How Will Different Control/Display Ratios Influence Muscle Fatigue and Game Experience in Virtual Reality Games?

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How Will Different Control/Display Ratios Influence Muscle Fatigue and Game Experience in Virtual Reality Games?

Hur Påverkar Olika Kontroll/Skärm förhållanden Muskeltrötthet och Spelupplevelse inom Virtual Reality Spel?

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Abstract

The dramatic evolvement of Virtual Reality (VR) technique in recent years has enabled a rapid growth of VR games. In order to provide intuitive interaction with a virtual world, VR hand controllers were developed. Since this kind of controller is based on hand movement, the risk of getting fatigued becomes very high. However, little current research has addressed the impact of fatigue generated by VR hand controllers. In this study, the influence of different Control/Display (C/D) ratios of hand controllers on muscle fatigue and the game experience in VR games was explored. Based on an established mobile VR fishing game, a test scenario was developed which uses Oculus Rift and Oculus Touch hand controller. A user study was conducted with 24 participants. The between subjects design was applied which spans three groups experiencing fishing with different C/D ratios (1.0, 0.5, 0.1 respectively). During the test, self-perceived fatigue data as well as game experience data was collected. The results showed that the fatigue was reduced gradually along with the decreasing of the C/D ratio, while different C/D ratios produced an impact on game experience depending on the margin between the exact ratio and 1.0. Based on the results, some implications for the design of VR games were introduced.

Keywords
Virtual Reality, Control/Display ratio, fatigue, game experience, hand controller.
Sammanfattning


Nyckelord
Virtual Reality, Control/Display ratio, trötthet, spelupplevelse, handkontroll
Preface

This degree project was performed at Resolution Games where I have had a wonderful six-month experience. Everyone in Resolution is talented and passionate about games. I have learned a lot about games and Virtual Reality. Thank you Tommy Palm for offering me this opportunity and telling me inspiring life stories.

I am specially indebted to my supervisor Björn Thuresson for always giving me inspiring and excellent suggestions when I was confused what to do next, keeping track of my progress and giving constructive feedbacks during the whole process, making sure the paper progressed and helping refine it.

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I would like to thank Mikael Eriksson for accompanying and giving me the support for programming and the thesis work.

Thank you Tino Weinkauf for examining this thesis.

Thanks to Lennart Jönsson for being my opponent and Li Ling for proofreading this paper.

Finally, I would like to convey my gratitude to VIC studio in KTH where I know the charms of interaction technology, its potential to change the world and what I would like to do in the future.
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## Key terminology

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<th>Word</th>
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<tr>
<td>VR</td>
<td>Virtual Reality</td>
<td>The computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors.</td>
</tr>
<tr>
<td>HMD</td>
<td>Head-Mounted Display</td>
<td>A display device, worn on the head or as part of a helmet, that has a small display optic in front of one (monocular HMD) or each eye (binocular HMD). In this paper, it refers to a virtual reality headset, a head-mounted device aimed to provide an immersive virtual reality experience.</td>
</tr>
<tr>
<td>VE</td>
<td>Virtual Environment</td>
<td>A computer-generated, three-dimensional representation of a setting in which the users perceive themselves to be and within which interaction takes place. This word will only be used in the quotes from previous research.</td>
</tr>
<tr>
<td>C/D ratio</td>
<td>Control/Display ratio</td>
<td>The magnitude of hand movement (Control) to the magnitude of cursor movement (Display) gives a ratio called the Control-to-Display (or C/D) ratio.</td>
</tr>
<tr>
<td>DOF</td>
<td>Degrees of Freedom</td>
<td>Number of independent motions that are allowed to the body.</td>
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1 INTRODUCTION

In recent years, VR has emerged as a relevant platform in many domains, e.g. visualizing architecture, simulation of accidents and emergencies, education and training, and — which is the topic of this text — gaming. There is a not insignificant hype around a number of hardware manufacturers such as Oculus VR, HTC & Valve, Samsung and Sony, just to name a few. Oculus VR is a VR company founded in 2012 and bought by Facebook in 2014, which released its first headset prototype in 2012, making it the leader of the industry. HTC, a manufacturer of smartphones and tablets, and Valve, a video game developer and digital distribution company creating the popular PC gaming platform Steam, came together and created the HTC Vive. Sony's PlayStation VR concentrates on bringing VR for console. Samsung's Gear VR headset makes mobile VR come to the market. 2016 is a key year in this recent trend where we'll see the commercial release of Oculus Rift (consumer version), HTC Vive, PlayStation VR, which symbolized the beginning of a new VR era. In fact, VR has existed for decades in technology circles and specific professional settings, applied in domains like industry design, medicine, training, etc., but was never successfully introduced to the consumer market. It is the booming of VR devices that officially has the potential to bring VR to consumers and enable VR to appear in our daily life, which makes it a hype for VR. The challenge now is to make these VR devices more affordable, wearable and support better VR experiences.

Among a wealth of VR application fields, VR games are currently in the limelight. As for traditional video games, interactivity is a focus area for VR games as well. How should players interact with the game content is at the center of many a heated discussion. In video games, players use traditional controllers as input devices, for example, gamepads, mice, keyboards, touch screens and joysticks. When it comes to VR, which provide a 360-degree exploration of the media content and more immersive experience, traditional controllers are far from sufficient or satisfactory. That is why there is a need for specific VR hand controllers. The position of the controllers can be detected in 3D space and these positions are typically shown inside the virtual environment with the presence of virtual hands. It enables hand movements of players for interaction, enhancing the sense of presence and supporting better game experience. However, if the game session lasts longer, players get fatigued (or tired) quite fast. How can we reduce fatigue to enable longer playing sessions while maintaining a good game experience? This degree project is going to explore this topic.

This chapter serves as an introduction part describing the background knowledge for the study, the specific platform and game content, as well as stating and contextualizing the research question.
1.1 Background

1.1.1 A brief history of Virtual Reality

The concept, “Virtual Reality”, is traditionally considered to be coined by Jaron Lamier, CEO of VPL Research, in 1989 (Krueger, 1991). Afterwards, it started to be described as “a computer simulated environment with and within the people can interact” (Riva, 2006).

![Image of Boom and CAVE](http://www.w2vr.com/archives/Fisher/07a_Boom_15.jpg)  
![Image of CAVE](https://upload.wikimedia.org/wikipedia/commons/6/6d/CAVE_Crayoland.jpg)

Figure 1: The pictures of Boom (left) and CAVE (right)

From the technological perspective, VR is defined as “a particular collection of technological hardware: computers, head-mounted displays (HMD), headphones and motion-sensing gloves” (Steuer, 1992). These hardware helps VR artificially create sensory experience, such as sight, sound, touch, and even smell. An integrated VR system is the combination of the hardware and software, which, according to Brooks (1999) and Burdea and Coiffet (2003), includes: “the output tools (visual, aural and haptic), that immerse the user in the virtual environment”; “the input tools (trackers, gloves or mice) that continually reports the position and movements of the users”; “the graphic rendering system that generates, at 20-30 frames per second, the virtual environment”; “the database construction and virtual object modeling software for building and maintaining detailed and realistic models of the virtual world.” The existing VR devices are the HMD, the Boom — a counterbalanced CRT-based stereoscopic viewing device (W2vr.com, 2016) — known as Binocular Omni-Orientational Monitor, and the CAVE — a projection-based VR display (Cruz-Neira, Sandin and Defanti, 1993) — known as CAVE Automatic Virtual Environment. For the images of Boom and CAVE, see Figure 1.

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1 Source for the image: http://www.w2vr.com/archives/Fisher/07a_Boom_15.jpg  
2 Source for the image: https://upload.wikimedia.org/wikipedia/commons/6/6d/CAVE_Crayoland.jpg
On the other hand, VR can also be described from an experiential aspect as “a real or simulated environment in which a perceiver experiences telepresence” (Steuer, 1992). This definition derives from an important standard in VR, the sense of presence. Presence is “the subjective experience of being in one place or environment, even when one is physically situated in another” (Witmer and Singer, 1998). Telepresence extends the definition of presence and concentrates one’s feeling “being there” (Reeves, 1991) in a mediated environment instead of a physical one.

