Aalto University
School of Science
Degree Programme in Computer Science and Engineering

Niklas H. Juslin

Increasing the immersive experience via the out-of-body illusion using head-mounted displays

Master's Thesis
Espoo, March 11th, 2016

Supervisor:	Professor Tapio Takala
Advisor:	Tuukka Takala M.Sc. (Tech.)

Aalto University
School of Science
Degree Programme in Computer Science and Engineering

ABSTRACT OF
MASTER'S THESIS

Author:	Niklas H. Juslin		
Title:	Increasing the immersive experience via the out-of-body illusion using head-mounted displays		
Date:	March 11th, 2016	**Pages:**	vii + 47
Major:	Media Technology	**Code:**	T-111
Supervisor:	Professor Tapio Takala		
Advisor:	Tuukka Takala M.Sc. (Tech.)		

This thesis investigates the possibilities of immersive virtual reality as a tool in cognitive research and in the game industry. The immersion is experienced on a self-conscious level. The purpose of virtual reality is to simulate reality by tricking our cognitive mechanisms with artificial stimuli. These cognitive manipulations can alter the neurophysiological processes in our bodies. To investigate if a change can be produced and measured in the experienced immersion we create an experimental set-up that enables the induction of an out-of-body illusion by presenting synchronized visuotactile stimulation. The hypothesis is that repeated visuotactile stimulus induces an out-of-body illusion as a psychophysiological response. The study examined the psychophysiological response to a visual threat under this illusory state of the mind. The participants' electrodermal activity was recorded and the subjective experience was evaluated using a questionnaire. The results were not statistically significant due to the limited amount of participants in the study. However, the results were in line with the hypothesis that an out-of-body illusion can be induced. The questionnaire results supported the hypothesis.

Keywords: immersive virtual reality, immersion, out-of-body illusion, out-of-body experience, body ownership, body image, electrodermal activity eda, skin conductance scr, stereo camera, oculus rift

Language: English

Aalto-yliopisto
Perustieteiden korkeakoulu

Aalto-yliopisto
Perustieteiden korkeakoulu
Tietotekniikan koulutusohjelma

DIPLOMITYÖN
TIIVISTELMÄ

Tekijä: Niklas H. Juslin

Työn nimi:
Immersioelämyksen kasvattaminen virtuaalilasien ja ruumiistairtaantumisilluusion avulla

Päiväys:	11. maaliskuuta 2016	**Sivumäärä:**	vii + 47
Pääaine:	Mediatekniikka	**Koodi:**	T-111

Valvoja: Professori Tapio Takala
Ohjaaja: Diplomi-insinööri Tuukka Takala

Tässä työssä tutkitaan immersiivisen virtuaalitodellisuuden hyödyntämistä työkaluna kognitiivisessa tutkimuksissa ja peliteolisuudessa. Immersioelämys koetaan itsetietoisuuden tasolla. Virtuaalitodellisuuden tarkoitus on simuloida todellisuutta huijaamalla kognitiivisia mekanismejamme keinotekoisten ärsykkeiden avulla. Nämä kognitiiviset manipuloinnit voivat muuttaa kehomme neurofysiologisia mekanismeja. Tutkiaksemme voidaanko immersion tunne havaita fysiologisesti ja voidaanko siihen vaikuttaa rakennamme koeasetelman, joka mahdollistaa ruumiistairtaantumisilluusion luomisen visuotaktiilisen ärsykkeen kautta. Hypoteesi on, että toistettu visuotaktiilinen stimulaatio synnyttää ruumiistairtaantumisilluusion psykofysiologisena reaktiona. Toteutettu tutkimus tutki psykofysiologista vastetta visuaaliseen ärsykkeeseen tämän illusorisen mielentilan aikana. Koehenkilöiden ihon sähkönjohtavuuden muutos mitattiin kokeen aikana ja subjektiivinen kokemus arvioitiin kyselyn avulla. Saadut tulokset eivät ole tilastollisesti merkitseviä pienen koehenkilömäärän takia. Tulokset olivat kuitenkin linjassa hypoteesin kanssa ruumiistairtaantumisilluusion aikaansaamisessa, jota kyselystä saadut tulokset tukivat.

