long-term user model to support personal informatics*).

This work is important because while some VR games are effective in providing exertion, they do not currently take into account information about the user, such as their tness level or goals and preferences, which can limit their exercise outcomes

[1] Following the University of Sydney's guidelines on a thesis by publication (`https://sydney.edu.au/students/hdr-research-skills/theses-including-publications.html`), a preliminary analysis documented in this chapter was published in: Soojeong Yoo, Tristan Heywood, Lie Ming Tang, Bob Kummerfeld, and Judy Kay (2017b). 'Towards a Long Term Model of Virtual Reality Exergame Exertion'. In: *Proceedings of the 25th Conference on User Modeling, Adaptation and Personalization*. ACM, pp. 247–255

(McClaran, 2003). Just this information would be used by a tness advisor who would create a workout plan. Without tailored exercises, individuals risk over-exertion, and signicant health problems (Haskell et al., 2007).

Personalisation offers a way to overcome such problems. Both personalised game recommendation and within-game personalisation could make VR games more effective in providing good exercise while being enjoyable. Such personalisation needs a user model that represents key aspects of the user, such as their game and exercise preferences, fitness and exercise goals. The emerging availability of consumer devices for sensing heart-rate (HR) make it possible to model exertion (Nes et al., 2013) within game play.

In this chapter, we present the design for a user model for VR exergames, the VRex (VR exergaming) model. This is intended to serve three main roles which we characterise in terms of key questions a system should be able to answer.

1. *Recommending VR games based on exertion and game preferences*:
   - Which games will give me a good cardio workout?
   - Which will work particular muscle groups eg arms?
   - Which will give me a good game experience?
2. *In-game personalization*: Personalize a particular game by taking account of the individual's goals and previous playthroughs of this game.
   - How hard is the user working compared with their target?
   - Should the game change to make the user exercise harder, use different muscles, or reduce the intensity?
   - Should the game provide the user with feedback on their exertion, and if so, how should this be timed and presented in order to avoid it being ignored or causing distraction from the VR game?
3. *Exertion and activity OLM*: Create open learner models (OLMs), that enable an individual to gain insights into their long term physical activity, based on the integration of data from multiple games and other sources, such as depth-sensing cameras, smartphones, smart-watches and worn activity trackers.
   - How much does a particular VR game contribute to my long term fitness goals?
   - How much does my VR gaming session contribute to my overall exercise?

We illustrate the use of VRex to represent 18 users who played 4 games, based on data about their actual and perceived exertion and their satisfaction with each game. This demonstrates the diversity of the user models, in terms of the user model's components. This is the first work to explore the design of user models for VR exergames and has the potential to serve as a foundation for game personalisation, recommenders and open model interfaces.

The next chapter (**Chapter 7**), builds on this work by contributing a user model based on multiple session data.

## 6.1 VRex Model

| ID | Model Component Name | Description (illustrative examples) |
|---|---|---|
| | | ***Game Model*** |
| G1 | ID | Unique game Identifier (eg. FN001v2017.1) |
| G2 | Name | Game name for use in interfaces, may not be unique (eg. Fruit Ninja) |
| G3 | Body parts | Tuple represents parts of body exercised and how much (eg. [arm:high, glutes:moderate]) |
| G4 | Scoring | Tuple representing format of scores from a session (eg [number:score, number:deaths]) |
| | | ***Long term exertion and fitness model*** |
| Fit1 | VO2max | User's VO$^2$Max fitness measure (eg 50) |
| Fit2 | rest-HR | Rest heart-rate (eg 60) |
| Fit3 | 2-min-recovery | Heart-rate drop in 2-min recovery protocol (eg 40) |
| Fit4 | Top Heart-rate | User's maximum heart-rate |
| PG1 | Daily moderate activity target | Target for moderate+ activity in minutes per day (eg 30) |
| PG2 | Daily vigorous activity target | Target for vigorous activity in minutes per day (eg 15) |
| WGA1 | Actual moderate activity | moderate+ activity in minutes each day (eg 40, 21, 55) |
| WGA1 | Actual vigorous activity | vigorous activity in minutes each day (eg 20, 0, 0) |
| | | ***Game Session Model*** |
| | | ***Game Summary – data source is the game*** |
| S1 | Game ID | Identifier for game, used to link to game model |
| S2 | Score | Tuple for game score in this session, depends on game (eg score:7; deaths:3) |
| S3 | Session Start | Time actual game play started (date and time) |
| S4 | Session End | Time actual game play ended (date and time) |
| | | ***User Preferences, perceived exertion, DOMS – data source is user answers*** |
| A1 | Game Preference | Enjoyment (1 - 7 scale) |
| A2 | Immersion Preference | Responsive, compelling, and proficient (1 - 7 scale) |
| A3 | Perceived exertion | This is determined through the Borg measure |
| A4 | DOMS | Tuple for perceived delayed-onset-muscle-soreness score (timestamp, score 1 - 7, body part) |
| | | ***Actual Exertion Measures – data comes from Heart-rate sensor when worn*** |
| E1 | HR-before | Estimated minimum heart-rate in period before game start |
| E2 | HR-peak | Peak 10-second HR level |
| E3 | HR-2-min-Recovery | From worn heart-rate sensor data, after game end |
| E4 | Player's max heart-rate | Gained by removing the player's age from 220 |
| E5 | Moderate activity time | Time in minutes of moderate intensity activity (50+%) |
| E6 | Vigorous activity time | Time in minutes of vigorous intensity activity (70+%) where this is a subset of E5 |

**Tab. 6.1.:** VRex user model. Top block is the game model. Next is the user's long term exertion and fitness model. Remainder is the model for a single session of a VR game.

As a starting point to designing a user model for exertion in VR games, we identified the competency questions for the user model. There are three classes of these, each related to the very different roles the user model could play. We listed them in the introduction and we return to them in the discussion section. While our broad goals need to involve both exertion and game preferences, this thesis restricts the focus to the former. For the latter, it will be important to link the VRex model with models of game preferences, such as Orji et al. (2014). In addition, it will be useful to link to work modeling user's goals (Barua et al., 2014).

Table 6.1 shows an overview of the VRex user model. The first column is the type ID for each category, for example the Game Model has four data types, each with their respective ID (G1-4). Next is the name of the model component and the third column is its description. The table shows the 3 parts of the model: Game Model describes each game; Long term exertion and fitness model; and Game Session Model. Components within these link to each other.

The data defined in the "Game Model" is related to the game itself. G1 provides a unique game ID and G2 provides the human-readable name of the game, to present in a user interface. G3 describes the parts of the body exercised in the game. G4 is linked to score, as it can give us a clearer picture about whether the player is having difficulties with the game and how many retries or attempts the player made.

The next block of the model represents long term exertion and fitness, representing the various measures described in the last section and we describe below how it fits with the part of the model for each game session.

Finally, the "Game Session" model represents a single game session, the user's enjoyment and actual exertion measures. The game summary models four aspects. Game ID (S1) is the game's unique identifier, which is used to link with the Game Model. Game score (S2) is a tuple for player achievements, such as a score and number of deaths. S3 and S4 track when the game started and ended. For example, is a player has a low score (S2) and a long playtime ($S4 - S3$), this may indicate the game is too difficult.

Since it is important to track user's responses to games, the Game Session Model records a player's enjoyment score (A1) and feeling of immersion within the virtual world (A2). Perceived exertion (A3) and DOMS (A4) track the user's assessed level of exertion to be interpreted along with the actual exertion in the "Actual Exertion Measure" part of the model.

Actual exertion represents how hard the player worked, based on their heart-rate before starting the game (E1), the 10-second heart-rate peak (E2), the 2 minute recovery rate (E3), the player's maximum heart-rate (E4), how many minutes the player exercised at moderate intensity activity (E5), and at vigorous intensity activity (E6). These parts of the model can then be used to determine the exertion in one session. This contributes to and can be compared against the long term exertion and fitness model to find out whether the player is meeting or exceeding their target and whether an easier or harder game should be recommended.

## 6.2 Study design

We designed a study to populate the VRex user models. This was done by capturing and analyzing data from people as they played a series of VR games. We transformed each participant's data into the relevant components of the VRex model components. Then we analysed the user model components from each game to gain insights into the variability of these between users since this points to the importance of personalisation across our three user modelling goals: game recommendation, within-game personalisation and long term OLMs.

Our lab-study involved 18 participants, each playing four VR games (Fruit Ninja, Holopoint, Hot Squat and *Portal Stories: VR*) from Steam VR using the HTC Vive head mounted display (HMD). The game order was varied so that three people used each of the 6 possible game orderings of the first three games. *Portal Stories: VR* was always the last session as we used this game as a baseline game since it involves limited exertion.

### Study Setup

The interactive space was approximately 3 x 3 meters, of a dedicated VR lab. The equipment was: 1 x HTC Vive HMD; 2 x HTC Vive Base Stations; 2 x Controllers; 1 x Desktop PC running Windows 8.1 with Intel Core i7 3.4 GHz, 16 GB RAM, and Nvidia Geforce GTX 960 graphic card; 1 x Speaker System; 1 x Microsoft Kinect version 2 (for video recording); and 1 x Heart-rate Chest Strap. Two Lighthouse sensors, tracking the user's position in the physical space, were mounted on tripods and placed on opposite corners of the room where they were approximately 2 metres from the floor. Users wore a Polar T34 heart-rate chest strap monitor for the whole study period, including preliminary paper work and all 4 game sessions and the break times between them.

We recorded video through a Microsoft Kinect and audio through the HTC Vive HMD itself. The video was later used for analysis.

### Data Collection

The heart beats detected by the Polar T34 chest strap were transmitted to a Moteino LoRa (Arduino Uno compatible) located on the participants body. The Moteino was powered by the spare USB port on the Vive and it sent the received heart beat data to a near by computer. We needed to process this raw data to account for noise, which involved both missing and extraneous data. This was based on a filtering and sliding window smoothing.

This part of the data collection was critical for the measure of actual exertion, E1-6 in VRex. We recorded the start and end time for each game (S3 and S4 in VRex). The recordings of the actual game play were then analysed to determine the scores achieved by participants (S2 in VRex).

### Selection of the Virtual Reality Games

We chose the four VR games, as shown in Figure 6.2, from the Steam online store for the HTC Vive so that they would involve a range of types and levels of physical activity. Table 6.2 summarises the parts of the body (G3 in VRex) each game involves. The table indicates the predicted level of exertion by the number of ticks. Broadly, Fruit Ninja involves just arms, Hot Squat, the large leg and gluteal muscles needed to squat and Holopoint has a mix. The fourth game, *Portal Stories: VR*, was our baseline low exertion condition; it is a puzzle game, requiring little movement. We now describe each game.

| Game | Arms | Legs | Steps |
|---|---|---|---|
| Fruit Ninja | ✓✓ | | |
| Hot Squat | | ✓✓✓ | |
| Holopoint | ✓✓ | ✓✓ | ✓✓ |
| Portal Stories: VR | ✓ | | |

Tab. 6.2.: Physical movement. ✓ = Light use; ✓✓ = Moderate use; ✓✓✓ = Heavy use.

### Hot Squat

The player stands still while a series of barriers move towards them. Players must squat in order to duck under the barriers and must stand up again between barriers. As the game progresses, the barriers move faster and the distance between them decreases, forcing the player to squat faster.

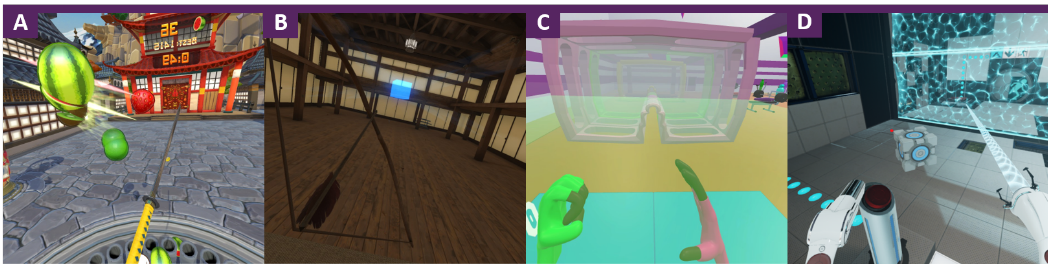



Fig. 6.2.: Screenshots of games: (A) Fruit Ninja, (B) Hot Squat, (C) Holopoint and (D) Portal Stories:VR

#### Holopoint

The player holds a virtual bow in one hand while the other hand draws arrows from behind the player's head. Enemies appear all around the player, making it necessary to continuously turn around to check for enemies behind. The enemies must be shot with the bow and arrow and upon being hit will launch a projectile at the player, which the player must either side-step or duck under to avoid being hit and killed.

#### Fruit Ninja VR

The player holds a virtual samurai sword in each hand. Fruit flies into the air in front of the player, who must slice as much fruit as possible in one minute; this is repeated for 10 minutes.

#### Portal Stories: VR

This is a puzzle game where the player moves through different rooms, each with their own puzzle. In one hand, the player holds a virtual device which allows them to teleport to any horizontal surface in their line of sight. In the other they hold a device which acts as a 'tractor beam', allowing the player to pull certain objects towards them.