1.1.2 Virtual Reality games and game devices

The usage of VR has spanned a wide range of fields. Generally it can be divided into two categories: “the simulation of a real environment for training and education” and “the development of an imagined environment for a game or interactive story” (WhatIs.com, 2016). This thesis concerns the latter. The graphics, sound and input technology in traditional video games can be contained into VR. Witmer and Singer (1998) argued that depriving users of sensation in physical environment will increase the degree of immersion in the Virtual Environment (VE). “If users perceive that they are outside of the simulated environment and looking in (e.g., while viewing the environment via a CRT display), the immersive aspect is lost” (Witmer and Singer, 1998). In this case, to generate fully-immersive VR, devices such as HMD are usually employed for VR games. From early 1990s, different HMDs have been gradually released for gaming, such as Virtual Boy from Nintendo, the iGlasses from Virtual I-O, the Cybermaxx developed by Victormaxx and the VFX1 Headgear released by Forte Technologies, shown in Figure 2.
Nowadays, several VR headsets from the new HMD generation enable incredible visual clarity for us to explore virtual worlds. A few examples of such headsets including Oculus Rift, Sony PlayStation VR, HTC Vive and Samsung Gear VR can be found in Figure 3. Most of these virtual reality headsets are tethered headsets which use special curved lenses to magnify and stretch the screen across the field of vision (Wikipedia, 2016c). Oculus VR’s previous two Development Kits, known as DK1 and DK2, were released in 2012 and 2014 in which Oculus DK1 started the current trend for the booming of VR. (For more description, see chapter 1.1.3 Oculus Rift and Oculus Touch) Sony PlayStation VR with codename Project Morpheus brings the VR to console games, which runs on PlayStation 4 home video game console instead of a PC. HTC Vive was developed by HTC teaming up with Valve, which is the first device to offer a “full room-scale” experience, “letting you get up, walk around and explore your virtual space, inspect objects from every angle and truly interact with your surroundings.” (D’Orazio

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3 Source for the image: https://en.wikipedia.org/wiki/File:Virtual-Boy-Set.jpg
5 Source for the image: http://i.ebayimg.com/images/g/6a8AAOSw8d9Uy~P0/s-l1600.jpg
6 Source for the image: https://upload.wikimedia.org/wikipedia/commons/thumb/1/12/Forte_VFX1_Headgear.jpg/600px-Forte_VFX1_Headgear.jpg
and Savov, 2015). Samsung Gear VR is the VR headset for the mobile platform released by Samsung collaborated with Oculus. The headset itself includes a touchpad and back button on the side acting as a controller while using a Samsung Galaxy device as the display and processor. Apart from the headsets introduced above, Google has newly announced a VR platform, Google Daydream, for high quality mobile VR coming in fall 2016 (Vr.google.com, 2016).

![Image of new generation of HMDs: Oculus Rift, Sony PlayStation VR, HTC Vive, and Samsung Gear VR.](image)

Figure 3: The pictures of new generation of HMDs: Oculus Rift (top left), Sony PlayStation VR (top right), HTC Vive (bottom left) and Samsung Gear VR (bottom right)

Besides marvelous vision and audio provided by the VR headsets, users can also interact with the virtual world through different controllers. With respect to the naturalness of mapping, there is one typology dividing controllers into four possible types: the “directional natural mapping” controller, the “kinetic natural mapping” controller, the “incomplete tangible natural mapping” controller, and the “realistic tangible natural mapping” controller (Skalski et al., 2010). The categories range from complete arbitrary to complete natural: an example of the directional natural mapping.

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7 Source for the image: http://www.wareable.com/media/images/2015/06/rift-1434103169-HeuX-column-width-inline.jpg
8 Source for the image: http://www.wareable.com/media/images/2016/04/10763-36b575e6509de1ae638e899c0723f588-1460473262-xx9-column-width-inline.jpg
9 Source for the image: http://www.wareable.com/media/images/2016/04/vive-1-1460470510-5ylD-column-width-inline.jpg

5
controller can be a QWERTY keyboard used to play a game by assigning key randomly; kinetic natural mapping refers to using body movement to control games, however, “without having a realistic and tangible controller”, such as Sony EyeToy, Kinect, etc; incomplete tangible natural mapping controllers such as Nintendo Wiimote provide a simulated feeling of an object in the game environment; finally, realistic tangible natural mapping controllers support complete natural feeling by adding realistic tangibility such as steering a wheel in a driving game. VR hand controller, the emerging controller for VR, belongs to the category of “incomplete tangible natural mapping”. Although the tangible feeling is not completely realistic (for example, there is no force feedback), it is flexible, portable and supports natural mapping and intuitive interaction with virtual world.

Figure 4: The pictures of different VR hand controllers: Oculus Touch\(^\text{11}\) (1), PlayStation Move controller\(^\text{12}\) (2) and HTC Vive controller\(^\text{13}\) (3)

The most famous VR hand controllers are Oculus Touch, PlayStation Move controller and HTC Vive controller, shown in Figure 4. Oculus Touch is the revolutionary controller interacting with Oculus Rift HMD. More detailed description can be found in chapter 1.1.3 Oculus Rift and Oculus Touch. The potential competitor comes from PlayStation Move controller and HTC Vive. The wireless PlayStation Move controller has “a dynamic color changing sphere”, “vibration feedback”, and “an easy to use button

\(^{11}\) Source for the image: http://core0.staticworld.net/images/article/2015/09/oculus-touch-2-100616982-orig.png
\(^{12}\) Source for the image: https://media.playstation.com/is/image/SCEA/psmove-imageblock-us-25nov14?$TwoColumn_Image$
\(^{13}\) Source for the image: http://vrgizmoz.com/wp-content/uploads/2016/04/vivecontroller.jpg
interface” (PlayStation, 2016). It allows tracking user’s hand movement by using two motion controllers, for example, drawing your arrow and release in an archery tournament. HTC Vive controllers work together with HTC Vive HMD to achieve precise motion tracking and natural controller gestures in room scale. As indicated in Figure 4, they have buttons such as home button, “triggers on each controller”, “two circular touchpads” and “pressure-sensitive grips” (Vrgizmoz.com, 2016).

1.1.3 Oculus Rift and Oculus Touch

Oculus Rift is one of the most popular VR HMD developed by the company Oculus VR. For the latest consumer version, Rift has an OLED display with 2160 x 1200 resolution (1080 x 1200 resolution per eye) and 90Hz refresh rates. The field of view is 110 degrees. It allows 360-degree positional tracking within 5 x 11 feet area by so-called "Constellation" tracking system supported by two IR LED sensors. It connects to a PC via USB and HDMI, and features integrated audio (Staff, 2016).

Oculus Touch is the controller working with Oculus Rift, which tries to unlock new possibilities for interactions in the VR field and our ability to interact with the content (Oculus.com, 2015). The pair of half-moon-shaped controllers delivers hand presence giving users the sensation of feeling their own hands in the virtual world (Oculus.com, 2015). As can be seen in Figure 5, each controller has a traditional analog thumb stick, two buttons, a trigger designed for putting the index finger and a ‘hand trigger' which rests near the middle finger. It also has a small, bracelet-sized ring that sits around the user's hands. The sensors on the ring allow the Touch controllers to be tracked in virtual space and, purportedly, track motions like waves, gestures, and other hand poses.

As briefly stated in the beginning of this chapter, Oculus started the VR trend. The previous two versions of the development kits have brought people impressive VR experiences which were the leader of VR industry. The first consumer version was officially launched on March 28th, 2016. Therefore, this degree project uses Oculus Rift and Oculus Touch to study user’s interaction with VR and the game experience in VR games.
1.1.4 Example game — *Bait!*

This study was conducted at Resolution Games\textsuperscript{15}, a VR games studio, and used their VR fishing game — *Bait!* — as an example game to conduct a case study on. The main gameplay for *Bait!* is fishing which mimics the behavior in reality. It requires repetitive motions such as casting and people get fatigue when doing it for a long time. There are a wealth of similar games, for example, sports games such as tennis games, golf, baseball, etc. This made the game a good example of which the results can be reused in other cases. For a detailed description of the game and the implemented scenario, see chapter 3.1 Development of the game scenario for testing.

1.2 Purpose of the study

1.2.1 Statement of the problem

VR hand controllers are designed to enhance the immersion and presence of VR games and amply improve the game experience. However, since this kind of controller is based on hand movements, the risk of getting fatigued (or tired) is higher compared to typical game controllers like Xbox or PlayStation gamepads, and the fatigue,

\textsuperscript{14} Source for the image: http://www.hardcoregamer.com/wp-content/uploads/2015/12/Oculus-Touch-2.jpg

\textsuperscript{15} http://www.resolutiongames.com/games/
obviously, will have an impact on playing duration and the general experience of the game. Researchers have been studying fatigue for a long time. There is a lot of existing research outlining design implications for reducing fatigue for gesture-based/mid-air interaction techniques; however, no prior research has, to my knowledge, examined the role of VR hand controllers and how to balance the fatigue with game experience.

One possible way to reduce fatigue is to adjust the mapping from control space (real world) to display space (VR), allowing a small hand movement to achieve a big movement in VR. A concept, Control/Display (C/D) ratio, can be used to explain this. The amplitude of hand movement (Control) to amplitude of cursor movement (Display) gives a ratio called the C/D ratio. If the ratio is less than 1.0, whatever you do in reality with the hand controller, the movement will be amplified in VR. The current studies relevant to C/D ratio concentrate on the improvement of performance in pointing and manipulating, or the influence on perception of objects’ properties such as pseudo-haptic textures. For more details, go to chapter 2.1 Control/Display Ratio in VR. Yet few studies to date have investigated the potential of C/D ratio to reduce fatigue.