Asiasanat: immersiivinen virtuaalitodellisuus, immersio, ruumiistairtaantumisilluusio, ruumiistairtaantumiskokemus, kehon omistus, kehonkuva, ihon sähkönjohtavuuden muutos, eda, scr, stereokamera, oculus rift

Kieli: Englanti

Acknowledgements

I would like to thank my friends and colleagues at the Computer Science department that have helped and guided me during this tedious project. Especially my supervisor Professor Tapio Takala, Nina Lehtinen (B.Sc.) for proof-reading and helping me out with the pilot testing, Jussi Hakala (M.Sc.) for his expertise on using the VarioPort EDA recorder and on analysing the study results using R, Kenta Kusumoto (M.Sc.) for helping out experimenting with different EDA recorders and hacking the Q sensor, Arto Rusanen for his expertise on camera hardware and photography, Meeri Mäkäräinen (M.Sc.) for her guidance on the study procedure, Klaus Lehtonen (D.Sc.) for his guidance and insightful comments, Tuukka Takala (M.Sc.) for helping out with the VR hardware, and Jussi Perämäki (M.Sc.) for being a happy person!

Additionally, I would like to thank Docent Kaisa Tiippana from the Institute of Behavioural Sciences at University of Helsinki and Professor Mikko Sams from the Department of Biomedical Engineering and Computational Science (BECS) at Aalto University. Kaisa Tiippana presented me Ehrsson's study on the out-of-body illusion during the course 'Advanced Course on Human Brain Functioning' and Mikko Sams encouraged me to replicate this study in my master's thesis.

Supportive peer pressure was provided at my workplace (Eficode) in our thesis support group that gave me motivation for the last crunch. Thanks Eficode for paying for the printing of this thesis!

Last but not least, I wish to express my gratitude to my family for their support and patience for my long journey in Otaniemi at whatever-this-department-and-university-is-called-at-the-moment.

Winland, March 11th, 2016

Niklas H. Juslin

Abbreviations and Acronyms

AR	Augmented reality
DSLR camera	Digital single-lens reflex camera
EDA	Electrodermal activity (skin conductance response)
fMRI	Functional magnetic resonance imaging
FOV	Field of view
HMD	Head-mounted display
IPD	Inter-pupillary distance
IVR	Immersive virtual reality
NDE	Near-death experience
OBE	Out-of-body experience
RHI	Rubber hand illusion
TMS	Transcranial magnetic stimulation
TPJ	Tempo-parietal junction
VR	Virtual reality

Contents

Chapter 1

Introduction

The entertainment industry, in particular the computer game industry, has an utmost interest for maximizing the immersive experience of their products. Augmented and virtual reality devices can provide thrilling experiences with life-like properties. These devices are gaining popularity among the consumers as the price level on the required technological solutions has dropped to more affordable levels. Increasing the feeling of immersion pushes the gained experience to a whole new level.

To better understand which factors affect the feeling of immersion the problem can be tackled from a neurological point of view. Between neurological research and the entertainment industry there has been a gap as games and other media have often been seen as entertainment meant for consumption without useful properties. Games that are not meant for pure entertainment have been given the term serious games. The idea of using games for educational or other purposes is not new and the term was introduced by Clark Abt in the year 1970 in his book "Serious games". Serious games have gotten more attention in the 21st century as increased corporate interest enables more profound academic research.

As the knowledge on the neurological background of perception and sensory signal processing has advanced the focus has shifted to map and understand deeper cognitive mechanisms behind perception. Computer games are a good target for neurological studies as they can provide a precisely controlled environment. The underlying cognitive processes of perception must be understood to increase the life-like properties of augmented or virtual reality experiences. Artificial stimulation of our senses and 'bluffing' the cognitive processes can affect our physiological mechanisms in yet unknown ways. The risk of causing long term or persistent changes must be taken into account.