### Study Procedure

We sent an email invitation to University mailing lists to recruit potential participants. They completed a screening questionnaire. We excluded participants with medical conditions and those susceptible to motion sickness. The day before each participant's study session, we informed them to avoid eating a heavy meal or drinking an hour before the study and to wear shoes that were comfortable to exercise in.

#### Sessions

Each session ran up to one and a half hours. At the beginning of the study, we asked participants to wear a chest strap heart-rate monitor (Polar T34) while they completed consent forms. Participants then did the standard Vive tutorial for 6.5 minutes. This introduced how to interact with controllers and how to move safely in the play area inside the virtual environment. Right after the tutorial, participants played their first game. This was varied across participants so that 3 of the 18 participants played one of the 6 possible ordering sequences of the three games chosen for exertion (Fruit Ninja, Holopoint and Hot Squat). We advised participants that we would stop them after 10 minutes in each game. However, we emphasised that they should stop whenever they wished, for whatever reason (which could have included feeling tired or bored). *Portal Stories: VR* was always the last game. Since it does not require much exertion, we could use this to compare the heart-rate measures across the participants both for this game as well as the games involving more exertion.

#### Post-study

The day after their session, participants were contacted and asked whether they were feeling any effects of the exercise, such as soreness in specific muscle groups. (✓ = light, ✓✓ = moderate, ✓✓✓ = hard). This provided the data for A4 in VRex.

### Eliciting user preferences and perceived exertion

Typically, it is recommended to take short breaks of at least two minutes between bouts of exercise, to increase exercise output and performance, with the actual time depending on the individual (Lee, 2016). In our study, after each game we asked the participants to take a break of at least 2 minutes, with a maximum of 10 minutes. During this time, participants filled out the Borg questionnaire (McClaran, 2003; Haskell et al., 2007) for perceived exertion, A3 in VRex. They also answered the Presence questionnaire (Witmer and Singer, 1998) as a measure of immersion, A2 in VRex. At the end of the last session, we asked for a rating of enjoyment for each game (likert scale, 1 to 7, 1 very boring and 7 high enjoyment) for A1 in VRex and we asked them to explain their score.

In addition, while participants took each break, they continued to wear the chest heart-rate monitor, which monitored their heart-rate. This enabled us to determine the 2 minute-recovery, E3 in VRex.

## 6.3 Results

The study enabled us to collect the data needed to populate the VRex model for a game session, for each of the 4 games. Since this game session model has 14 components, we provide an overview of selected components to illustrate the variability of these parts of the model across our participants and the ways we could use them. We then illustrate the VRex Game Session Model, for one game, Holopoint and two participants.

Table 6.3 summarises participants' background information. Our 18 participants were 18 to 36 (mean 26). Three (P1, 5 and 8) indicated they exercised regularly. (The VRex long term model could represent this in Fit1 - Fit3). Participants were also asked about prior experience with VR gaming, as this could affect the results. For example, experienced players may reach higher and more difficult levels, possibly increasing exercise intensity. Equally, they may play more efficiently, with less exertion. Long term data from many users will reveal the actual impact of game experience on exertion levels. Only P7, 8 and 12 had prior experience with VR gaming. The table shows each participant's maximum heart-rate, calculated as 220 minus age (Mesquita et al., 1996).

| | Participant ID | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| **Age** | 26 | 21 | 22 | 18 | 36 | 23 | 24 | 34 | 24 | 31 | 27 | 26 | 26 | 35 | 25 | 34 | 24 | 26 |
| **Exercise** | ✓ | | | | ✓ | | | ✓ | | | | | | | | | | |
| **VR games** | | | | | | | ✓ | ✓ | | | | ✓ | | | | | | |
| **MAX HR** | 194 | 199 | 198 | 202 | 184 | 197 | 196 | 186 | 196 | 189 | 193 | 194 | 194 | 185 | 195 | 186 | 196 | 194 |

Tab. 6.3.: Participant background information.

Table 6.4 summarises the user model component values of each game in a heat map for moderate and vigorous minutes of activity and rating of perceived exertion (RPE). We would expect the Borg perceived exertion to match the minutes of vigorous activity. In addition, we include the score or level achieved in the games, but only score for Fruit Ninja as it only had one level.

The table caption explains the mapping of colors to minutes and Borg RPE. The table shows that only a few participants perceived Fruit Ninja as highly exerting and most did not actually have >=8 of the 10 minutes in vigorous or even moderate exercise. Most participants rated Hot Squats higher for perceived exertion than they did the other games. Despite this, however, participants usually had the most minutes of moderate exercise when playing Holopoint. This is in line with the fact that participants found the muscle fatigue of the squats made them stop before their heart-rate became high. A set of models like this could drive a recommender.

| ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fruit Ninja | | | | | | | | | | | | | | | | | |
| Score | 788 | 1415 | 1380 | 723 | 855 | 801 | 998 | 1180 | 851 | 744 | 1180 | 1413 | 871 | 603 | 1262 | 892 | 1213 | 941 |
| Moderate | 0:00 | 11:15 | 10:20 | 10:01 | 10:12 | 10:33 | 10:03 | 9:21 | 9:40 | 9:53 | 12:01 | 10:22 | 9:46 | 9:49 | 9:37 | 10:08 | 1:56 | 10:18 |
| Vigorous | 0:00 | 6:40 | 0:00 | 0:00 | 0:00 | 9:53 | 7:46 | 0:00 | 0:00 | 3:04 | 4:41 | 0:00 | 2:45 | 0:00 | 6:11 | 0:00 | 0:00 | 0:19 |
| RPE | 7 | 6 | 11 | 8 | 12 | 9 | 6 | 12 | 13 | 14 | 14 | 13 | 8 | 11 | 9 | 12 | 13 | 13 |
| | Hot Squat | | | | | | | | | | | | | | | | | |
| Level | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Moderate | 3:33 | 7:37 | 9:43 | 8:54 | 7:34 | 10:05 | 2:45 | 7:45 | 9:54 | 4:49 | 5:39 | 3:03 | 10:03 | 6:09 | 6:00 | 4:21 | 9:06 | 10:15 |
| Vigorous | 0:00 | 6:31 | 5:03 | 0:57 | 0:00 | 8:59 | 1:18 | 0:00 | 8:28 | 1:16 | 2:46 | 0:00 | 7:08 | 1:27 | 4:31 | 0:29 | 2:17 | 6:39 |
| RPE | 14 | 15 | 18 | 12 | 13 | 17 | 20 | 15 | 18 | 16 | 18 | 19 | 17 | 17 | 16 | 18 | 17 | 16 |
| | Holopoint | | | | | | | | | | | | | | | | | |
| Level | 3 | 4 | 7 | 5 | 5 | 5 | 6 | 11 | 6 | 4 | 3 | 11 | 5 | 2 | 5 | 5 | 4 | 9 |
| Moderate | 5:30 | 11:15 | 10:27 | 9:52 | 10:50 | 11:41 | 10:13 | 9:24 | 8:42 | 9:57 | 10:16 | 9:42 | 10:12 | 9:51 | 9:55 | 7:42 | 10:01 | 10:25 |
| Vigorous | 0:00 | 7:40 | 0:00 | 2:06 | 1:08 | 8:07 | 7:46 | 1:56 | 0:19 | 6:43 | 5:42 | 0:58 | 0:48 | 1:56 | 7:51 | 0:00 | 3:55 | 8:19 |
| RPE | 8 | 13 | 12 | 8 | 14 | 9 | 10 | 14 | 14 | 12 | 17 | 16 | 13 | 13 | 11 | 14 | 15 | 15 |
| | Portal Stories : VR | | | | | | | | | | | | | | | | | |
| Level | 5 | 9 | 6 | 5 | 6 | 4 | 8 | 9 | 7 | 6 | 6 | 8 | 7 | 4 | 6 | 4 | 6 | 9 |
| Moderate | 0:00 | 10:37 | 8:33 | 8:03 | 0:00 | 9:07 | 10:10 | 0:00 | 9:58 | 10:19 | 9:50 | 0:00 | 10:01 | 10:11 | 11:14 | 0:00 | 0:00 | 11:13 |
| Vigorous | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 | 0:00 |
| RPE | 6 | 6 | 11 | 6 | 7 | 6 | 6 | 6 | 9 | 6 | 7 | 7 | 6 | 8 | 6 | 6 | 8 | 6 |

Tab. 6.4.: Participant game scores and heat mapped minutes of moderate and vigorous exercise (white: 0-1, light-blue: 2-7; dark-blue: 8-10). Borg RPE (white: <9; light-blue: 9-12; dark-blue: >=13

We now consider the key actual exertion components of the VRex model, E5 and E6, which represent the minutes of moderate and vigorous activity and the perceived exertion A3. Figure 6.3 shows these for Holopoint. We chose this because participants achieved considerable levels of activity in this game and they also seemed to enjoy it, reflected both in the scores and that we had to stop them. The x-axis shows the participants, sorted by the amount of vigorous activity measured (E6). The left axis shows the number of minutes of moderate (first blue bar in each set) and vigorous (red, third bar) exercise. So, for example, three participants (P1, 3 and 16) never reached the threshold for vigorous activity, at 70% of their maximum heart rate. At the other end of the scale, the last 5 participants (P2, 7, 15, 6 and 18) had over 7 vigorous activity minutes out of the 10 for the game, indicating considerable exertion, about half the daily recommended dose. The three participants who reported doing regular exercise, P1, 5 and 8 are all in the first half of the graph (at ranks 1, 7 and 8).

The right axis labels shows Borg RPE with individual scores in the green bar (in the middle of the moderate and vigorous minutes). It is important to gain understanding of the accuracy of this score since it would be valuable to know whether it is a good measure for people to provide for a recommender. If it correlates well with the proportion of game time in moderate or vigorous activity, it would be valuable. Equally, if the correlation is less strong, it may be important to have actual exertion measures. We might have expected the Borg RPE to rise across the graph, along with minutes of vigorous activity, however this does not seem to be the case. Qualitatively, these results have some interesting cases. The lowest scores are for P1 and the on the left and P4 in the middle of the graph. The next lowest scoring group appear as 3 of the rightmost 4 participants. So the Borg RPE does not appear to reflect minutes of vigorous activity for individuals. Overall, the actual heart-rate consistently correlated with Borg RPE for the three active games, Fruit Ninja, Hot Squat and Holopoint but it was consistently lower for Portal Stories: VR.

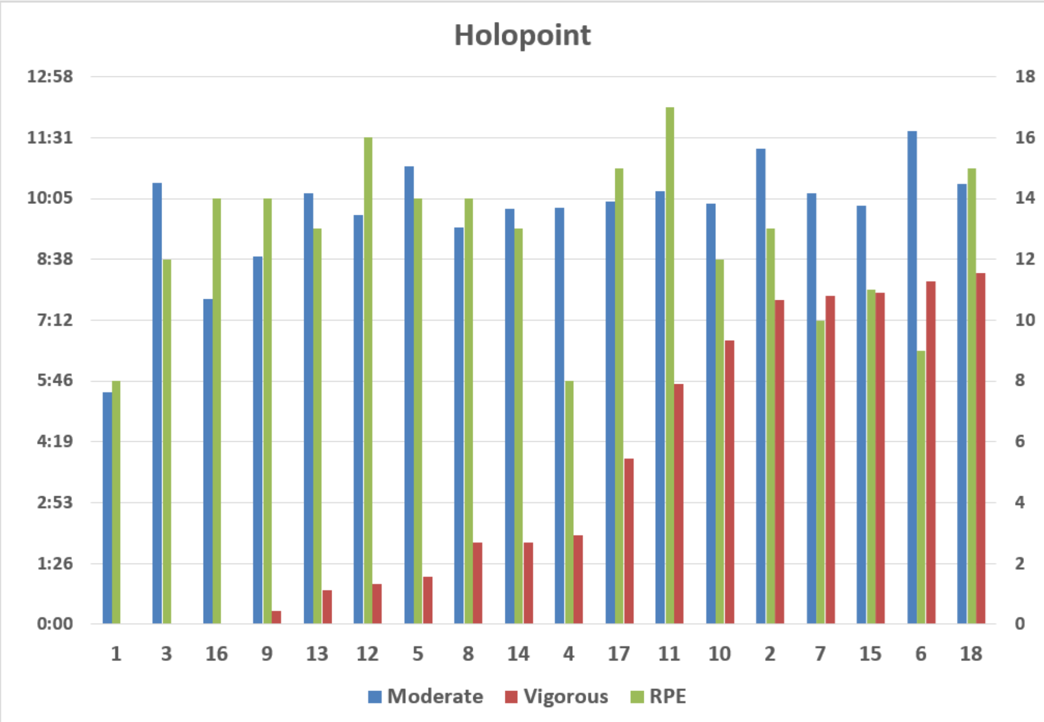



**Fig. 6.3.:** All 18 participants minutes of moderate+ (50+% of max minutes) and vigorous (70+% of max minutes) activity, and Borg perceived exertion (RPE) in Holopoint