In this study, I will investigate the relationship among mappings of the hand controller — through changing C/D ratios — from control space to virtual display space and explore the effects on fatigue and game experience in VR.

1.2.2 Research question

In short, the research question is how different C/D ratios of the hand controller, from control space to virtual display space, would influence fatigue and game experience in VR games over time.

If C/D ratio equals 1, which is one-to-one mapping, the game experience may remain high but the fatigue will increase obviously. The fatigue may decrease the game experience as playing time increases. On the other hand, the low C/D ratio enables small hand movements, which can remove fatigue to some extent; however, it may decrease the game experience because of lack of naturalness. This report is going to explore if there is a way to balance the naturalness of mapping to limit the fatigue yet still generate a better sense of game experience.

1.2.3 The audience for the study

The possible audiences for the study are people working in the VR game industry that want to get some inspiration for game mechanics design using a VR hand controller, and researchers working on interaction technology.
1.3 Delimitations

The research question was explored through a case study. The specific type of gameplay, fishing, was taken as an example and the specific platform Oculus Rift and its hand controller Oculus Touch were deployed.

The fatigue stated in the research question only refers to muscle fatigue exclusive of mental fatigue. The measurement of fatigue only concerns the subjective feeling, with no psychobiological data collected.

Besides, the long-term effect (e.g., more than one hour and more than one gaming session) of C/D ratios on fatigue and game experience was not investigated.

1.4 Ethical concerns

My research is independent and impartial. The participation in this study is entirely voluntary and all the participants gave their consent to participate in the study by signing a consent form (for more on the details, see APPENDIX A. Consent form). The confidentiality and anonymity of respondents was respected and there is no risk for physical harm to the participants for participating the study.
2 THE LITERATURE REVIEW

This chapter describes the scientific background to the three main categories adding up to the research question: Control/Display ratio, fatigue and game experience.

2.1 Control/Display Ratio in VR

2.1.1 Mapping from reality to VR

Mapping, according to Jonathan Steuer in the seminal article on the definition of virtual realities, is “a function of both the types of controllers used to interact with a mediated environment and of the ways in which the actions of these controllers are connected to actions within that environment” (Steuer, 1992). Specifically, in this study, mapping refers to the ways on how the actions of VR hand controllers are linked to the actions in VR. Mapping is an important variable in VR, which directly affects the interaction between users and VR and then, in turn, influence the perception of the VR experience.

In VR, virtual cursors are usually applied to provide interactivity – “the extent to which users can participate in modifying the form and content of a mediated environment in real time” (Steuer, 1992) – such as reaching, manipulation and reshaping. People can achieve different mappings from reality to the virtual world through reproducing the movement of the user’s real hands for the virtual cursors. In this case, we introduce a concept Control/Display ratio.

2.1.2 Definition of Control/Display ratio and its applications

Literally, the Control/Display ratio (or C/D ratio) represents the ratio between “the amplitude of movements of the user's real hand and the amplitude of movements of the virtual cursor” (Dominjon et al., 2005). If the ratio equals 1, the user’s real motion will be directly mapped into the VR, which then represents a one-to-one mapping. If the ratio is less than 1, there is an amplification of user’s actual motion so as to cover larger scale movements in VR. One example is the famous Go-Go Interaction Technique (Poupyrev et al., 1996) which uses a non-linear mapping from nearby to further distance with ratio decreasing in order to seamlessly reaching and manipulating objects at any distance. In the CAVE, introduced in chapter 1.1.1 A brief history of Virtual Reality, the C/D ratio usually is smaller than 1 in order to make sure the user can cover the whole workspace. On the contrary, if the ratio is more than 1, a diminution of actual motion is achieved. One application of such a ratio is Precise and Rapid Interaction through Scaled Manipulation.
(PRISM). In contrast to Go-Go, PRISM dynamically changes C/D ratio making the virtual cursor less sensitive to user’s real hand movements to increase precision (Frees and Kessler, 2005). One good example of applying C/D ratio can be mouse acceleration. The moving distance of the cursor on the screen depends on the moving speed of the physical input device (typically a mouse). The cursor will go much further if the user moves the mouse quickly than that if user moves the mouse slowly. In other words, the C/D ratio changes along with the speed of the mouse. Moreover, C/D ratio can be used to improve target acquisition through semantic pointing (Blanch, Guiard and Beaudouin-Lafon, 2004).

There are several studies trying to discover the effects of different C/D ratios on the perception of objects’ properties. Dominjon and his colleagues have studied “the influence of the C/D ratio on the perception of mass of manipulated objects in Virtual Environment” (Dominjon et al., 2005). Participants were asked to weigh two virtual balls and tell which one was heavier. Balls were displayed on a computer screen, and participants could manipulate them via a haptic interface. The reference ball maintains a constant mass with C/D ratio 1.0. The comparison balls are a set of the certain mass and certain C/D ratio. The results show that manipulated objects “tended to be perceived as significantly lighter than its actual weight when using a C/D ratio smaller than 1” (Dominjon et al., 2005). Another example comes from the research of Lécuyer et al. (2004) on pseudo-haptic textures. They modified the C/D ratio of the cursor on the screen to create an illusion of texture feelings such as bumps and holes. An evaluation conducted later indicated that participants can successfully draw the profile of bumps and holes simulated which shows the possibility of “simulate textures on desktop without haptic feedback” (Lécuyer et al., 2004).

As was stated in chapter 1.2.1 Statement of the problem, this study will investigate the potential of C/D ratio to reduce fatigue. The next section will introduce the definition of fatigue and its measurement.

2.2 Muscle Fatigue

2.2.1 Definition of fatigue

Fatigue, “also referred to as tiredness, exhaustion, lethargy, and listlessness, describes a physical and/or mental state of being tired and weak” (Medical News Today, 2015). Fatigue is essentially a subjective feeling usually identified as a symptom, which people feel and describe, rather than a sign, which can be detected. There are basically two kinds of fatigue: psychological (mental) fatigue and physical fatigue. Mental fatigue
refers to “a temporary inability to maintain optimal cognitive performance” (Wikipedia, 2016a). Simplified, it means “concentrating on things has become harder” (Medical News Today, 2015). On the contrary, physical fatigue concentrates on muscle effort. Since this study is going to explore player’s muscle fatigue after gaming, only physical fatigue will be focused. When a person’s muscles cannot do things as easily as they used to, the person is experiencing physical fatigue, also known as muscle fatigue. It is also defined as the decline in ability of a muscle to generate force (Wikipedia, 2016b). Several factors can result in muscle fatigue that may relate to mental fatigue as well.

2.2.2 Measurement of Muscle Fatigue and the implications for VR applications

Muscle fatigue can be assessed by either self-reported subjective assessment or objective measurement. A large number of self-report scales have been developed to measure fatigue. There is even a paper (Dittner, Wessely and Brown, 2004) giving the guidance for selection of the suitable scale, since different scales can measure different aspects of experienced fatigue. Among them, the most widely used are Borg’s range model and the NASA Task Load Index (NASA-TLX). NASA-TLX (Hart and Stavenland, 1988) is “a multi-dimensional rating procedure that derives an overall workload score based on a weighted average of ratings on six subscales” (Humansystems.arc.nasa.gov, 2016). It is considered to be a robust measure of subjective workload (Moroney et al., 1995). Bustamante and Spain, however, think the TLX lacks “scalar invariance, thereby biasing the estimation of mean scores and making the examination of mean differences misleading” (Bustamante and Spain, 2008). Borg’s range model (Borg, 1998), also known as Borg’s perceived exertion, can be further divided into the Borg RPE (Rating of Perceived Exertion) and CR10 scales, with more details discussed later.

Objective measurement covers detection for muscle oxygenation and swelling, heart rate, blood pressure and so on, which usually needs specialized apparatus like clinical dynamometers. One widely used measurement is electromyography (EMG), “a diagnostic procedure to assess the health of muscles and the nerve cells that control them (motor neurons)” (Mayoclinic.org, 2016). It usually requires relatively long duration to record enough data to analyze muscle fatigue.

Apart from traditional measurements, many studies created new methods to evaluate the degree of fatigue especially for gesture-based or mid-air interaction where users report higher fatigue than normal interaction. Neera Pradhan and his colleagues (Pradhan et al., 2015) proposed a novel, more predictable measure of fatigue. Based on Human Motor Coordination, they calculated Continuous Relative Phase (CRP) for any two joints and evaluated the variability of CRPs. Later they found the correlation
between the variability of CRPs and fatigue through comparison with subjective measurement tools. Bachynskyi et al. (2013) first came “biomechanical simulation with performance analysis to inform design”. They applied optical motion tracking to record the actual movements and derived performance data such as speed and accuracy. With these data, they conducted a biomechanical simulation and derived an index of fatigue. In this way, they avoided difficult and expensive measurements such as EMG.

Within different categories of muscle fatigue, arm fatigue is prone to receive more concern because it’s the main fatigue generated in gestural interaction, which will be the focus of this study as well. Gorilla-arm effect is the special term for fatigue in the arm muscles. Zavala-Ibarra and Favela (2012) assessed fatigue using ambient videogames and measured arm fatigue utilizing a custom-designed interaction device. Hincapié-Ramos et al. (2014) proposed an objective and non-invasive metric, Consumed Endurance (CE), collecting data through a low-cost gestural tracking system to quantify arm fatigue. Moreover, they compared the proposed method with the Borg CR10 scale of perceived exertion to find if the two correlate or not. Actually, studies tended to use self-perceived Borg's scale together with objective measurement to make their study more reliable and valid. For example, Chan et al. (2000) combined Borg RPE with EMG to measure fatigue during a training session of violin players.

Since the motivation of the study is to understand both the game experience and fatigue, player's subjective feeling when playing a game tend to be of critical importance. Moreover, an individual's perception of exertion has been suggested to be the best indicator of the degree of physical strain (Borg, 1982) and a reliable way to measure fatigue (Noble and Robertson, 1996); thus, the study will concentrate on subjective assessment for fatigue instead of objective measurement. Furthermore, objective measurement usually includes obtrusive and cumbersome apparatus such as gloves for data collection, which will influence user's game experience. Among a substantial number of self-perceived scales, Borg’s range model has been widely tested and considered a benchmark and therefore will be used in this study for fatigue measurement.

2.2.3 Borg’s range model

Borg’s range model (Borg, 1961, 1962, 1998), as Elisabet Borg (2001) stated, “with the assumption that the subjective range from a minimal to a maximal intensity perception may be set equal for all persons”, “provided the theory needed for the development of a series of verbally level-anchored scales”. Among them, the RPE scale (Borg, 1970, 1998) and the CR10 scale (Borg, 1982, 1998) are the ones widely acknowledged.
The Borg RPE scale is a scale for ratings of perceived exertion (RPE). The RPE scale tends to indicate data along with “stimulus intensity, heart rates (HR) and oxygen consumption for steady state aerobic work on bicycle ergometer (4 to 6 minutes)” (Borg, 2001). Thus, the scale starts with 6 (instead of 0 such as CR10), and the number range from 6 to 20 corresponds to “a HR range from 60 to 200 beats per minute in healthy people, about 30 - 40 years old” (Borg, 2001).

The Borg CR10 scale is a general intensity category scale with ratio properties with numbers from 0 to 10 (Borg, 1998). “On the CR10 scale the verbal anchors and numbers are placed congruently to render ratio data that mimic what is obtained by magnitude estimation” (Borg, 2001).

The Borg RPE is a tool for estimating effort and exertion, breathlessness, and fatigue during physical work; while the Borg CR10 is a general scale for most subjective magnitudes (Borg, 1998). In this study, the Borg CR10 will be used to measure participant’s arm fatigue. More details about the content of Borg CR10 and the way it is used in the user study can be found in chapter 3.5 Measures in the user test.

Having introduced the concepts of C/D ratio and fatigue, the next section focuses on the remaining key variable in the research question, game experience.

2.3 Game Experience and its measurement

2.3.1 What is Game Experience?

The Game Experience, or in this case, digital game experience, refers to “the feelings and experiences people have when they play digital games” (Poels, de Kort and Ijsselsteijn, 2007). Since the feelings can never be measured by only one dimension, there is a wide range of studies investigating different dimensions of game experience. Among current research, a model of 9 User Experience Dimensions proposed by Poels et al. (2007) was considered comprehensive. Based on these 9 dimensions, a self-report measure of game experience — Game Experience Questionnaire (IJsselsteijn, de Kort and Poels) — was identified and is widely used in many studies.

2.3.2 Game Experience Questionnaire

Game Experience Questionnaire (GEQ) is part of the FUGA project. “The main objective of the FUGA project was to create novel methods and improve existing measures in order to examine how the different aspects of gaming experience (e.g.,
different emotions and cognitions) can be assessed comprehensively with high temporal resolution.” (Fuga.aalto.fi, 2016). The GEQ so far has been applied in a number of experimental research studies (Gerling, Klauser and Niesenhaus, 2011).

GEQ has a modular structure and mainly consists of four parts: the core questionnaire, the social presence module, the post-game module as well as an in-game version of the GEQ. There are seven different dimensions of player experience for the core questionnaire: Sensory and Imaginative Immersion, Tension, Competence, Flow, Negative Affect, Positive Affect, and Challenge (IJsselsteijn, de Kort and Poels).

The in-game version of GEQ selects items from core questionnaire and can be regarded as a concise version, which is developed for assessing game experience at multiple intervals during a game session. In the in-game version, the interpretations for seven dimensions can be read in Table 1: Seven dimensions and interpretations for the in-game version of Game Experience Questionnaire.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Interpretations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensory and Imaginative Immersion</td>
<td>How is the player interested in or impressed by the game</td>
</tr>
<tr>
<td>Tension</td>
<td>How does the player feel frustrated and irritable</td>
</tr>
<tr>
<td>Competence</td>
<td>How skillful and successful does player feel</td>
</tr>
<tr>
<td>Flow</td>
<td>How immersive and absorptive does player feel</td>
</tr>
<tr>
<td>Positive Affect</td>
<td>The player’s positive feeling towards the game such as good, content, etc.</td>
</tr>
<tr>
<td>Negative Affect</td>
<td>The player’s negative feeling such as bored, tired, etc.</td>
</tr>
<tr>
<td>Challenge</td>
<td>How much effort player need to put into the game</td>
</tr>
</tbody>
</table>

The post-game module assesses how players feel after they have stopped playing the game. It consists of four dimensions: Positive Experience, Negative experience, Tiredness and Returning to Reality. Similar to in-game version, the dimensions of Positive/Negative Experience measures the player’s positive/negative feeling towards the game. The dimension of Tiredness measures to which extent the player feels tired after playing the game. The dimension of Returning to Reality measures if the player was absorbed in the story just like returning back from a journey.
2.3.3 Game Engagement Questionnaire

The tendency to become engaged in playing video games is one important sub-dimension of game experience. In this case, Game Engagement Questionnaire (GEnQ) (Brockmyer et al., 2009) was designed to explore player engagement in video games, assuming that “more engagement could lead to a greater impact for game-playing” (Brockmyer et al., 2009). GEnQ examines the four dimensions: Immersion, Presence, Flow and Absorption.

The definitions of these four high level dimensions vary in the research literature. In GEnQ, the definition of Immersion is similar to Presence and helps to measure Presence. Immersion is used to “describe the experience of becoming engaged in the game-playing experience while retaining some awareness of one’s surroundings” (Brockmyer et al., 2009). Presence refers to: a subjective experience of being in one place or environment, even when one is physically situated in another” (Witmer and Singer, 1998). When it comes to VR, it means experiencing the virtual environment rather than the actual physical locale. Flow is the term used to “describe the feelings of enjoyment that occur when a balance between skill and challenge is achieved in the process of performing an intrinsically rewarding activity” (Brockmyer et al., 2009). Absorption is the term used to describe total engagement in the present experience (Irwin, 1999). The common characteristic of both flow and absorption is to “induce an altered state of consciousness”, which is kind of opposite to immersion and presence, knowing situated in another place. The difference between flow and absorption can be the motivation because good sense of flow is the result from good performance feedback (Brockmyer et al., 2009).

Since the study is about VR games and two of the four dimensions, Presence and Immersion, are key characteristics for VR, the results of GEnQ together with GEQ can be helpful to indicate the answer to the research question.
3 METHODOLOGY

This chapter describes the main methodology used to explore the research question. First of all, a fishing game scenario was implemented for the Oculus Rift HMD and Oculus Touch hand controller, based on a fully-developed VR fishing game, Bait!, from Resolution Games for Samsung’s mobile platform. This game scenario was the basis for a user study. The between subjects design was applied which uses three settings with C/D ratios, equal to 1.0, 0.5, 0.1 respectively. During the test, game experience data as well as user’s self-evaluated fatigue data was collected at regular intervals along the test period. After the test, participants filled out two post-game questionnaires and a post-test debriefing session was conducted. The collected data was later analyzed with the results summarized in later chapters.

3.1 Development of the game scenario for testing

3.1.1 Introduction to Bait!

*Bait!* is a VR fishing game developed by Resolution Games for the mobile platform Samsung Gear VR. The game begins with the player coming to *Bait! Island*. In order to save a struggling aquarium where the player works, he or she has to catch a rare fish. During the game, the player catches a lot of different fish and makes friends with the locals. There are four different lakes in the game, each with a distinct style and its own unique set of fishes.