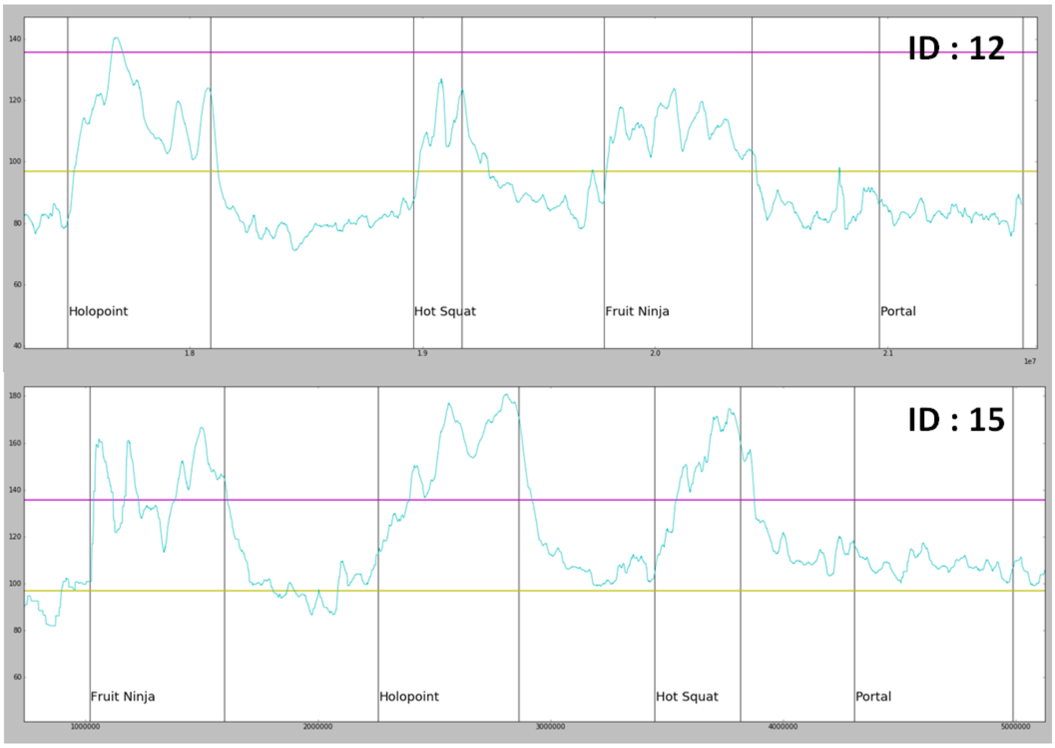



**Fig. 6.4.:** Moderate and Vigorous intensity exercise for P12 and 15, red horizontal line = vigorous and yellow line = moderate

Now we show examples of the heart-rate over the full 4 games and the breaks between them. Figure 6.4 shows this for two participants with very different profiles. These participants played the games in different orders. Participant 12 (top) had just a short time of vigorous activity, in Holopoint, and in most of the time in the active games, they reached moderate (50%) intensity. (This was not the case for the final *Portal stories: VR*). Participant 15, has a very different profile, with considerable vigorous activity time for all three games (Fruit Ninja, Holopoint, and Hot squat) and moderate for Portal stories: VR.

Table 6.5 illustrates the VRex Game Session Model Holopoint for the case of these two participants, P12 (left) and P15. We chose these participants as their ages are similar (26 and 25 respectively) so our calculations give a similar maximum heart-rate.

For the "Game Summary" components of the Game Model, P12 appears to be a better player, as the S1 component shows they reached wave 11 with 3 deaths while participant 15 reached only wave 5 with 5 deaths. S3 and S4 shows similar session lengths, due to the 10 minute limit on games in our study design. Despite P12's high game performance, they rated the game as 5 for enjoyment (A1) and 6 for

| ID | Model Component | Participant 12 | Participant 15 |
|---|---|---|---|
| | ***Game summary*** | | |
| S1 | Game ID | Holopoint (12) | Holopoint (15) |
| S2 | Score | Max wave:11, deaths:3 | Max wave:5, deaths:5 |
| S3 | Session Start | 20:34:20, 14/12/2016 | 15:57:00, 27/01/2017 |
| S4 | Session End | 20:44:35, 14/12/2016 | 16:07:05, 27/01/2017 |
| | ***User preferences*** | | |
| A1 | Game Preference | 5 | 7 |
| A2 | Immersion Preference | 6, 7, 7 | 7, 7, 7 |
| A3 | Perceived Exertion | 13 | 11 |
| A4 | DOMS | Legs (✓) | Legs (✓✓✓) |
| | ***Actual exertion*** | | |
| E1 | HR-before | 75 BPM | 79 BPM |
| E2 | HR-peak | 143 BPM | 183 BPM |
| E3 | HR-2 min recovery | 117 BPM | 146 BPM |
| E4 | Player's max HR | 194 BPM | 195 BPM |
| E5 | Moderate activity time | 9:42 | 9:55 |
| E6 | Vigorous activity time | 0:58 | 7:51 |

**Tab. 6.5.:** VRex model for P12 (left) and P15 (right)

immersion, with compelling and proficient scores being maximum (A2). P15 rated A1 and A2 with maximum scores. In terms of perceived exertion (A3), P12 gave a moderate intensity rating of 13, while P15 rated it 11, which means that it was light intensity. The A4 measure here is clearly confounded by the fact that all players played 4 games; including it for all games reflects collecting a single score. Now we consider the E1-6 measures. It turns out that both had similar initial heart-rate (E1) and their similar age gives them a similar max level (E4). However, all the measures suggest that P12 is fitter than P15: P15's peak actual heart-rate was 183 (E2), far higher than P12's at 143; 2-minute recovery (E3) for P15 level was 146, while P12 was 117. In addition, while both players had at least moderate activity for most of the game (E5), P15 had almost 8 minutes at a vigorous level.

In light of this model, a recommender might offer different games to P12 and P15. For example, P12 might prefer a game that is more immersive, has more difficult gameplay than Holopoint, and provides more exertion. P15, on the other hand, seems to like Holopoint very much, even though they are not skilled at it. Longer term data may be needed, from subsequent sessions (if any) to assess whether such players will keep playing Holopoint.

## 6.4 Discussion

We now assess the VRex model in terms of its design goals. We do this in terms of the questions posed in the introduction, explaining how our study indicates that the VRex model addresses them. In our work, we have demonstrated how to build the models, based on data from the user, the game itself and a heart-rate monitor. In the future, we envisage that these could be automatically captured and delivered to a long term user model. This could be done by suitable augmentation of the hardware and game software. Since the HMD can utilise head-phones to deliver the audio, these could be altered to capture in-ear pulse measures, as in the Bragi-dash[2], which uses oximeter sensors.

The game software could send information about game performance, such as the player's score, how many retries, or the time it took to complete a level. Even the elicited measures, such as the Borg rating, could be incorporated in the game. After the game, we could also elicit this and the post-game DOMS measure using message-based queries with tools like Telegram[3] or Slack chat-bot[4].

### Recommending VR games for their exertion as well as game preferences.

Our VRex model could be used to drive a collaborative recommender for VR games. Since such a recommender requires models for many people, we would need to consider privacy concerns. In the spirit of ensuring user control, we would need to add interfaces that enable people to specify the parts of the model they are willing to share. This could be a simple measure such as the amount of time a person played a game as this could be surrogate for enjoyment.

Our rich and detailed models could also support content-based recommenders. These would not require the sharing described above and they could be used to explain their recommendations in terms of the components of the model. Our results suggest that the most important are the actual levels of exertion and enjoyment. The Borg measures may be of limited use if actual exertion is what is important to people.

We return to the questions.

[2] https://www.bragi.com/thedash/
[3] https://www.telegram.org
[4] https://www.slack.com

- Which games will give me a good cardio workout? Recommendations should draw on the exertion levels combined with game play time and overall game rating since length of play as well as exertion level are both important.
- Which will work particular muscle groups eg arms? Games could be described in terms of the muscle groups involved and the VRex model could combine this with the elicited DOMS rating to advise users about the games that can help them build muscles they want to target.
- Which will give me a good game experience? This requires the elicited measures. Suitable game design could make it easy to report these at the end of the game (or even at major stages, such as going to a new level).

### In-game personalisation

There are potential benefits from using the VRex model to drive personalisation that answers our questions:

- How hard is the user working right now, compared with their own goal targets (and medical knowledge and advice)?
- Should the game be changed now to make the user work harder, use different muscles, or cut back, and even stop?
- Should the game provide the user with feedback on their exertion, and if so, how to time this and present it to avoid it being ignored or causing distraction from the VR game?

To make games adaptive the VRex model needs to be available in a long term model that different games can access. Of course, this would only be an effective approach if game developers are willing to make use of the model. Personis has an API that makes this straightforward from a technical perspective. However, it is a research system and there are many pragmatic issues that may affect its adoption in commercial games. Our work can, however, serve as demonstration of the approach with commercial groups creating their own versions of similar user models.

In addition, it is important that the player can keep track of their progress on the fly so they can determine whether they should push themselves harder. However, the information needs to be presented in a way that suits their preferences. For example, if a player prefers a game that is not very realistic, which can be determined by their game and immersion preference, then it may be acceptable to display information within their view in the form of a head up display (HUD). Another aspect to consider is if the player is performing vigorous activity, it may be difficult to gain their attention; it may be better to use visual indicators over text, such as slowly fading in a red tint, indicating they are close to over-exertion.

### Exertion and activity OLM

Over the long term, the VRex model can help us answer questions such as: how much does a particular VR game contribute to my long term fitness goals; how much does my VR gaming session contribute to my overall exercise. Current wearable

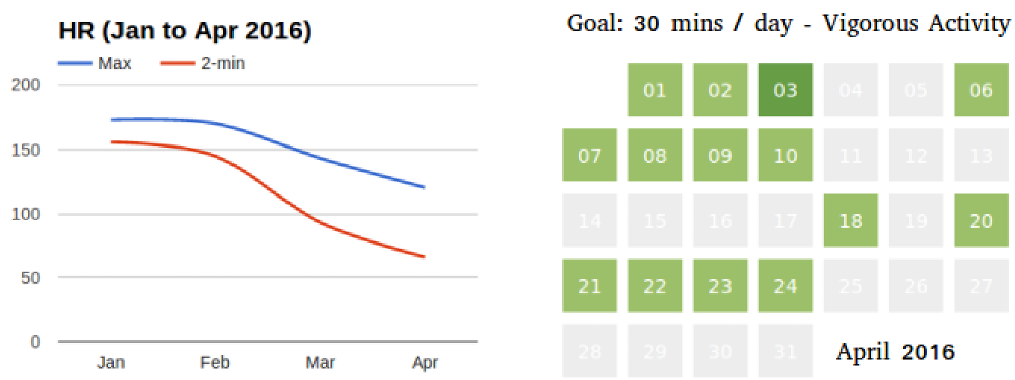



**Fig. 6.5.:** Mockup of long-term views of the VRex model. Left is max and 2-min HR from playing Holopoint over 4 months. Right is a calendar where green indicates meeting their target 30 minutes of vigorous activity.

each provide their own dedicated interfaces for overall activity but they do not enable a user to see other perspectives, particularly those needed to answer such questions about the contribution of VR games to such goals. Figure 6.5 illustrates how the VRex user model could help, based on the mockup of an interface onto a hypothetical user's VRex long term model (left) from Jan to Apr 2016 and meeting their target for vigorous activity minutes (right) in Apr 2016. This hypothetical user had 2 goals: improve HR and to achieve 30 minutes of vigorous activity per day. In this example, the left figure shows that the user's max HR dropped over the 4 months and the 2-min HR has dropped even more. This suggests that the user not working as hard but is recovering faster after each game. The right figure shows a calendar view, with green for 14 days the model recorded data indicating they met their target of 30 minutes of vigorous activity a day, during the month of April in 2016. This allows users to see when and how often they reach their goal over time.

## 6.5 Conclusions

This work was motivated by the potential for VR games to be both fun and good exercise. Our particular goal is to harness data as people play VR games so that we can build a user model which could serve three main roles: recommending games; personalising the game and exercise experience; and enabling people to track their exercise within VR games. We have described how we designed the VRex model to meet these goals. We then presented a user study which was designed to capture the data to build the game session part of VRex models. Our results demonstrate the richness of the models and the very different game and exercise experiences of our participants. This points to the need for personalisation that accounts for both people's fitness and how much they like games. The current work was limited to game play in a single block of somewhat over 1 hour. This is a promising foundation for future work that explores long term user modelling.