3.1.2 How to fish in Bait!

The original game uses a one button control. By tapping on the touchpad on the Samsung Gear VR HMD combined with aiming using “virtual anchor”, players can achieve actions such as casting, reel in, confirm, etc. The “virtual anchor” is a pointer between user’s two eyes indicating the direction where the user looks at. The fishing rod will move along with the movement of the player’s head. A glowing marker on the water surface gives a hint of where the bobber will hit the water, shown in Figure 6: The marker on the water surface. By judging the elevation of the player’s head above the horizon, a marker will reach into the lake on the corresponding distance. Players tap to throw the bobber into the water and tap & hold to reel in.
3.1.3 Fishing using Oculus Touch

Based on the original game, the game was transferred from the mobile platform to the PC platform and the Oculus Rift HMD and implemented control of fishing using the Oculus Touch hand controllers. One of the fishing scenes — Ocean Lake — was chosen as the game scene for testing, shown in Figure 7.

Players can hold and swing the fishing rod that moves with the motion of the real hand. The bobber on the edge of the fishing rod moves along with the motion of the fishing rod. When it comes to casting, it mimics the way it’s done in real-life fishing. As shown in Figure 8, players press the index finger trigger to start casting, similar to locking the line. When players release the trigger, the fishing line will fly away. The direction and...
distance where the fishing line flies depend on the velocity of bobber the moment trigger was released. When the bobber is in the water, to press the index finger trigger will lock the line, enabling players to drag the line to adjust the bobber position. After a fish bites the hook, either of buttons A or B can be used to reel in.

![Image of Oculus Touch controllers with instructions: "Press to reel in" and "Press to start casting. Release to release the line. After line is released, press to lock the length of the line."

*Figure 8: The control instruction for fishing using Oculus Touch*

In order to achieve different mappings from reality (control space) to virtual world (display space), I implemented different C/D ratios for casting. To begin with, I would like to introduce a conceptual framework (Keijser et al., 2007) to explain the mapping between control and display. In general, the mapping between input Degrees of Freedom (DOF) and output DOF can be described as a function:

\[ f : R^n \rightarrow R^m \]

where \( n \) refers to the control DOF and \( m \) refers to the display DOF. Specifically, if we described a mapping from 3DOF input space to 3D position in display space, the function can be written in a specific form:

\[ f : R^3 \rightarrow R^3 \]

The C/D ratio particularly describes the scale relationship between control space and display space, which can be defined as follows:

\[ f(\Delta x, \Delta y, \Delta z) = (S_x \Delta x, S_y \Delta y, S_z \Delta z), S_i \in R \]

Usually the scale for each axis remains the same \((S_x = S_y = S_z)\), which is applied to our study as well.
When it comes to the casting, I wrote a function to have different scales of movement between player’s real hand and the virtual hand. Once the casting starts — index finger trigger is pressed — the position of the starting point of the real hand will be recorded. Based on the distance between the starting point and the real hand position afterwards, as well as C/D ratio setting, the corresponding change will be applied to the position of the virtual hand. For example, if the C/D ratio equals 0.5, all the movement of the real hand will be doubled in the virtual world after casting starts, which allows for smaller movements of the real hand than that in one-to-one mapping. When the casting ends — index finger trigger is released — the position of the virtual hand will be back to the position of the real hand after 1 second. The range of C/D ratio is \((0, 1]\).

3.2 Research participants

A total of 26 participants took part in the user study, including two pilot testers. They were recruited through Facebook, email, message, etc. All of them are attending university or have graduated from university. For the 24 participants, the proportion of female and male equals 50%. Participants’ age ranged from 20 to 39 (M=23.79, SD=3.92), with 21 out of 24 participants under 25. None of them has experience with VR hand controller and none of them has played Bait! before.

While the potential participants were being recruited, the following characteristics were considered: people who show interest in VR and games and new interaction technology; people who can be potential purchasers for VR products; people with age ranging between 20 and 40 years old. There are several motivations for choosing the target group: First of all, in order to make the results meaningful and practical, it is preferred to have the participants who are interested in VR and even the potential purchasers. In addition, for Bait!, the game itself aims for offering relaxing experience for casual gamers and has no specific user segment. Thirdly, because of the limited number of participants and the between-subjects design, it is important to spread out the age groups and be aware of that it means only having a small number of users from each age group. Furthermore, for user group above 40 years old, it is easier for them to get fatigue than the group between 20 and 40. For the user group under 20 years old, most of them do not have individual economic capability to purchase VR products.

3.3 User test design

Based on the key variable C/D ratio, a between subjects design was used to compare fatigue and game experience in each condition. The 24 participants were divided into
three groups, with 8 participants (4 males, 4 females) in each group. Each group was assigned to play the fishing game with one of the following three settings: (1) C/D ratio equals 1.0, (2) C/D ratio equals 0.5, or (3) C/D ratio equals 0.1.

The purpose of the study is to figure out users’ fatigue and game experience over time. The consideration for between subjects design is that both fatigue and experience are subjective experience and will change with time. The fatigue will be accumulated when participants perform lengthy task sessions, while the game experience may wear off. Thus, it is preferred that each condition is tested by a unique set of users with similar characteristics.

The whole user test session lasted for around 70 minutes. The first 15 minutes of each session was for welcoming, participant filling out the consent form (see APPENDIX A. Consent form) and background questionnaire (see APPENDIX B. Background questionnaire), explaining control instructions for fishing (see APPENDIX D. Instructions for fishing) to the participant. This process was organized with an introduction script (see APPENDIX C. Introduction script), read verbatim to participants to make sure the instructions to everyone are the same. The background questionnaire was used to help to understand participant’s behavior and opinions.

The last 15 minutes was for participants to fill out post-test questionnaires and the moderator to conduct a post-test debriefing session. Post-test questionnaires consisted of two parts: Game Experience Questionnaire (GEQ) post-game module (see chapter 2.3.2 Game Experience Questionnaire) and Game Engagement Questionnaire (GEnQ) (see chapter 2.3.3 Game Engagement Questionnaire). The post-test debrief topics (see APPENDIX F. Post-test debriefing guide) were made of two parts: self-perceived fatigue and mapping from reality to the virtual world. The debriefing shed light on participant’s own thoughts directly related to the research question and what he or she thought about that.

During the middle, around 40 minutes, of the session, participants played the fishing game and finished several tasks (see APPENDIX E. Task scenarios). The purpose of setting tasks was to keep the participants active during the whole test, so as to study the fatigue and game experience during a certain period of time (40 minutes). Participant did not have to finish all the tasks. During the game, questionnaires collecting participants’ self-perceived fatigue popped up in the game three times at 15 minutes, 30 minutes, 40 minutes respectively after the game began; questionnaires collecting participants’ in-game experience popped up twice at 10 minutes and 40 minutes respectively. The duration participants used to answer in-game questionnaire will not be counted into the 40 minutes. The popup of questionnaires was controlled by the game program itself.
3.4 Technology set-up for the user test

The game ran in the Unity game engine (version 5.2.1f) on a Windows 8.1 PC connected to an Oculus Rift HMD with two trackers. The Oculus Touch hand controller was used to play the game. The test was conducted in a separate room. Participants sat on an unbacked chair around one meter away from the computer. A digital voice recorder was used to create audio recordings for backup for post-test debriefing. The same set-up was employed for all tests.

3.5 Measures in the user test

Data was collected about participants’ self-perceived fatigue, participants’ in-game experience, how many times players cast, participants’ post-game experience, qualitative data about participants’ experiences towards fatigue and mapping from reality to the virtual world.

**Fatigue.** The self-perceived fatigue of player’s right forearm during the game was measured by the Borg CR10 scale. The questionnaire shown in Figure 9 was used in the test. The fatigue of the right forearm was collected because it is the part used most for casting in the game. The Borg CR10 scale “provides a ratio-scale measure of physical exertion which values are matched to verbal anchors” (Hincapié-Ramos et al., 2014). Borg CR10 values range from 0 to 10, where 0 corresponds to "Nothing At All" and 10 to "Extremely strong".
In addition, qualitative data about how participants felt about tiredness was also collected through post-test interview. The questions in detail can be read in APPENDIX F. Post-test debriefing guide.

**Game Experience.** The participants’ in-game experience was measured by the Game Experience Questionnaire in-game version (see chapter 2.3.2 Game Experience Questionnaire) and participants’ post-game experience was measured by the Game Experience Questionnaire post-game module, see chapter 2.3.2 Game Experience Questionnaire as well, and Game Engagement Questionnaire, described in chapter 2.3.3 Game Engagement Questionnaire.

**Number of casting.** How many times each participant has cast was collected by the game program itself.

**Opinions towards mapping from reality to the virtual world.** Participant’s opinions about the mapping from reality to the virtual world was collected through post-test interview. For more on the questions, see APPENDIX F. Post-test debriefing guide.
3.6 Test procedure

Upon arriving at the company, participants were asked to fill out a consent form. They were then invited into a room containing the testing devices. Once they sat down, the moderator started guiding the test session through an orientation script. First, the moderator briefly introduced the whole study and the procedure of the test session; then the moderator explained how to play and control the game with the use of the Oculus Touch controller. Afterwards, the calibration of the Oculus Rift was conducted, after which the game was started. The participant played the game in VR, following task scenarios read to the participants by the moderator who sat near the participant collecting data and offering help if needed. After the allotted time, the participants was asked to fill out the post-test questionnaires. Once finished, the participant was debriefed and dismissed. The moderator wrote down the player’s casting times by inspecting the log file in the game program. The test procedure was the same for all the different groups. The entire test took about 70 minutes. A picture of a participant playing the game can be seen below in Figure 10.