# 7 Exer-model: A User Model for Scrutinising Long-term Models of Physical Activity Based on Multiple Sensors

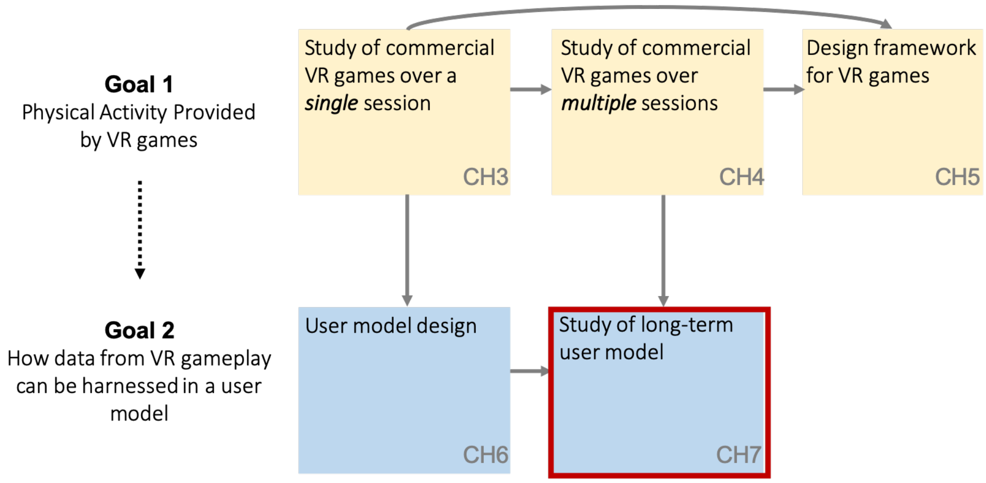



**Fig. 7.1.:** Structure of the relationships between this chapter (red outline) and others

This chapter[1] contributes towards **Goal 2** (*Understand how to use data from virtual reality gameplay to create a long-term user model to support personal informatics*).

The work in the first part of this thesis (Goal 1) contributed toward the knowledge of how much exertion people can gain from VR games and how they should be designed to ensure people become exerted but also retain an engaging experience. One of the key findings from Part I was that VR games and workouts with VR games should be tailored to individuals and their preferences. In response to this,

[1]Following the University of Sydney's guidelines on a thesis by publication (`https://sydney.edu.au/students/hdr-research-skills/theses-including-publications.html`), a preliminary analysis documented in this chapter was published in: Soojeong Yoo, Jisu Jung, Cécile Paris, Bob Kummerfeld, and Judy Kay (2019). 'Exer-model: A User Model for Scrutinising Long-term Models of Physical Activity from Multiple Sensors'. In: *Adjunct Publication of the 27th Conference on User Modeling, Adaptation and Personalization, UMAP 2019, Larnaca, Cyprus, June 09-12, 2019*, pp. 99–104

**Chapter 6** presented the design of a user model to enable personalised VR games and workouts, informed by the single session VR gameplay study in **Chapter 3**. However, while a single session can provide a lot of useful data about an individual, it has been well documented that people are interested in their long-term data from sensors of physical activity (Choe et al., 2014; Epstein et al., 2016b; Li et al., 2012). Moreover, people want to keep their personal data in a store that they control, so they can review it flexibly in the future (Barua et al., 2013). However, it is currently very difficult for people to manage data from multiple sensors and understand it in a meaningful way. Importantly, this means that people currently make little use of long-term data from these wearable physical activity sensors (Fritz et al., 2014; Meyer et al., 2017; Tang and Kay, 2017). A key reason is the difficulty of managing the data – to access and then to organise it so that they can explore it to make sense of it.

User models have the potential to provide a valuable solution to this problem by enabling people to answer core questions about their long-term physical activity by exploring their model. While there is a long history of user modelling shells (Kobsa and Pohl, 1994; Kobsa, 2007; Kay and Kummerfeld, 2012; Dim et al., 2015), there has not yet been work to provide *general purpose interfaces* for users to explore user models. There has also been considerable work on user model ontologies (Heckmann et al., 2005; Carmagnola et al., 2011), but this too has not placed a focus on how to support users to answer core questions about the data collected and organised within the model.

This is the first work to ever take a strongly user-centred approach to the challenge of creating a user model that enables people to harness their own long-term sensor data to answer important questions about their physical activity. We do this for a user model built from two main data sources collected during the study in **Chapter 4**: (1) a heart-rate monitor worn when the user played room-scale VR-games; and (2) a smart-watch which captured per-minute step-counts to track incidental walking exercise.

Our driving research questions were:

1. Can participants navigate their **Exer-model** to answer core questions about their long term physical activity from playing VR games and incidental walking exercise?
2. What do participants find most interesting in their **Exer-model**?

The model could be interacted with through a web interface. Participants were re-invited to review their data using the interface and from this we gained feedback to help understand preferences when interacting with physical activity data in a user model.

## 7.1 The Exer-model and interface

This section has three sub-parts. First is the design of the **Exer-model** ontology. We call it an ontology, following Gruber's definition (Gruber, 1993) "*an explicit specification of a conceptualisation*" and Uschold and Gruninger's (Uschold and Gruninger, 1996) "*a shared understanding of some domain of interest*". We particularly focus on the ontology's role for people to build understanding of their user model. The second part describes how we built the user models and the third introduces the **Exer-model** interface.

| ID | Model Component Name | Description |
|---|---|---|
| | | ***Context: Cardio Physical Exercise*** |
| | | ***Context: Goal*** |
| PGoal1 | Moderate Mins Goal | Moderate minutes daily target, from user or default of 30 minutes |
| PGoal2 | Vigorous Mins Goal | Vigorous minutes daily target (default: 15 minutes) |
| PGoal3 | Active Mins Goal | Combined daily moderate + vigorous minutes target |
| | | ***Context: VR Minutes*** |
| VR1 | Moderate Mins HR | Minutes of moderate HR from VR games ($50-69\%$ of user max HR) |
| VR2 | Vigorous Mins HR | Minutes of vigorous HR from VR games (70+%of user max HR) |
| VR3 | Active Mins HR | Minutes of moderate+ HR from VR games (50+% of user max HR) |
| | | ***Context: Incidental Activity*** |
| Step | Active Mins Step | Active minutes of step data from activity tracker (100 steps per minute) |
| | | ***Context: VRGame*** |
| | | ***Context: [name-of-game]*** *(one subcontext per game)* |
| A1 | Preference | Enjoyment 1 - 7 (Likert scale) |
| | | ***Context: HR*** |
| E1 | Rest HR | Measured heart-rate at rest just before game |
| E2 | MaxHR | Peak 10-second maximum HR level (from HR sensor) |
| E3 | Recovery HR | HR 2 minutes after game end (from HR sensor) |
| A2 | Perceived HR | Perceived exertion (user response to Borg measure) |
| | | ***Context: VR Minutes*** |
| S1 | Playtime | Time actual game play started and ended (date and time) |
| E4 | Moderate Mins HR | Minutes of moderate heart rate (50 - 69%) |
| E5 | Vigorous Mins HR | Minutes of vigorous intensity activity (70+%) |
| E6 | Active Mins HR | Minutes of moderate+ intensity activity (50+%) |

Tab. 7.1.: Contexts and components of the **Exer-model**. The actual evidence in the model comes from multiple sources: the user provides PGoal1-3 (or they are set to a default), A1 and A2; VR1-3, E1-6, are from the heart-rate sensor; Step is from the smart-watch; S1 is from the game tracker.

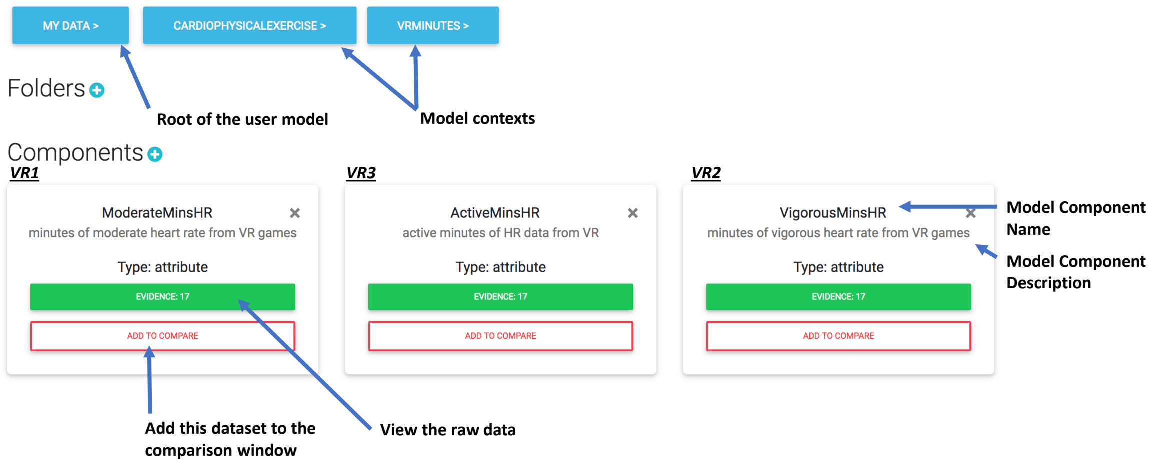



**Fig. 7.2.:** Scrutiny interface showing three components. VR1–VR3 match Table 1 row IDs.

### 7.1.1 Design of Exer-model and ontology

In the spirit of competency questions for an ontology (Noy, McGuinness, et al., 2001), we identified the core questions a user should be able to answer:

- What exertion did I get from playing a particular VR game?
- What exertion did I get from playing multiple games?
- What exertion did I get from daily steps?
- What were enjoyment ratings for a particular VR game?
- How does any one of the above compare with another?

Table 7.1 shows the key parts of the **Exer-model** ontology. We implemented the user model in the Personis framework (Assad et al., 2007) which is organised in a tree-hierarchy of *contexts* and *sub-contexts*, with the leaf contexts containing the user model *components*. Each component then holds the *evidence* about that component and it has *resolvers* which interpret the evidence to conclude the value of each component.

The table shows the contexts and the components within them. At the top level, there are two contents: *Cardio Physical Exercise* and *VRGame*. The table has three columns for the components. The first is a reference ID and next is the short name. The third column has a description.

The *Cardio Physical Exercise* context was designed to represent the overall activity tracked by all sensors. It has three sub-contexts: *Goal*, *VR Minutes*, and *Incidental*

*Activity*. *Goal* subcontext has components for three physical activity goals: moderate and vigorous activity and the combined active minutes target. The next sub-context, *VR Minutes*, has the actual minutes of activity. These are provided by a heart-rate sensor worn during VR game play. The last subcontext, *Incidental Activity*, has one component, *Active Mins Step*, holds data from the smart watch, as the number of steps in each minute.

The second context in the table is for all modelled aspects of the *VR Games*. It has a sub-context for each modelled game. The components in this part of the model rely on data from user's answer's questions during their VR game sessions as well as analyses of the heart-rate data during gameplay.

The first *VR Games* component is the user's rating of enjoyment of the game at the end of play. The *HR* context models aspects of exertion. *Rest HR* is potentially useful as a long term measure of fitness; it tends to be inversely related to physical fitness and low values are associated with lower mortality (Jensen et al., 2013). It is also relatively easy to measure before a game session.

The *Max HR* component is calculated as the 10 seconds of peak heart-rate within game play. This is one important indicator of how hard the user worked. Next is another fitness measure, *Recovery HR*, how quickly a person's heart-rate returns to their resting heart-rate following intense exercise. A faster recovery rate is associated with increased fitness (Ostojic et al., 2011). The *Perceived HR* is based on user responses to the 16 level Borg measure of perceived exertion questionnaire (Borg, 1998), which users report at the end of the game. This can be mapped to an estimated heart-rate by multiplying the level by 10 (e.g. 7 * 10 = 70 beats per minute) (Borg, 1982; Yoo et al., 2017a; Yoo et al., 2017b). Then the perceived and actual heart rate can be compared.

The *VR Minutes* has components about exertion in a game. The *Playtime* enables calculations of the other aspects from the correspondingly named heart-rate components, VR1, 2 and 3.

### 7.1.2 Populating the user model

We ran a study where 11 participants were invited to use a workplace VR game studio over 8 weeks. They could book convenient times. In VR sessions participants wore a Polar heart-rate monitor. They also wore Pebble watches to give the daily step count. We also recorded their VR game sessions, for details of the games they played and playtime. The raw heart-rate data was processed to create evidence for all VR exertion measures in **Exer-model** (ie VR1 - VR3 and E1 - E6) After each VR game, participants were asked about their enjoyment (A1) and perceived exertion (A2). The playtime (S1) of each game played was recorded through video to gain an accurate start and stop time. As we used commercial games, we have to capture A1, A2 and S1, to add to the model.

Participants had a choice of five VR games for the HTC Vive: Holoball, Hot Squat, Fruit Ninja, Longbow and Holopoint. This selection of VR games was based on a combination of factors: (1) game popularity; (2) amount of movement needed to play; (3) specific part of body exercised eg arms, glutes; and (4) recommendations from online discussion boards. The five games gave enough diversity to cater for individual preferences and also enabled participants to work particular parts of their body. We set the physical activity goals, PGoal1/2, to default values based on Australian Government physical activity recommendations[2] and work by (Haskell et al., 2007), based on meta-analyses of many studies (Pate et al., 1995; Haskell et al., 2007). We took their simple form – 30 minutes of moderate activity most days or 15 minutes of intense activity (or a combination of these, weighting intense activity). A future system should enable users to set and change their own goals as in (Barua et al., 2014).