*Figure 10: The participant was playing the game in VR*
3.7 Analysis of the collected data

To begin with, different collected data were categorized with charts constructed. The author has all the raw data, which can be accessed upon request until the end of 2016. Based on the data type, there were 1/ chart of background questionnaire, 2/ chart of number of casting & fatigue, 3/ chart of in-game experience, 4/ chart of GEQ post-game module (see chapter 3.5 Measures in the user test), 5/ chart of GEnQ (see chapter 3.5 Measures in the user test) 6/ chart of opinions about mapping.

Following the instructions from the questionnaires, the scales of different items were categorized into different dimensions (for more on dimensions, see chapter 2.3.2 Game Experience Questionnaire and chapter 2.3.3 Game Engagement Questionnaire) and the scores for each dimension of each participant were calculated. For different types of data, the average value and standard deviation for each group were figured out.

Finally, all the data were summarized and filled into the charts. For quantitative data, different figures were drawn.

The analysis software Numbers (Apple, 2016) was used for data analysis and figure generation.
4 RESULTS

This chapter presents the results from all the conducted user studies. The results were organized by different measures collected during the test, with four parts in total: number of casting, fatigue data, game experience data and opinions about mappings. For each part, the results were illustrated depending on different groups, with comments immediately following. There were three groups: the group of C/D ratio = 1.0, the group of C/D ratio = 0.5 and the group of C/D ratio = 0.1. For simplification and easy understanding, the symbols $C/D_{1.0}, C/D_{0.5}, C/D_{0.1}$ would be used in the following part.

4.1 Results on numbers of casting

Based on different C/D ratios, the average number of casting as well as Standard Deviation (SD) has been calculated for each condition, shown as Figure 11.

![Figure 11: The average number of casting for each group based on the C/D ratio. There was an obvious increase in the number (100) where $C/D_{0.1}$ compared to other groups (83 and 77)](image)

As Figure 11 indicated, there was an obvious increase in the average number of casting for the $C/D_{0.1}$ condition, compared to other conditions. This may result from the easier and smaller movement with low C/D ratio.

The average number of casting for the conditions of $C/D_{1.0}$ and $C/D_{0.5}$ were of a comparable value with a small margin.
4.2 Results from the fatigue measurement

4.2.1 In-game self-perceived fatigue by Borg CR10 Scales

![Figure 12: Participants’ self-perceived fatigue of their right forearms through Borg CR10 Scales, recorded three times at 15 mins, 30 mins and 40 mins. The letters refer to different participants.]

The results of the participants’ self-perceived fatigue of their right forearm during the game through Borg CR10 Scales can be seen in Figure 12. The fatigue scales were recorded three times at the timestamp 15 minutes, 30 minutes and 40 minutes.

For the $C/D_{1.0}$ group, 5 out of 8 participants’ Borg CR10 increased compared the first record with the last one, 4 of which rose significantly.

For the $C/D_{0.5}$ group, 6 out of 8 participants’ Borg CR10 climbed; however, 5 of them stabilized between 30 minutes and 40 minutes.

For the $C/D_{0.1}$ group, all first records of Borg CR10 Scales were above 0, distinguishing from the other two group; but 6 of them either remained constantly or went up slightly from 15 minutes to 40 minutes.

4.2.2 Results from post-test debriefing

Apart from in-game questionnaires, the perceived fatigue was also collected through post-test debriefing. The summary of the results shows the following:

For the $C/D_{1.0}$ group, 6 out of 8 participants reported tiredness of their right forearm, with different levels. Most of them felt slightly tired and felt different compared to before the test. 2 out of 8 participants did not feel tired because they go to the gym regularly. The average time when they started feeling tired range from 15 to 30 minutes.
For the $C/D_{0.5}$ group, 6 out of 8 participants reported tiredness of their right forearm. They used the words such as “a little bit”, “kind of”, “slightly”, “moderately” to describe the fatigue extent. Similar to the $C/D_{1.0}$ group, 2 out of 8 participants did not feel tired because they go to the gym regularly. The average time when they started feeling tired is around 25 to 30 minutes.

For the $C/D_{0.1}$ group, 2 out of 8 participants reported slight tiredness of their right forearm and the times at which they started feeling tired were around 25 minutes and 30 minutes. The other 6 did not feel tired when being interviewed.

Besides the fatigue data stated above, some other interesting results were found as well. First, players tried to find a way to rest when they started feeling tired. 12 in the 24 participants mentioned that they rested their hand in their laps when they were not casting. One participant said “I didn’t have to hold like that all the time; if I hold my arm straight, I will easily get tired”. In addition, there were a lot of other problems reported which may not be related to physical fatigue but were also noteworthy. After a 40-minute gaming session, all of them felt uncomfortable wearing the VR headset. The cause can be fatigue in their eyes, the feeling of tightness from the headset, the pressure on the nose (the headset is pretty heavy). 3 of them felt tired in their fingers because of grabbing hand controllers and pressing the buttons.

4.3 Results from data collected on game experience

4.3.1 Results from in-game experience data collection

The Figure 13 below reflected in-game experience of different groups and how they changed during the game from 10 minutes to 40 minutes.

![Figure 13: Results from data collected through Game Experience Questionnaire in-game version, recorded twice at 10 mins and 40 mins. The colored lines represent different dimensions.](image-url)
As is illustrated in chapter 2.3.2 Game Experience Questionnaire, the dimension of Sensory and imaginative immersion referred to the extent players were interested in or impressed by the game itself, and the dimensions of Positive/Negative affects referred to the player’s positive/negative feeling towards the game. In this case, different C/D ratios were not supposed to have any impact on these three dimensions and the results have proved this: all the three groups for these three dimensions kept the same level with a moderate upward trend for negative affect and minimal downward trend for the other two dimensions along with the time.

As for the dimension of Competence, both the $C/D_{1.0}$ group and $C/D_{0.1}$ group dropped while the $C/D_{0.5}$ group rose from 10 minutes to 40 minutes. The values of the $C/D_{1.0}$ group were the highest for both the records at 10 minutes and 40 minutes despite a slight drop. For the $C/D_{0.1}$ group, the value at 10 minutes was higher than that of $C/D_{0.5}$ group; however, it fell quickly and was lower than that of the $C/D_{0.5}$ group at 40 minutes.

The figure reveals that the $C/D_{0.1}$ group had a relatively low value for the dimension of Flow, compared to the other groups. The value of flow decreased along with the novelty of the VR technology fading off.

There was an upward trend for all the groups concerning the dimension of Tension. The level of player’s frustration increases with the decrease of C/D ratios.

The dimension of Challenge for the $C/D_{0.1}$ group increased rapidly compared to the two records at different time stamps. The values for the other two groups were constant with a relatively low value.

4.3.2 Results from post-game experience data collection

The quantitative data were from two post-test questionnaires: Game Experience Questionnaire post-game module and Game Engagement Questionnaire. For more on the details of these questionnaires, see chapter 2.3.2 Game Experience Questionnaire and chapter 2.3.3 Game Engagement Questionnaire.

Figure 14 indicated the average values as well as SDs for the different groups of each dimension on Game Experience Questionnaire post-game module.
Figure 14: Results from data collected through Game Experience Questionnaire post-game module, indicating the average scale for each dimension of different groups (C/D₁, C/D₀.₅ and C/D₀.₁).

As was mentioned in chapter 2.3.2 Game Experience Questionnaire, the purpose of post-game experience questionnaire is to evaluate how players felt after they stopped playing from an overall perspective while in-game questionnaire aimed to evaluate continuous and real-time experience.

For the Positive Experience, the average value of the C/D₀.₁ group was the highest, with a value of 2.02; however the SD was also very high. It indicated that different participants valued the positive feeling differently within the group, which can be supported by the qualitative data shown later. On the contrary, the average value of the C/D₀.₅ group was the lowest.

The Negative Experience increased along with the decrease of the C/D ratios. Similar to Positive Experience, the SD for the C/D₀.₁ group remained very high compared to the other two groups.

After a 40-minute game session, the Tiredness levels for groups of C/D₁ and C/D₀.₅ remained the same while participants from the C/D₀.₁ group felt less tired. In this case, tiredness referred to the overall feeling, not limited to muscle fatigue.

The dimension of Returning to reality for the three groups remain at a comparable level.
Figure 15: Results from data collected through Game Engagement Questionnaire, indicating the average scale for each dimension of different groups ($C/D_{1.0}$, $C/D_{0.5}$ and $C/D_{0.1}$).