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### 7.1.3 User View of the scrutiny interface

Figure 7.2 shows the scrutiny interface when the user has navigated from the root of the model to the context *CARDIOPHYSICALEXERCISE*, then its sub-context *VRMINUTES*. The user can see components for active, moderate, and vigorous minutes, measured by the heart-rate monitor while they played VR games. Users can click the green "Evidence" button to see each evidence item in the component. There is a graphical dashboard, as in the example in Figure 7.3 showing exertion from VR games against daily activity. In this case, the individual's VR active minutes (red) vary considerably and on most days this user had more VR active minutes than their incidental steps. To add a component to their dashboard, the user clicks "ADD TO COMPARE" (Figure 7.2). This simple bar graph interface was designed to be simple and easy for people to learn. Similar visualisations of activity are used in many commercial interfaces to activity data. The important difference is that those commercial apps do not enable people to take any combination of their data. This

[2]Australian Government Physical Activity Recommendations - `https://www.health.gov.au/internet/main/publishing.nsf/content/health-pubhlth-strateg-phys-act-guidelines#apaadult`

was discussed at length in the design of an interface to long term physical activity data (Tang and Kay, 2017). This interface provides flexibility so that the user can select any pair of aspects to see together.

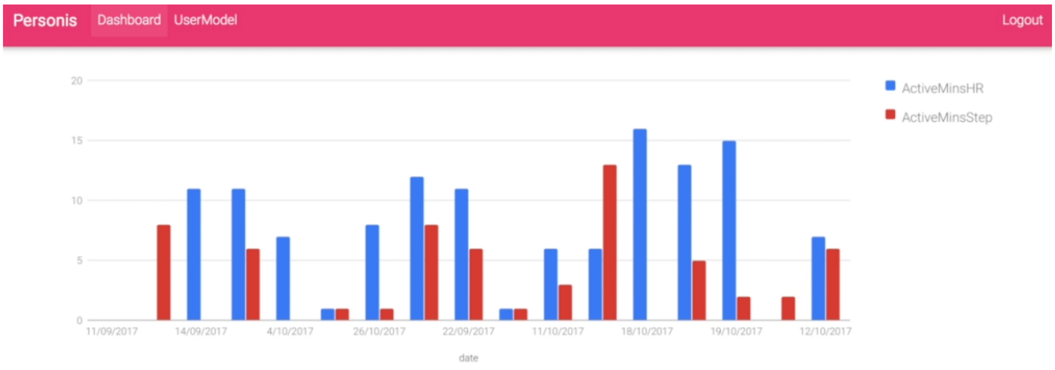


**Fig. 7.3.:** Dashboard for Task T5 in Table 7.2, comparing active minutes from VR games (blue) and daily steps (red).

## 7.2 Evaluation study design

### 7.2.1 Participants

We recruited 16 participants, in two groups:

1. *own-data* group: participants had used the workplace VR studio and explored their own data;
2. *synthetic data* group: participants explored the model of a hypothetical user.

We anticipated that the first group would be more interested in the data. But we also wanted the see the results for the second group since they all saw the same data and are more directly comparable for that aspect. For the first group, we sent email to the previous participants and 8 agreed to return for this study. We used email to University mailing lists to recruit the second group. We created the synthetic user data from anonymised user data from the study.

## 7.2.2 Study Procedure

Figure 7.4 shows the steps in the study. When each participant arrived for the study, we went through a participant information sheet (PIS) and they completed the participant consent form (PCS). Then we showed a one minute video on how to think-aloud[3]. We then ran a five minute tutorial – walking through the structure of the model, explaining terms (eg active minutes). Figure 7.4 shows the two paths through the rest of the study. One involved *free exploration* (labelled A in the figure) before doing the set tasks. Half of each of the group (*own-data* and *synthetic data* took each path, giving 4 groups, each of 4 people. The *synthetic data* group explored the model they would use in the later tasks. This split study design aimed to give insights about the actual use of an exploration phase as well as its impact on the later set tasks.

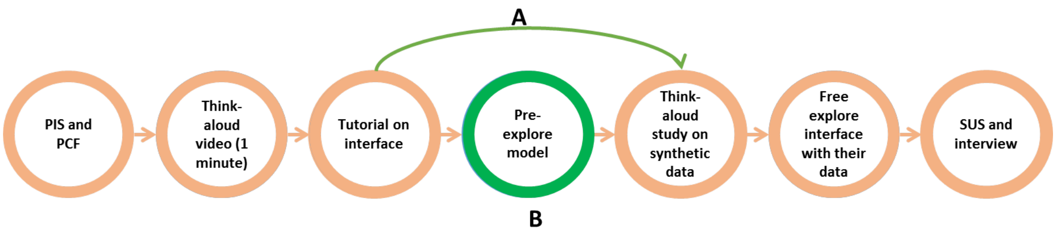


**Fig. 7.4.:** Study protocol steps: only Path B has pre-exploration.

After the think-aloud tasks, any participant who had been unable to do any task was shown how to do and asked to help us understand their difficulties. The last use of the interface involved free exploration for all participants. The *own-data* group explored their own user model and the *synthetic data* group were asked to pretend it was their data and explore it. At this stage we wanted to find out how participants would use explore the model and what interested them. We asked them to complete a System Usability Scale (SUS) survey as the final step of the study.

## 7.2.3 Think aloud questions

Table 7.2 shows the user tasks, along with the associated parts of the **Exer-model**.

[3] https://www.nngroup.com/articles/thinking-aloud-demo-video/

| ID | Task | Exer model ID |
|---|---|---|
| T1 | How many active minutes did I gain from playing VR games? | VR3 |
| T2 | How many active minutes did I gain from daily steps (Pebble or Fitbit)? | Step |
| T3 | Compare how many active minutes did I gain from playing VR games with recommended level of active minutes? | VR3 vs PGoal3 |
| T4 | Compare how many active minutes did I gain from daily steps (Pebble or Fitbit) with recommended level of active minutes? | Step vs PGoal3 |
| T5 | Compare how many active minutes did I gain from playing VR games with how many active minutes did I gain from daily steps (Pebble or Fitbit)? | VR3 vs Step |
| T6 | How many moderate minutes did I gain from playing Holpoint game and Longbow? | E4 vs E4 |
| T7 | Compare perceived heart-rate with maximum heart-rate for Fruit Ninja game? | A2 vs E2 |
| T8 | Compare enjoyment between Holopoint and Longbow? | A1 vs A1 |

Tab. 7.2.: Think-aloud questions and how they link with **Exer-model**

## 7.3 Results

Table 7.3 overviews the participant demographics and overall results. We had 16 participants (six women), 9 from a computer science background (C) and 7 from design. The 8 *own-data* participants are first (P1 - P8), followed by the 8 *synthetic data* participants (P9 - P16). Within these two groups, the first 4 were from the *pre-explore* subgroup (P1 - P4 & P9 - P12). We will now present our results in terms of our two research questions.

### RQ1: Can participants navigate their Exer-model to answer core questions about their long-term physical activity from playing VR games and incidental walking exercise?

For this research question, we draw on the think-aloud tasks and SUS scores, both summarised in Table 7.3. Each white cell indicates the user in that row successfully completed the task in that column. Black means fail, and H with a yellow background means the participant asked for and was given help.

The most difficult tasks were T1, T3, and T5. For T1, 9 participants either failed or needed help. They looked for the active minutes under VR games, instead of *Cardio Physical Exercise*. Five participants tried to go to each VR game to find the active minutes for each game and calculate the total, by memorising the number or writing it down with pen and paper while the other 2 participants simply just chose one of the VR games such as Fruit Ninja and explained the active minutes for that game. P11 and P13 asked for help as they were unsure if they were doing the task correctly. In such cases, the researchers gave hints to help them work out where to look. From the think-aloud comments, participants seemed to understand the parts of the model needed for Tasks 1 and 2, even though they had difficulty navigating to the right component for T1.

Of the 7 participants who could not do T1, 5 also failed on T3 and T5 – these tasks involved comparisons with T1 results. Notably, the two participants who asked for help were able to succeed on T3 and T5. Task 3 involved comparing the active minutes from VR games (as in Task T1) with their goal target.

It is striking that the success rate on these tasks was far higher for those who pre-explored the model. Of these 8 participants, just P2 failed on all three tasks and P11 asked for help on T1. The consistent picture is that the problem was in gaining familiarity with the organisation of the model.

| | Gender | Age | Major | Previous study | Pre-explore | SUS | Think-aloud tasks | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | T1 | T2 | T3 | T4 | T5 | T6 | T7 | T8 |
| **P1** | F | 24 | C | o | o | 80 | | | | | | | | |
| **P2** | M | 46 | D | o | o | 80 | ■ | | ■ | | ■ | | | |
| **P3** | M | 34 | C | o | o | 73 | | | | | | | | |
| **P4** | F | 24 | C | o | o | 78 | | | | | | | | |
| **P5** | M | 31 | C | o | | 45 | ■ | | H | | ■ | ■ | ■ | H |
| **P6** | M | 28 | D | o | | 25 | ■ | | H | | | | | |
| **P7** | M | 36 | D | o | | 40 | ■ | ■ | ■ | ■ | ■ | | | ■ |
| **P8** | M | 33 | C | o | | 55 | | | | | | | | |
| **P9** | M | 36 | C | | o | 75 | | | | | | | | H |
| **P10** | F | 23 | C | | o | 93 | | | | | | | | |
| **P11** | M | 32 | D | | o | 38 | H | | | | | ■ | | |
| **P12** | M | 28 | C | | o | 75 | | | | | | | | |
| **P13** | F | 30 | D | | | 30 | H | | | | | | | |
| **P14** | M | 35 | C | | | 55 | ■ | | ■ | | ■ | | | |
| **P15** | F | 14 | D | | | 78 | ■ | | ■ | | ■ | | | |
| **P16** | F | 37 | D | | | 55 | ■ | | ■ | | | ■ | H | |

**Tab. 7.3.:** Information for each participant (C:Computer science and D:Design).

Task T4 involves a very similar comparison to T3, this time comparing daily active minutes from steps against the target goal. This task was had very high success rates, with just one participant (P7) having difficulty. For Tasks 3 and 4, eight participants commented that they would like to see the recommendation and goal as a line graph as it would be visually easier to compare. For example, "*I think the bar chart is clear but as the goal doesn't change it might be better to represent the data in a line graph*".

In Task 5, comparing active minutes from VR games against daily steps, most participants thought this was useful and said that this helped them to understand their activity would make it easier. One of the participants comments that "*This is more interesting because its things I've done so I can see that I had more active minutes from VR and steps overall play more than I walked*". Also, during this task, some participants asked to combine more than 2 components to see a full day's activity, from both VR games plus from steps, compared against their daily active minutes target. Additionally, one participant wanted the goal/recommendation always present.

Task 6, comparing moderate minutes for the Holopoint and Longbow games, required navigation to each game's VR minutes. Most participants were able to do this (13 out of 16). The 3 participants who failed simply clicked the enjoyment component. Task 7 was also well done, with just P5 failing and P16 needing help. T8, another comparison, the only one involving the game enjoyment component. The SUS score gives an overall usability score, with 68 indicating an average level (**sus_info**). Half the participants had scores over 68. Table 7.3 shows that all 7 of the 8 participants who pre-explored their model had ratings over 68 (P1-P4, P9,10,12). Of those who did not pre-explore, only P15 had a score above 68. This is in line with participants comments and the task performance, which as noted above, indicated the need to gain a mental model of the organisation of **Exer-model**.

Overall, it seems that giving participants time to pre-explore the interface improved their performance (in terms of success on the tasks), satisfaction (indicated by SUS score and general comments) and their understanding of how to navigate the **Exer-model**. The major difficulties were due to problems building a mental model of the organisation of the **Exer-model** ontology. The key problem was that some participants did not expect *Vigorous Mins HR* to be within the *Cardio Physical Exercise/VR Minutes* folder. Aside from this difficulty, most participants were successful in completing most tasks. The participants who explored their own data seemed more interested in it, spending more time and exploring more of the model.

### RQ2: What do participants find most interesting in their Exer-model?

We observed three main patterns of exploration by participants and categorise these into three general personas: VR gamer, Hybrid, and Athlete based on the user type.

**VR gamers** were mainly interested in the VR games part of **Exer-model**; they did not care about their activity tracker data or physical activity goal recommendation. All gamers were from the *own-data* group, and they represent 5 of the 8 members of this group (P2, P4, P5, P6, and P8). These participants all compared how many active minutes they received from each game and then compared each game. The gamers were also interested in the number of times they played certain games during the previous study. P8 stated: "*I want to know how many times I played the games - in terms of physical activity I don't care about my goal or steps*". P4 also found that the model very interesting: "*I don't think I did move around that much when I played Longbow. But the HR seems relatively similar - but I am very surprised that Longbow had a higher HR than Holopoint*". This participant also wanted to see other people's game data such as heart-rate, active minutes, game duration and score.

**Hybrid** users were different, wanting to compare either steps or VR games with recommended active minutes targets, or compare VR data with daily steps. The Hybrid users were P1, P7, P9, P10, P11, P13, P14 and P15. Out of the Hybrid users, three participants (P9, P10, P13) were mainly interested in daily steps compared with their recommended active minutes. Three participants compared daily steps and daily physical activity recommendation (P9, P10, and P13). These participants had suggestions to improve the comparison by adding more information or against day of the week. More specifically, P10 mentioned that the comparison is useful but they wanted further information - "*what I also want to know is whether I am getting better. I think I feel like I'm kind of more like polarised to be really bad or really good*". Four participants compared VR games against the physical activity recommendation (PG1 - PG3 in the cardio physical exercise model): P1, P7, P14, P15. These participants wanted to see how VR could contribute to their recommended level of exercise "*I'm not a big game player but if the game helps me to burn more calories then I would probably play it more often*" and "*I wanted to know how much games can contribute in my normal day*". One participant, P11, was interested in comparing VR and their daily steps as they did not care about the goal and just wanted to see what they were receiving for their daily activity.

**Athlete** describes participants who were very interested in the physical activity they gained from each source and wanted to compare all their physical activity data: P3, P12, and P16. They were the only users to compare VR minutes with their recommended activity target, VR minutes compared with daily steps, and daily steps compared with recommended activity target. P5 and P16 particularly went through all the games and tried to find out which game gave higher active minutes. P5 commented that "*if I just click just one component such as moderate minutes from VR, it would be good to see that by itself but broken up by each game as a quick way to adding all of them in. That would be interesting to me so I could actually compare which games would give me more exercise*". People in this group also wanted stacked components displayed, they could add active minutes from VR and daily steps and compare that data with recommended active minutes. P16 also suggested the monthly graph to see whether the improvement would be helpful too.

## 7.4 Discussion

The results from this study allowed us to gain the following insights.

- **Make the hierarchy of data clear** - people need to build a mental model of the user model. The overall hierarchy of data, the contexts and component organisation in **Exer-model**, should be on-screen at all times.
- **Explanation of the data** - our participants did not always know what data or comparisons were important. Future systems should scaffold their browsing.
- **Pre-explore to become familiar** - the participants who pre-explored the model interface did better on the tasks and rated usability higher than those who did not.
- **More power to comparisons** - when comparing data, users should have control over the format and the system should highlight key trends or differences.
- **Utilise multiple data sources** - people typically get their exercise from multiple sources. Therefore, systems like ours give new ways for people to see these together.

## 7.5 Conclusion

In this work, we evaluated a user model ontology (**Exer-model**) and scrutiny interface that allows users to explore the model and make comparisons across it. The model integrates and interprets multiple sources of sensor data as well as other information from the user. Our evaluation provided qualitative and quantitative insights about the 16 participants who reviewed **Exer-model** for exertion from VR games and incidental activity outside of VR gameplay sessions. Our results provide a number of insights that can inform the design of future ontologies for scrutable user models as well as for the interfaces. Since people had very different interests, the model should represent these and use them to drive personalisation of the ontology. Our work highlights the challenges for creating a user model ontology and scrutiny interface that enables people to build an effective mental model for navigation.

# Part III

Conclusions

# 8 Conclusions

## 8.1 Contributions

This thesis explored how to harness commercial virtual reality (VR) games as a new way for people to gain beneficial levels of exercise. Our work presented the first study of a diverse set of commercial VR games by investigating both short- and long-term VR gameplay. We then explored how to create a user model that represents long-term exercise during VR gameplay as well as other activities, such as walking and a study of the ways people scrutinise such a model. Figure 8.1[1] provides an overview of this work and how its respective chapters link together.

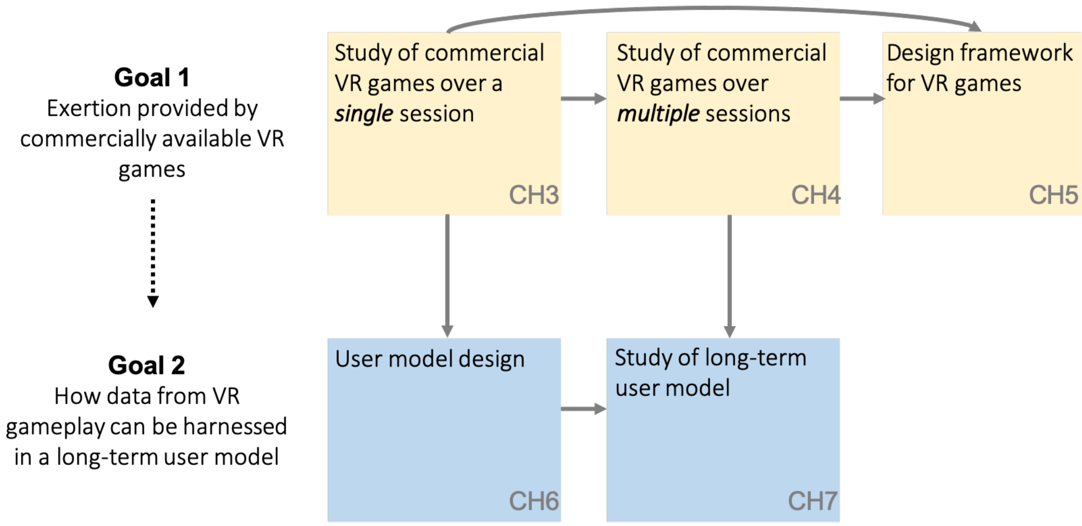


**Fig. 8.1.:** Structure of the relationships between the studies.

Table 8.1 shows the summarises the studies, with the number of participants in each, the length of time, and the chapters they appeared in. We now discuss the key contributions of this thesis, which emerged from a synthesis of the key findings for each chapter.

In Chapter 3, we studied commercial VR games over a single session. This was the first study of a diverse set of commercial VR games and it reported the insights

[1]This is a copy of Figure 1.3, repeated here for convenience

| Chapter | Number of Participants | Length of Study |
|---|---|---|
| CH 3 | 18 | Single session |
| CH 4 | 11 | Multiple sessions (8 weeks) |
| CH 5 | 9 | Single sessions |
| CH 6 | 18 | Single session |
| CH 7 | 16 | Single session |

Tab. 8.1.: Summarises the studies, with the number of participants in each, the length of time, and the chapters they appeared in.

gained about the levels of actual and perceived exertion that can be experienced while playing VR games. From this, the main contribution was that VR games are effective at providing beneficial levels of exertion and the fun and immersion of the game meant that players' attention is shifted away from the exercise itself and moved to the experience. When a player is immersed in the virtual world, they can perceive less exertion than they are actually experiencing.

Chapter 4 explored the ways that people used a VR game studio in a sedentary workplace and how much the exertion contributed to their overall levels of exercise from playing commercial VR games over multiple sessions within a period of 8 weeks. We setup the VR studio in a workplace environment, making it convenient for participants that worked in the same building to participate. We focused on the physical activity participants gained from VR games compared with their daily incidental step data (collected from wearable activity tracking devices) when they were not playing VR games. The study featured in this chapter was the first long-term study of VR games in a sedentary workplace. From this, the work made three key contributions. Firstly, we found that VR games are very promising for providing valuable levels of exertion, while being engaging, over a period of time. This was based on most of the participants visiting over 10 times. Secondly, VR games can contribute towards the recommended minutes of moderate and vigorous activity (Haskell et al., 2007). This is particularly the case for VR games that require a lot of physical movement. Finally, participant self-reports indicate that the VR games can provide positive mental benefits, improving the participant's focus in the workplace. We found from analysing participant feedback and our own observations that playing VR games can not only provide physical fatigue but can also make participants relaxed after a gameplay session.

Building on the work from the previous chapters, Chapter 5 presented the design of a framework to help researchers and designers balance exertion and enjoyment for the types of VR games that require physical movement during gameplay. This framework was used it to create a VR game called Snowballz. The work contributed the framework along with four guidelines that are based on the experience gained from lab studies reported in Chapter 3 and 4 towards designing room-scale VR games that provide beneficial levels of exercise.

Based on the data collected from the single session study in Chapter 3, the work featured in Chapter 6 defined a VR exergame user model called VRex. This model was designed to serve three potential roles for a user model: (1) Recommending VR games based on exertion and game preferences; (2) In-game personalisation; and (3) as an exertion and activity OLM. The key contributions from this chapter were as follows. Firstly, we presented a design of a user model for representing data from long-term VR games. Secondly, we found that as individuals may well have different goals and preferences, these should be taken into consideration when choosing VR games for exercise. Therefore, it is important that user model based personalisation be used to tailor exercise to individual needs, ensuring they are meeting their goals. Finally, a long-term user model for VR games should be used to organise data about an individual and their preferences, such as the VR games they play and their performance.

The final study discussed in Chapter 7, utilised 8 weeks worth of participant data from the study in Chapter 4 to create a user model that was designed with an ontology that represents both gameplay exertion, based on heart-rate sensor data, and broader daily activity based on steps tracked by a smart watch. We then conducted a study into the ways that people can scrutinise their user model. The study involved 16 users: 8 participants returned from the study in Chapter 4, and 8 new participants scrutinised the model of a hypothetical user. This work made the following contributions. Firstly, the results from the study gave us a number of insights into the design of ontologies for scrutable user models as well as for the particular interface onto the Personis representation of the model. Secondly, as people have diverse interests, we concluded it would be valuable to explore ways to enable users to determine the ontology of their own model. Overall, this work highlights the challenges around creating a user model ontology and scrutiny interface.

## 8.2 The Way Ahead

The work in this thesis has provided an understanding around the exertion provided by VR games and explored the ontology of long-term user models to support recommendation and personalisation of VR games. Future work should build on the contributions of this thesis to explore how VR games can now utilise the VRex and Exer models proposed in Chapters 6 and 7. Furthermore, Chapter 5 provides a framework that can be used to design and develop VR games that are balanced between enjoyment, movement and exertion. Further work could explore how this framework could be used to extend long-term capabilities of the Exer model.

This section explores three potential future directions for research that builds on the work in this thesis. In-game personalisation, Recommending VR games with a Content Based Recommender System, and Visualising Exertion through a dashboard. These are explained further below.

## In-Game Personalisation

A particularly promising next step from this thesis would be to explore in-game personalisation in VR games. While VR exergames are effective at delivering exertion and motivating people to exercise, they have the potential to over-exert people as they lack detailed information about the player's level of exertion (Haskell et al., 2007). Personalisation has an important role to overcome this, as it can tailor the VR exercise experience to individuals, potentially leading to safer sessions, higher engagement, and guided progression towards set goals. As discussed in Chapter 6, detecting fitness levels is feasible through heart-rate and step sensors, which can be used to feed that data in real-time to drive the personalisation of the games that support it.

Work by Kang et al. (2016) explored some aspects of this, proposing a model for personalisation that utilised the information from the human body to prescribe appropriate exercises, which users could perform while wearing a head mounted display (HMD). Other work by Shaw et al. (2016) implemented a VR exergame with the Oculus Rift and an exercycle. It was personalised based on heart-rate, where the virtual trainer would slow down if the exercise became too intense or if the player slowed down. The virtual trainer would send motivating messages to the player during the exercise to encourage them to work harder.

We now illustrate our vision, showing how we designed a personalised exergame that takes into account the player's fitness levels and gameplay performance and adjusts accordingly. This was explored through the design and development of a personalised VR game prototype called Snowballz (Yoo et al., 2017c)[2]. Snowballz involves players picking up and throwing snowballs at encroaching virtual enemies (Figure 8.2, Right). The game was first introduced in Chapter 5 as a game that was

[2]A preliminary analysis documented in this chapter was published in: Soojeong Yoo, Callum Parker, and Judy Kay (2017c). 'Designing a Personalized VR Exergame'. In: *Adjunct Publication of the 25th Conference on User Modeling, Adaptation and Personalization*. ACM, pp. 431–435

designed and developed based on the framework introduced there. We now describe how we adapted the game to include personalisation. The prototype utilised a user model and an adapted version of the dynamic difficulty adjustment (DDA) model (Tremblay, 2011) to deliver a personalised gameplay experience. The difficulty level of the game affects the amount and speed of the enemies, and is adjusted dynamically based on gameplay performance and player's heart rate (Figure 8.2, Left). This means that, if the player plays games really well, the number of snowmen will increase and the speed of the level will become faster. To illustrate a simple approach to prevent over-exertion, the game stops when the player's detected heart-rate is vigorous for 2 minutes. We created it to gain insights into ways to introduce such personalisation of the exertion, but further work is needed to test the game in a user study to measure the effectiveness of the personalisation at delivering tailored experiences and exercise over time.

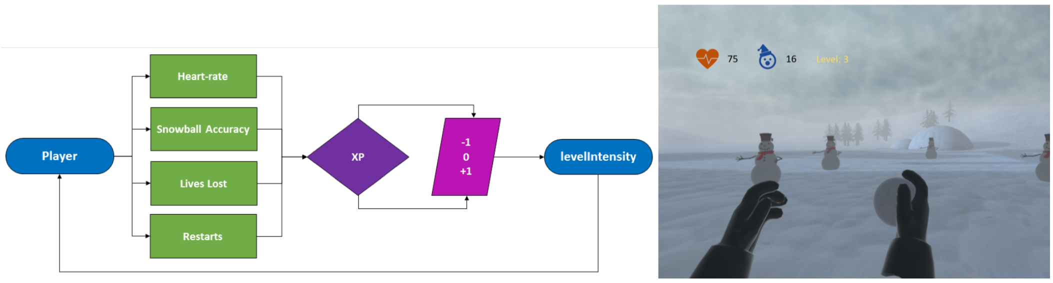


**Fig. 8.2.:** Left: dynamic difficulty adjustment (DDA) model for the Snowballz game; Right: in-game screenshot of Snowballz. The player can use both the hands to throw snowballs at oncoming enemies (snowmen)

## Recommending VR games with a Content Based Recommender System

The second aspect of the future work is to explore the design of a content based recommender system – described by Pazzani and Billsus (2007) as a system that can recommend an item to a user based on the item's properties and a profile of the user's interests.