The goal of Game Engagement Questionnaire is to investigate how engaged the players were with the game. As can be viewed in Figure 15, the values of the $C/D_{0.1}$ group remained the lowest in all the four dimensions with the highest SD. For the dimensions of Flow and Presence, the $C/D_{1.0}$ group was the highest while the $C/D_{0.5}$ group was the highest for the dimensions of Absorption and Immersion.

4.4 Results of viewpoints towards different mappings

This section will present a summary of the participant’s opinion about the different mappings, from control space to virtual display space in four aspects: if the mapping is natural, if the difference in the mapping has been noticed, if the mapping is fun, if the mapping can limit fatigue.

The $C/D_{1.0}$ group can be regarded as the reference group since it represented one-to-one mapping. All the participants from the group remarked on the mapping from reality to the virtual world. They thought it was intuitive and natural. Comments like “feel very natural”, “I have the illusion of controlling my own hand even though there was no force feedback” were given.
For the $C/D_{0.5}$ group, the results are listed as follows:

- All participants thought the mapping felt natural.
- There was an interesting phenomenon that 6 out of 8 participants have not noticed the mapping differences from reality to the virtual world if not mentioned in the interview.
- All participants thought the mapping was fun. Comments like “feel easier than reality”, “it’s better to have mappings different from the reality”, “fun, like the mapping”, etc. were noted.
- 3 out of 5 participants thought this mapping could reduce fatigue; comments like: “it’s good I don’t need to do the whole movement” were given. The other 3 participants couldn’t tell whether it can remove fatigue because they had not noticed the difference of mapping.

For the $C/D_{0.1}$ group, the results were listed as follows:

- 5 out of 8 participants thought the mapping felt natural, but the other 3 participants felt it to be unnatural.
- All participants noticed the mapping differences. Comments like: “when you move the wrist, the whole forearm can move” were given.
- 2 out of 8 participants thought the mapping wasn’t fun, e.g. “no control of movement, it’s hard for me to release the line properly”, “lose control of the rod”, “decrease the game experience”; On the other hand, 6 out of 8 participants thought the mapping was fun, e.g. “more fun, different from reality”, “do less effort”, “It’s fun; you just have to get used to that”; however, 3 out of 6 preferred one-to-one natural mapping, e.g. “prefer more realistic way”.
- All participants thought this way can limit fatigue, e.g. “do small movement”; “do less efforts”, “although there was no comparison but I have not felt fatigue during the whole session”, “don’t have to move largely in reality; feel tired if you always do large movement”, “it helps if you want to play a longer time”, etc.

In addition, among all the 24 participants, two of them have tried all the three mappings. Having compared different versions, one thought $C/D_{1.0}$ felt difficult to cast very far away, and both of them like the $C/D_{0.5}$ mapping, with comments like “sth in the middle”, “like the momentum”, etc. given. Although the data was not a part of the main data, it still reflected interesting points.
5 DISCUSSION

The purpose of this thesis was to explore how different C/D ratios of VR hand controllers, from control space to virtual display space, would influence muscle fatigue and game experience in VR games over time. Based on the results from chapter 4 RESULTS, a number of indicative answers to the question can be given. In addition, a few implications for the design of VR games are introduced.

5.1 How different C/D ratios from reality to VR influence fatigue and game experience

5.1.1 The relationship between C/D ratios and fatigue

When C/D ratio equals 1.0, which was the one-to-one normal mapping, Borg CR 10 for the fatigue of right forearm rose quickly during the game session and most participants reported tiredness in their right forearm after the game. When the C/D ratio decreased, the upward trend of fatigue evened out during the game. Especially when C/D ratio equaled 0.1, the fatigue level of most participants stayed low, even when the number of castings significantly increased. After the game, fewer participants reported fatigue in their right forearm. Furthermore, all of the participants from the $C/D_{0.1}$ group believed that mapping principle can limit the fatigue to some extent.

To summarize, the lower C/D ratios of the hand controller from control space to virtual display space would help to limit fatigue compared to the condition where the C/D ratio equals one.

5.1.2 The relationship between C/D ratios and game experience

When C/D ratio became very low (C/D ratio = 0.1), it had a relatively obvious impact on game experience. For example, in the results for in-game experience of the $C/D_{0.1}$ group, the value for Flow dimension was much lower and the value of Tension and Challenge increased rapidly, which may result from the unnatural mapping; in the results for game engagement questionnaire, the values for all the dimensions were lower than for the other two groups. In this case, the very low C/D ratio will have a negative impact on game experience, especially for VR. However, the SDs of $C/D_{0.1}$ condition for all the dimensions, from all the quantitative data collected concerning game experience, were relatively high, which indicate a substantial difference of
opinions among different players. Especially when it comes to Positive Experience and Negative Experience from GEQ post-game module, the value of $C/D_{0.1}$ condition were the highest for both of the Positive/Negative dimensions, with high SDs. The results are heavily dependent on the individual participants and it is unclear whether this kind of mapping enhanced or reduced game experience. This conclusion can also be supported by the qualitative data from post-test interviews.

On the other hand, when the C/D ratio was less than 1.0 but with a certain margin, the players may not notice the difference (as was indicated in the result from post-test interview in chapter 4.4 Results of viewpoints towards different mappings) and therefore it had a small impact on the game experience. There was little difference in the game experience results between $C/D_{1.0}$ and $C/D_{0.5}$.

5.2 The implications for design

5.2.1 You don’t always need one-to-one mapping

Although many studies have suggested that the one-to-one mapping from control space to virtual space provides the best game experience because of naturalness and intuition, given the impact of fatigue, more considerations are required in order to achieve the optimal results.

As was stated in chapter 5.1.2 The relationship between C/D ratios and game experience, players may not notice the mapping difference if the difference between control space to display space is within a certain range. In this way, players will feel easier in control and play longer game sessions. However, if the difference exceeds a particular limit, there exists a risk of having a negative impact on the game experience. Therefore, to discover the threshold is very important. In this study, the condition where C/D ratio equals 0.5 is the optimal mapping. It can limit the fatigue to some extent and, as illustrated in chapter 4.4 Results of viewpoints towards different mappings, “All participants thought the mapping was fun.” Special user tests can be conducted to investigate the proper value of C/D ratio for other game scenarios. In this way, we can balance the naturalness of mapping and fatigue to have a better sense of game experience.

Another method is to allow players to customize the mapping settings. They can change the value of C/D ratio according to individual taste. The results from the post-test interview about opinions towards different mappings indicated that everybody have their own thoughts. Some want to escape from the reality, preferring a game control different from the real life, while others would like to experience the feeling closer to real life.
although it may generate fatigue and increase difficulty because to remove fatigue means to remove the real feeling, which they do not expect.

5.2.2 What you can do for other VR games

As was mentioned in chapter 1.1.4 Example game — *Bait!*, the fishing game served as a good example because a lot of games, such as many sports games, etc., have similar characteristics regarding the way the interaction with the game world is designed, which require repetitive movements and so more easily generate fatigue. Our findings may provide some new insights for interaction design.

Consider the design of a VR golf game for example. In order to sink the ball into the hole, the player has to swing the golf club repeatedly. Instead of always having one-to-one mapping during the whole game, distinguished mapping can be applied, for example, when the golf club is swung to hit the ball. The movement of the golf club can be amplified to achieve different game experiences, just as illustrated in chapter 5.2.1. You don't always need one-to-one mapping, “You don't always need one-to-one mapping”.

However, this principle may only benefit certain types of gameplay. Features such as centralizing gameplay in virtual environment, using hand movement to interact with the game world, etc. are identified.

Moreover, the mapping here only refers to the mapping of a hand controller from reality to VR. When it comes to mapping for whole body movement in room tracking VR supported by, for instance, HTC Vive, conditions become different. If different mappings are applied to a whole body movement from reality to virtual world, unwanted effects could be produced, such as cybersickness.

5.3 The potential of changing the C/D ratio to limit fatigue

As can be found in chapter 2.1.2 Definition of Control/Display ratio and its applications, the current research on C/D ratio concentrates on improving performance in pointing and manipulating, namely semantic pointing for target acquisition (Blanch, Guiard and Beaudouin-Lafon, 2004), the Go-Go technology for reaching and manipulating objects from nearby to further distance (Poupyrev et al., 1996), PRISM for precise and rapid interaction (Frees and Kessler, 2005), etc, or investigates the influence on perception of object’s properties, such as perception of bumps & holes (Lécuyer, Burkhardt and Etienne, 2004), mass of manipulated objects (Dominjon et al., 2005), etc.
This study, I would argue, has uncovered a new potential for applying different C/D ratios in order to limit the impact of fatigue, given that the application is in VR gaming and not, for example, simulation or training scenarios, which still heavily depend on one-to-one mappings.
6 CONCLUSION

6.1 Findings of the study

This study examined how different C/D ratios of a hand controller from control space to virtual display space would influence fatigue and game experience in VR games. The results show that the C/D ratio less than 1.0 with a small margin can help limit the impact of fatigue and maintain a comparable level of game experience compared to that where C/D ratio equals 1.0. However, when C/D ratio decreases and is lower than a certain value, it will still limit the fatigue while having an impact on the game experience. It is depending on the individuals whether the impact is positive or negative. Based on the results, we can implement different C/D ratios of the hand controller trying to balance the naturalness of the mapping and fatigue to have a better sense of the game experience, or allow players to customize C/D ratio settings to have their favorite mappings. The results can be applied to other VR games having similar interaction such as a number of sports games. This study has also uncovered the potential to limit fatigue by applying the C/D ratio.