Such a system could automatically recommend VR games an individual might select to play, based on the user model of previous game preferences available as well as automatically collected sensor data from multiple sources, such as previous VR gameplay and incidental steps from walking during the day. Such recommendation systems draw information from user models, like the Exer-Model presented in Chapter 7, to make recommendations. Therefore, future work should explore how such models could be used with a recommender system to help recommend games based on a user's needs or interests. Such systems are not only useful for VR exergames but can also be featured in normal commercial VR games that require a lot of movement, to ensure players can select games with guidance on the likely exertion.

## Visualising Exertion through a Dashboard

Based on the findings from Chapters 6 and 7, there are two aspects that can be explored when it comes to visualising exertion: (1) visualising during gameplay; and (2) visualising post gameplay. These are explained further in the following points.

**Visualising during gameplay**
As VR games can provide much exertion, it is important to inform players throughout their gameplay how close they are towards reaching their goals and to alert them when they are getting close to being over-exerted. To explore this, we expanded the Snowballz VR game from Chapter 5 by creating two different visualisations for displaying live heart-rate data and gameplay information: (1) situated within the virtual environment itself where the player's heart-rate intensity is represented as a 3D heart (Figure 8.3A); and (2) the head up display (Figure 8.3B), showing from the left the player's current actual heart-rate from the sensor, number of enemies hit, and the game's current level (Yoo et al., 2018c)[3]. The live heart-rate data displayed in this prototype was enabled by the Windows Bluetooth Low Energy Sample[4].

Therefore, future work should explore the design of such interfaces within VR games and define a set of standards that all game designers and researchers can follow.

**Visualising post gameplay**
Another aspect that is an important focus for future work is understanding how we can present gameplay data to players after they finish playing the game. The studies from Chapters 3 and 4 revealed that people wanted to know how much exertion they experienced after their gameplay sessions. Currently, there is no established way to describe the type and level of physical activity a person can expect to gain when playing a VR game. It is also difficult for people to understand how much exercise they get when their activity is sensed from multiple devices. This may

[3]A preliminary analysis documented in this chapter was published in: Soojeong Yoo, Callum Parker, and Judy Kay (2018c). 'Adapting Data from Physical Activity Sensors for Visualising Exertion in Virtual Reality Games'. In: *Proceedings of the 2018 ACM International Joint Conference and 2018 International Symposium on Pervasive and Ubiquitous Computing and Wearable Computers*. ACM, pp. 307–310

[4]https://github.com/ Microsoft/Windows-universal-samples/tree/master/Samples/

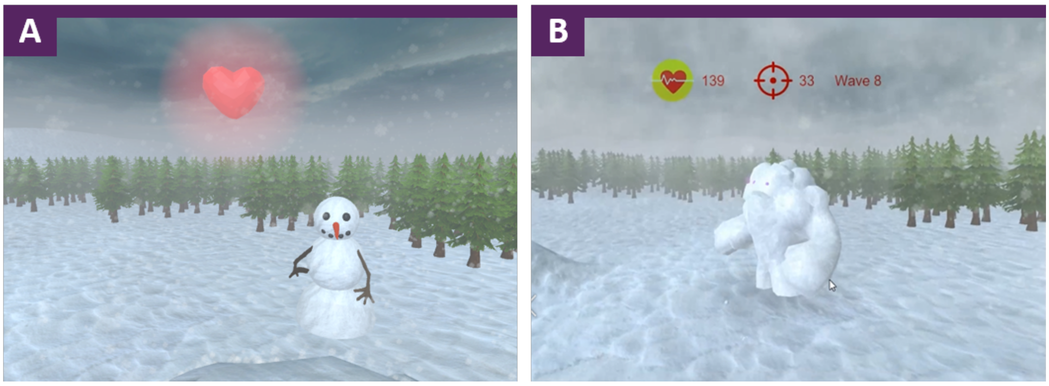


**Fig. 8.3.:** Different data visualisation modes - A: The Snowballz VR game with the heart-rate information displayed in the environment. The 3D heart represents the heart-rate and its glow intensifies and pulsates as the player becomes exerted; B: The player's heart-rate is coloured red due to the player becoming vigorously exerted.

include incidental steps accumulated throughout the day as well as other activities, such as playing games in VR. To address this, we designed a visual overview called Bodymap, which depicts the nature of exercise an individual actually did (Yoo and Kay, 2017)[5]. It can classify VR games based on the part of the body being utilised (Figure 8.4 left) so that players are better informed regarding the games they play to achieve their fitness goals. Additionally, multiple sensor data sources can be harnessed to provide visual feedback to users allowing them to see their long-term physical activity user models within aesthetic user interfaces that support the review of physical activity data from activity trackers and VR games (Figure 8.4 right) (Yoo et al., 2018b)[6].

Future work should expand on the preliminary 2D dashboard we created by exploring how such visualisations could be used in a 3D virtual world. Furthermore, the visualisations could also link with our VRex model from Chapter 6 to display the user model data (combined with their incidental steps and enjoyment along with any other data outside of their VR gameplay).

Such interfaces would need to be tested to gain a better understanding around their understandability and utility, supporting iterative refinement of the design. While

[5]A preliminary analysis documented in this chapter was published in: Soojeong Yoo and Judy Kay (2017). 'Body-map: visualising exertion in virtual reality games'. In: *Proceedings of the 29th Australian Conference on Computer-Human Interaction*. ACM, pp. 523–527

[6]A preliminary analysis documented in this chapter was published in: Soojeong Yoo, Phillip Gough, and Judy Kay (2018b). 'VRFit: an interactive dashboard for visualising of virtual reality exercise and daily step data'. In: *Proceedings of the 30th Australian Conference on Computer-Human Interaction*. ACM, pp. 229–233

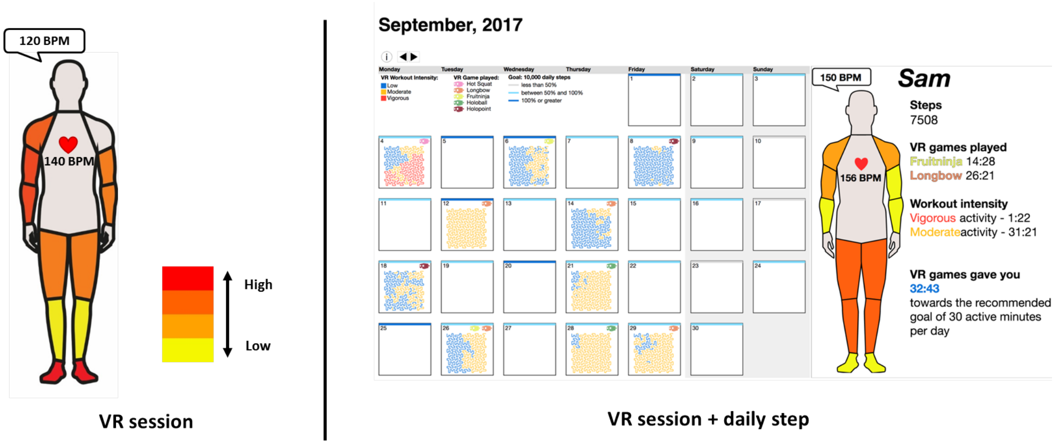


**Fig. 8.4.:** (Left) Bodymap with different color codes for intensity level; (Right) Monthly view visual dashboard where the user can see their physical activity data from multiple VR games and how much recommended level of physical activity they reached.

the current work compared perceived and actual exertion, future work will extend this to the muscle groups and compare with the measured activity over long-term.

## 8.3 Summary

This thesis revealed the actual and perceived exertion that is provided by VR games, in both a single session in a lab setting and multiple sessions in a workplace VR studio setup comparing incidental activity. The work in this thesis also led us to designing an ontology of a long-term user model for VR game data.

The main contribution of this thesis is an understanding of how commercial VR games can be harnessed as a new way for people to gain beneficial levels of exercise. As VR technology improves, it will be easier to setup within people's homes and office environments – this is already becoming easier with the release of VR HMDs that do not require external tracking sensors, like the Oculus Quest[7] and HTC Vive Cosmos[8] which include tracking technology built in without cables.

This thesis has implications not only for VR exergames but also for commercial VR games that are not necessarily designed for exercise. We propose that exertion be a factor that should be considered when designing VR games to ensure it does not get

[7]Oculus Quest - https://www.oculus.com/quest/
[8]HTC Vive Cosmos - https://www.vive.com/au/cosmos/

in the way of a player's enjoyment and allows them to play safely. This is important as VR gaming opens up to a mainstream audience.

# 9 Terminology

## 9.1 Terminology

**Virtual Reality (VR)**
This is a term used for computer systems which utilise various displays and interfaces that aim to provide the user with the feeling of immersion. In the context of this thesis, the term VR is used to describe fully-immersive applications that completely isolate the user from the physical world. This usually involves using some form of head mounted display, like the Oculus Rift or HTC Vive.

**Head Mounted Display (HMD)**
A head mounted display (HMD) is a type of display that is worn on the head. They feature a small display optic for each eye like binoculars.

**Exertion**
This term is used for describing the physical or perceived use of energy. In the context of this thesis, we quantify the amount of exertion someone experiences through worn health sensors and questionnaires.

**Exergame** This term describes the combination of physical exercise and video games (Rizzo et al., 2011).

**Active Minutes**
The active minutes measurement tells you when you have spent at least 10 minutes in an activity that burns three times as many calories as you do at rest. In this thesis, we refer active minutes the heart-rate can be converted to moderate (50%) and vigorous (70%) minutes (Mesquita et al., 1996; Haskell et al., 2007) or 100+ steps (Pedišić and Bauman, 2014)

**User Model**
A user model is the collection and categorisation of personal data associated with a specific user. A user model is a (data) structure that is used to capture certain characteristics about an individual user, and a user profile is the actual representation in a given user model.

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# Appendix A

## A.1 Participant Information Statement

Please note that at the time this document was written for a 10 week study, but we did not end up running the studies for that long.

THE UNIVERSITY OF SYDNEY

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**Exercise motivation through a fully-immersive gamified virtual reality experience**

**PARTICIPANT INFORMATION STATEMENT**

**(1) What is this study about?**

You are invited to take part in a research study with the aim of understanding the user experience when exercising within a personalised 3D virtual world with a dashboard to show long-term progress. It will also enable you to discover how much exercise you get from the VR games, compared with your steps exercise you get, measured by a physical activity tracker. This study involves trialling a series of VR games and prototypes. It allows you to view a 3D virtual world through a head mounted display while physically running on the spot to traverse through the virtual world. Other physical actions include jumping and tilting to avoid virtual objects that may appear in the virtual world.

You have been invited to participate in this study because *you are on one of the university's mailing lists or you responded to a poster.* This Participant Information Statement tells you about the research study. Knowing what is involved will help you decide if you want to take part in the research. Please read this sheet carefully and ask questions about anything that you don't understand or want to know more about.

Participation in this research study is voluntary. So it's up to you whether you wish to take part or not.

By giving your consent to take part in this study you are telling us that you:

- ✓ Understand what you have read
- ✓ Agree to take part in the research study as outlined below
- ✓ Agree to the use of your personal information as described.

You will be given a copy of this Participant Information Statement to keep.

**(2) Who is running the study?**

The study is being carried out by the following researchers:

- Prof. Judy Kay, Lecturer in Design Computing, University of Sydney.
- Soojeong Yoo, PhD Candidate, University of Sydney.

Soojeong Yoo is conducting this study as the basis for the degree of Doctoral of Philosophy at The University of Sydney. This will take place under the supervision of Prof. Judy Kay.

**(3) What will the study involve for me?**

You will be invited to attend an average of one VR session a week over 10 weeks. In this time, we will ask you to wear a physical activity tracker daily and when you come to VR session you will receive access to a virtual reality headset running prototype software for a trial period. You will be instructed on how to use the system before commencement of the trial period. During the trial period you will be encouraged to interact with the virtual world as much as possible and may be asked to perform some basic tasks so that we can measure the difficulty of the system's usability.

Additionally, during the trial period you will be recorded via audio and video. These recordings will not be shared or published in any form and will only be used by the researchers for their observations. No personal data will be collected and data about your usage of the smartphone application will not be shared with anyone else.

Your heart-rate will be collected during the trial for finding out your level of exertion in a particular game. It will be used only to classify the game by the amount of exertion it provides and will also be used to create a dashboard where you can visualise your performance after you have completed the game.

Following the trial period, you will be asked to participate in an interview to discuss the prototype. You may be shown footage of yourself interacting with the system and asked to discuss what is shown.

**(4) How much of my time will the study take?**

*This study runs over 10 weeks timed to fit your preferences. Each session will involve a minimum of 10 minutes of VR game-play but you may continue playing if you wish. Also, each session has a short pre-session and post-session questionnaire takes 5 minutes each. In addition, at the end of the final session, we will ask you to complete a 20 minutes questionnaire and interview.*

**(5) Who can take part in the study?**

*Anyone that is 18 years or older.*

**(6) Do I have to be in the study? Can I withdraw from the study once I've started?**

Being in this study is completely voluntary and you do not have to take part. Your decision whether to participate will not affect your current or future relationship with the researchers or anyone else at the University of Sydney.

If you decide to take part in the study and then change your mind later, you are free to withdraw at any time. You can do this by notifying either researchers via the contact details provided on page 1.

If you decide to withdraw from the study, we will not collect any more information from you. Please let us know at the time when you withdraw what you would like us to do with the information we have collected about you up to that point. If you wish your information will be removed from our study records and will not be included in the study results, up to the point that we have analysed and published the results.

You are free to stop the interview at any time. Unless you say that you want us to keep them, any recordings will be erased and the information you have provided will not be included in the study results. You may also refuse to answer any questions that you do not wish to answer during the interview.

**(7) Are there any risks or costs associated with being in the study?**

It is well documented that potential exists for people to experience motion sickness while wearing a head mounted display to view a virtual world. Not everyone experiences this, but if it does occur you may have a break at any time and quit the study.

**(8) Are there any benefits associated with being in the study?**

We cannot guarantee or promise that you will receive any direct benefits from being in the study.

**(9) What will happen to information about me that is collected during the study?**

By providing your consent, you are agreeing to us collecting personal information about you for the purposes of this research study. Your information will only be used for the purposes outlined in this Participant Information Statement, unless you consent otherwise.

Your information will be stored securely and your identity/information will be kept strictly confidential, except as required by law. Study findings may be published, but you will not be individually identifiable in these publications.

The information collected will only be used to help guide our system's design. The video and audio recordings will be used for observational purposes only and will not be publically broadcasted or distributed.

**(10) Can I tell other people about the study?**

Yes, you are welcome to tell other people about the study.

**(11) What if I would like further information about the study?**

When you have read this information, *Soojeong Yoo* will be available to discuss it with you further and answer any questions you may have. If you would like to know more at any stage during the study, please feel free to contact *Soojeong Yoo via email (syoo6624@uni.sydney.edu.au) or Professor Judy Kay via phone (02 9351 4502) or email (judy.kay@sydney.edu.au).*

**(12) Will I be told the results of the study?**

You have a right to receive feedback about the overall results of this study. You can tell us that you wish to receive feedback by *ticking the receive feedback box on the consent form.* This feedback will be in the form of *a one page summary via email.* You will receive this feedback after the study is finished.

**(13) What if I have a complaint or any concerns about the study?**

Research involving humans in Australia is reviewed by an independent group of people called a Human Research Ethics Committee (HREC). The ethical aspects of this study have been approved by the HREC of the University of Sydney *[2016/089].* As part of this process, we have agreed to carry out the study according to the *National Statement on Ethical Conduct in Human Research (2007).* This statement has been developed to protect people who agree to take part in research studies.

If you are concerned about the way this study is being conducted or you wish to make a complaint to someone independent from the study, please contact the university using the details outlined below. Please quote the study title and protocol number.

The Manager, Ethics Administration, University of Sydney:

- **Telephone:** +61 2 8627 8176
- **Email:** ro.humanethics@sydney.edu.au
- **Fax:** +61 2 8627 8177 (Facsimile)

*This information sheet is for you to keep*

# A.2 Participant Consent Form

1

THE UNIVERSITY OF SYDNEY

**Faculty of Engineering and Information Technologies**

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**Professor Judy Kay**
*CHAI Principal*

**Soojeong Yoo**
*PhD Candidate*

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**Exercise motivation through a fully-immersive gamified virtual reality experience**

**PARTICIPANT CONSENT FORM**

I, ................................................................................. [PRINT NAME], agree to take part in this research study.

In giving my consent I state that:

- ✓ I understand the purpose of the study, what I will be asked to do, and any risks/benefits involved.
- ✓ I have read the Participant Information Statement and have been able to discuss my involvement in the study with the researchers if I wished to do so.
- ✓ The researchers have answered any questions that I had about the study and I am happy with the answers.
- ✓ I understand that being in this study is completely voluntary and I do not have to take part. My decision whether to be in the study will not affect my relationship with the researchers or anyone else at the University of Sydney now or in the future.
- ✓ I understand that I can withdraw from the study at any time.
- ✓ I understand that I may stop the interview at any time if I do not wish to continue, and that unless I indicate otherwise any recordings will then be erased and the information provided will not be included in the study. I also understand that I may refuse to answer any questions I don't wish to answer.
- ✓ I understand that personal information about me that is collected over the course of this project will be stored securely and will only be used for purposes that I have agreed to. I understand that information about me will only be told to others with my permission, except as required by law.

I understand that the results of this study may be published, but these publications will not contain my name or any identifiable information about me unless I consent to being identified using the "Yes" checkbox below.

☐ Yes, I am happy to be identified.

☐ No, I don't want to be identified. Please keep my identity anonymous.

I consent to video-recording and photos which will be used purely for research analysis:

- **Video-recording** YES ☐ NO ☐
- **Photos** YES ☐ NO ☐

I consent to the video recordings being used in public presentations about the research:

- **Video-recording** YES ☐ NO ☐
- **Photos** YES ☐ NO ☐

I consent to data being recorded and analysed:

- **Heart-rate** YES ☐ NO ☐
- **Physical activity tracker (such as Fitbit)** YES ☐ NO ☐

**Are you happy to attend 10 VR sessions and wear a physical activity tracker over the 10 weeks period?**

**YES** ☐ **NO** ☐

**Would you like to receive feedback about the overall results of this study?**

**YES** ☐ **NO** ☐

If you answered **YES**, please indicate your preferred form of feedback and address:

☐ Email: ______________________________________________________

................................................................
**Signature**

..................................................................
**PRINT name**

.................................................................................
**Date**

## A.3 Pre Study Information Email

Dear <INSERT NAME HERE>,

We are seeking participants for a study which aims to understand exercise gained and the user to experience when exercising within a 3D virtual world over a long-term period (over 10 weeks). Participants will be asked to wear a physical activity tracker such as Fitbitt during their day-to-day activities and attend weekly VR sessions where they will be asked to wear a virtual reality headset to play virtual reality exercise games and heart-rate monitor to measure the level of exercise.

There is a short (5 minutes) questionnaire before at the start and end of each sessions. Also at the very end of session, an interview will be conducted which involves answering questions about the experience, system and motivation.

The study is being conducted by Professor Judy Kay (Director, CHAI Lab, University of Sydney) and Soojeong Yoo (PhD candidate, CHAI Lab, University of Sydney).

Please email Soojeong Yoo at syoo6624@uni.sydney.edu.au if you would like participate in the study.

Kind Regards,

Judy Kay – Chief Investigator

Soojeong Yoo – PhD Candidate

## A.4 Pre Study Questionnaire

THE UNIVERSITY OF SYDNEY

Faculty of Engineering and Information Technologies

**Professor Judy Kay**
*CHAI Principal*
*Chief Investigator*

**Soojeong Yoo**
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*Student Investigator*

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**PRE-STUDY QUESTIONNAIRE**

| OFFICE USE ONLY | |
|---|---|
| **Participant Number:** | |

**Diversity Questions**

1. **Age:**

2. **Gender:**

3. **Occupation:**

**Physical Health Questions**

4. **Are you pregnant?**

5. **Has your doctor ever told you that you have a heart condition or have you ever suffered a stroke?**

6. **Do you ever experience unexplained pains in your chest at rest or during physical activity/exercise?**

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7. **Do you ever feel faint or have spells of dizziness during physical activity/exercise that causes you to lose balance?**

8. **Have you had an asthma attack requiring immediate medical attention at any time over the last 12 months?**

9. **If you have diabetes (type I or type II) have you had trouble controlling your blood glucose in the last 3 months?**

10. **Do you have any diagnosed muscle, bone, or joint problems that you have been told could be made worse by participating in physical activity/exercise?**

11. **Do you have any other medical condition(s) that may make it dangerous for you to participate in physical activity/exercise?**

**Cybersickness Questions**

12. **Do you frequently experience any of the following (please circle all that apply):**
    a. **Claustrophobia**
    b. **Vertigo**
    c. **Epilepsy**
    d. **Seizures**

**Important:** **If you answered "yes" to any of the questions in the physical and cybersickness sections, you will not be included in the study for your safety. If you have any concerns, please seek the advice from your GP.**

**Thank you for your participation.**

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# A.5 Post Study Questionnaire

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**QUESTIONNAIRE (post-study)**

**System Usability Scale**

| | Strongly disagree | | | | Strongly agree |
|---|---|---|---|---|---|
| 1. I think that I would like to use this system frequently | 1 | 2 | 3 | 4 | 5 |
| 2. I found the system unnecessarily complex | 1 | 2 | 3 | 4 | 5 |
| 3. I thought the system was easy to use | 1 | 2 | 3 | 4 | 5 |
| 4. I think that I would need the support of a technical person to be able to use this system | 1 | 2 | 3 | 4 | 5 |
| 5. I found the various functions in this system were well integrated | 1 | 2 | 3 | 4 | 5 |
| 6. I thought there was too much inconsistency in this system | 1 | 2 | 3 | 4 | 5 |
| 7. I would imagine that most people would learn to use this system very quickly | 1 | 2 | 3 | 4 | 5 |
| 8. I found the system very cumbersome to use | 1 | 2 | 3 | 4 | 5 |
| 9. I felt very confident using the system | 1 | 2 | 3 | 4 | 5 |
| 10. I needed to learn a lot of things before I could get going with this system | 1 | 2 | 3 | 4 | 5 |

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**General feedback**

1. Was there anything you particularly liked about the application?

2. Was there anything that you think could be improved?

3. Do you have any other comments?

Thank you for your participation.

## A.6 Post Study Presence Questionnaire

THE UNIVERSITY OF SYDNEY

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**QUESTIONNAIRE (post-study)**

**Presence questionnaire (immersion)**

1. How responsive was the environment to actions that you initiated (or performed)?

|________|________|________|________|________|________|________|

NOT AT ALL MODERATELY COMPLETELY RESPONSIVE

3. How natural did your interactions with the environment seem?

|________|________|________|________|________|________|________|

COMPLETELY ARTIFICIAL BORDERLINE NATURAL

4. How much did the visual aspects of the environment involve you?

|________|________|________|________|________|________|________|

NOT AT ALL SOMEWHAT COMPLETELY

6. How compelling was your sense of objects moving through space?

|________|________|________|________|________|________|________|

NOT AT ALL MODERATELY VERY COMPELLING

7. How much did your experiences in the virtual environment seem consistent with your real world experiences?

|________|________|________|________|________|________|________|

NOT AT ALL MODERATELY VERY CONSISTENT

9. How completely were you able to actively survey or search the environment using vision?

|________|________|________|________|________|________|________|

NOT AT ALL SOMEWHAT COMPLETELY

10. How compelling was your sense of moving around inside the virtual environment?

|________|________|________|________|________|________|________|

NOT AT ALL MODERATELY VERY COMPELLING

11. How closely were you able to examine objects?

|________|________|________|________|________|________|________|

NOT AT ALL PRETTY CLOSELY VERY CLOSELY

12. How well could you examine objects from multiple viewpoints?

|________|________|________|________|________|________|________|

NOT AT ALL SOMEWHAT EXTENSIVELY

14. How much delay did you experience between your actions and expected outcomes?

|________|________|________|________|________|________|________|

NO DELAYS MODERATE DELAYS LONG DELAYS

16. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?

|________|________|________|________|________|________|________|

NOT AT ALL REASONABLY PROFICIENT VERY PROFICIENT

17. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?

|________|________|________|________|________|________|________|

NOT AT ALL INTERFERED SOMEWHAT PREVENTED TASK PERFORMANCE

**Exercise questionnaire**

1. In terms of exercise how strenuous do you feel today's workout was on a scale of 1 to 5?

1 |________|________|________|________|________| 5

2. How exhausted do you feel on a scale of 1 to 5?

1 |________|________|________|________|________| 5

3. How difficult did you feel today's video game was on a scale of 1 to 5?

1 (not difficult) |________|________|________|________|________| 5 (very difficult)

4. On a scale of 1 to 5 how interesting did you find today's game?

1 |________|________|________|________|________| 5

5. How difficult was it to focus on the game?

Not difficult|________|________|________|________|________| Very difficult

6. How difficult was it to control the game?

Not difficult|________|________|________|________|________| Very difficult

# A.7 Interview Questions

1

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**LAB STUDIES INTERVIEW QUESTIONS**

**Before the sessions**

- How tired are you feeling now?
    - Physical (1 – 7)
    - Mental (1-7)
- Why did you come today for study?
- Which game do you want to play and why?

**After sessions**

- Body map and RPE
- Game (Fun)
- Exertion (physical)
- Exertion(mentally)
- Beginner (interaction)
- Anything particularly like about this game?
- Or dislike?

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