6.2 Limitations of the study

The in-game fatigue was only measured by self-perceived questionnaire, which was answered by the respondents based on his or her own interpretation. The answers were subjective because users may be influenced by their own tolerance level. The impact can be viewed from the results of Borg CR 10 of each condition in chapter 4.2.1 In-game self-perceived fatigue by Borg CR10 Scales, there are at least two “outliers” of which the fatigue value may either be extremely high or extremely low.

6.3 Suggestions for future research

Possible further research can be addressing the objective measurement of fatigue to complement the measure of muscle fatigue. The objective measurements need to be unobtrusive and unencumbered in order to limit the influence on the game experience.

In addition, since the fully immersive panoramic game scene provided by VR technology required more attention from the player compared to traditional video games, the player will get weary much easier and possibly quicker. Therefore, how to reduce the overall
impact of fatigue, which contains mental fatigue as well as muscle fatigue, is also worth investigating.

Thirdly, more user studies can be conducted either on other platforms, such as HTC Vive or PlayStation VR, or on other types of gameplay, such as pure sports games or simulation games, in order to validate the results and the generated principles for design.

Last but not least, longevity effects on fatigue and game experience can also be interesting for further study. For example, how will the level of perceived fatigue as well as game experience change if the participant has been playing VR games on a daily basis for a year using a VR headset?
REFERENCE


Humansystems.arc.nasa.gov. (2016). NASA TLX Homepage. [online] Available at: http://humansystems.arc.nasa.gov/groups/tlx/ [Accessed 30 May 2016].


APPENDIX A. Consent form

Consent for Participation in Virtual Reality (VR) User Testing

I volunteer to participate in a research project conducted by Huiting Wang at Resolution Games. I understand that the project is designed to evaluate the game enjoyment in VR. I will be one of 24 people being interviewed for this research.

1. My participation in this project is voluntary. I understand that I will not be paid for my participation. I may withdraw and discontinue participation at any time without penalty.

2. I understand that if I feel uncomfortable in any way during the testing session, I have the right to decline to answer any question or to end the interview.

3. Participation involves being interviewed by students from KTH Royal Institute of Technology. The test session will last approximately 70 minutes. Audio as well as a written transcript of my answers will be recorded. If I do not consent to this, I will not be able to participate in the study.

4. I understand that the researcher will not identify me by name in any reports using information obtained from this testing session, and that my confidentiality as a participant in this study will remain secure. Subsequent uses of records and data will be subject to standard data use policies that protect the anonymity of individuals and institutions.

5. I understand that the raw data will be saved until the end of 2016, after which it will be removed.

6. I understand that this study has been reviewed and approved by faculty members of the Computer Science and Communication school at KTH Royal Institute of Technology. For research problems or questions regarding subjects, I should contact Björn Thuresson at thure@csc.kth.se

7. I have read and understand the explanation provided to me. I have had all my questions answered to my satisfaction, and I voluntarily agree to participate in this study.

________________________________________________________________________
My Signature                                           Date

________________________________________________________________________
Interviewer                                           Date

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APPENDIX B. Background questionnaire

Part 1: Background
1) Name ____________
2) What is your age? ___
3) What is your gender?  ___ female  ___ male

Part 2: Experiences of game playing
4) Do you play computer games?  ___ No  ___ Yes

If you answered ‘no’, please go to question 6.

5) Please indicate the degree to which you agree with the following statements.

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neither agree nor disagree</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compared to people of my age, I play a lot of games.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

I would describe myself as a gamer.

Part 3: Experiences of Virtual Reality (VR)
6) Do you have experience with VR before?  ___ Yes  ___ No

If you answered ‘no’, please go to question 8.

7) What kinds of VR products have you experienced?
   ___ Oculus Rift
   ___ HTC Vive
   ___ Samsung VR Gear
   ___ Google Cardboard
   ___ Microsoft Hololens
   ___ PlayStation VR
   ___ others, please specify here ____________

8) Do you have experience with any kind of VR hand controller before?  ___ Yes  ___ No

If you answered ‘no’, please go to question 10.

9) What kinds of hand controller have you experienced?
   ___ Oculus Touch
   ___ PlayStation Move controller
   ___ HTC Valve Vive controller
   ___ others, please specify here ____________

10) Have you already owned VR products?  ___ Yes  ___ No

11) Please indicate the degree to which you agree with the following statements.

<table>
<thead>
<tr>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neither agree nor disagree</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>I would like to buy VR products in the future</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX C. Introduction script

“Thank you for agreeing to take part in our research study. My name is Huiting. May I have your signed consent form, please? Thanks. [If they haven't brought a signed one with them, give one to them now and have them review and sign.]

[You can have some cookies and drinks :) ]

“During the rest of the session, I’ll be working from a script to ensure that my instructions to everyone who participates in the study are the same.

“I’m here to learn about the sense of game enjoyment in Virtual Reality.

“We will be in this room during the whole session. The devices we will use are a laptop, the Oculus Rift headset and the Oculus Touch hand controller.

“During the session, I will ask you to play a VR fishing game and finish several tasks. I will observe you when you do them. While you are playing the game, random question figures may pop up and you are supposed to tell me the answers. As you do these things, please try to do whatever you would normally do. I will always be available to remind you what to do and how to do the tasks, if need be.

“Please try to think out loud while you’re playing. Just tell me whatever you see, feel, experience in the game and whatever is going through your mind. There is no such thing as a wrong answer because we are testing the subjective feelings.

“The whole session will take about 40 minutes.

“Do you have any questions before we begin? [Answer any questions.]

“First, please fill out the Background Questionnaire. [They finish questionnaire]

“Now, I will show you the control instructions using Oculus Touch and how to fish in the game [Show them the instruction figures]

“It’s time to start!”
APPENDIX D. Instructions for fishing

Control Instructions

- Turn off questionnaires
- Press to reel in
- Press to start casting
  Release to release the line
  After line is released, press to lock the length of the line
- Confirm in gaze mode

How to fish?

1. Cast the line into the water.
2. Let the line sink until you feel resistance.
3. Reel in the line slowly.
4. Catch a fish!
5. Enjoy your catch!
APPENDIX E. Task scenarios

Welcome to Bait! World:) Now you are in one of the most classical scenes - OceanLake. Here you will experience a wonderful fishing experience!

Scenario A
Now you can start by exploring the game world first and getting used to Touch controller. Try to master the basic control and catch your first fish. Practice thinking aloud while you are doing this. [After this task is finished, you can ask me any questions about think aloud protocol, if you need to.]

Scenario B
Congratulations! Now you know how to catch the fish. There are a lot of fancy fishes in OceanLake. Try catching different species and tell me five different names of the fishes.

Scenario C
Have you noticed the stars shown in the display when you catch a fish? Try to catch 2 three-star fish and tell me the names and numbers of star.

Scenario D
In the Bait! world, you can earn remarkable money by catching different kinds of fish. Try to get 1000 coins and tell me the fish names and the money you get.

Scenario E
Jim Bob is the owner of a fish shop near OceanLake, maybe you know him. He has been quite busy recently. Could you do him a favor to catch 5 Parrot Perch and 5 Tangerine Tang?

Scenario F
Jim Bob’s sister, Darma Mae, is the owner of another fancy fish shop near Cherry Falls. Different from Bob, she loves uncommon species. Could you catch 1 Cow Koi, 1 Groovy Gourami and 1 Zebra Tuna for her?

Scenario G (Backup)
Now you have enjoyed most awesome parts of Bait!, try to catch one more species you have not caught to finish your fishing adventure!
APPENDIX F. Post-test debriefing guide

_Self-perceived Fatigue_

1. Do you feel tired with your right forearm now?

2. (If the answer is yes) When do you start to feel tired (e.g. in which task)?

_Mapping from reality to virtual world_

3. Do you feel natural about the mapping of hand controller from reality to virtual game world when you fish?

4. Do you like this kind of mapping?

(For participants trying the version C/D ratio = 0.5 or C/D ratio = 0.1)

5. When did you notice the differences between reality and virtual world where your hand were?

6. Do you think mapping in this way is fun or will you prefer one-to-one natural mapping?

7. Do you think this kind of mapping can remove the tiredness of your arm?