Recently, a lot of research has been made connecting virtual reality experimentation with neurological, behavioural and cognitive research. In 2007 H. Ehrsson introduced [Ehrsson, 2007a] an experimental method for inducing an out-of-body illusion using a head mounted display (HMD) and a stereo camera. Ehrsson's experimental set-up provides a method to simulate and study an out-of-body experience in a controlled environment. Ehrsson's findings have provided new ways to approach and test cognitive models related to the body image and multisensory integration.

To understand the consequences of immersive experiences this thesis studies how life-like a presented stimulus can feel on a HMD device. An experiment is conducted to study if immersion can be measured physiologically by replicating parts of Ehrsson's study on the out-of-body illusion. An experimental set-up is constructed using equipment intended for consumers. 'Does a virtual threat feel life like?' is a central question in the context of this study.

In this thesis the background concepts related to immersion and the out-of-body illusion are explained in chapter two. Before introducing the out-of-body illusion a neuropsychological view is presented on the concept of self-consciousness and body ownership. Chapter three describes the experiment to be conducted in this thesis to study the out-of-body illusion. Chapter four presents the acquired results of the experiment. In chapter five we discuss the results and compare them to the results in Ehrsson's study. Additionally, the conclusion in chapter six takes a look at the implications of these neuropsychological findings on serious gaming and computer games in general.

Chapter 2

Immersion and the out-of-body illusion

In this chapter we define what is meant by immersion in the context of virtual reality. The out-of-body illusion is an immersive experience that can be purposefully crafted and used in various scientific experiments. The out-of-body illusion is linked to the encoding of the internal body image. Sensory information is compared against this body image to resolve its relevance and to generate a feeling of body ownership. Before one can fathom the impact of the out-of-body illusion on the scientific field of neurocognitive research the complex cognitive paradigms behind self-consciousness and body ownership are elaborated.

2.1 Virtual Reality

Virtual Reality (VR) is an artificial environment mimicking real life generated by a computer simulation. Currently this is achieved by showing the generated environment on a display and using some kind of peripherals for interaction. A head-mounted-display (HMD) provides better visual feedback than a traditional computer screen. A stereoscopic display configuration is easier to implement on a HMD device than on a traditional computer screen. A stereoscopic image enables the user to perceive depth. There are different techniques to achieve this with their own limitations. HMD devices provide deeper interaction as the display follows the user and the head's movements can be tracked accurately. Most HMD devices also offer one big advantage over conventional ways of showing stereoscopic images - they block the surroundings and provide the user a controlled visual environment. Augmented Reality (AR) is often linked to the same subject as it contains same concepts as VR. The main difference is that the real environment is not totally isolated from the user. Instead, the environment is enriched using artificially generated elements.

HMD devices are not new on the market. The first patent on a HMD device was granted to Heilig in the year 1960. The HMD was based on two television tubes and had a construction that is similar to the consumer-level devices on the market today. It is widely believed that the first experimental HMD devices were created by Ivan Sutherland and his colleagues from the year 1966 onwards. The first virtual reality (VR) and augmented reality (AR) capable device was created in 1968 by Sutherland. It was far from a portable device – mounted to the ceiling along with a mechanical rig with ultrasound sensors for head tracking. [Heilig, 1960; Sutherland, 1968]

Since then, many experimental HMD devices and see-through glasses have been introduced to the markets. Still, the economical and technological limitations on suitable display panels or projectors, and raw computing power have kept the AR and VR more as interesting concepts than successful immersive media platforms. The smartphone revolution has accelerated the development and production of cheap high resolution display panels and graphic rendering hardware. This has enabled the development of consumer-level HMDs to take a significant leap towards a wider market that would also activate content producers and customers. These devices can also cause discomfort as a kind of simulation sickness. There are technological ways to evade some of the sources of discomfort in AR/VR simulations. These are discussed in the next section.

2.2 Simulation sickness

Augmented reality or virtual reality (AR/VR) devices can cause discomfort and sometimes induce a feeling of motion sickness. The susceptibility varies from person to person. The main cause is the visually perceived sense of movement and the lack of corresponding signals from the sensory organs in the ear, the semicircular canals. The discrepancy between the seen visual motion and felt non-existing physical motion can then induce a state called motion sickness or simulation sickness. Motion sickness causes discomfort and a feeling of puking. The state is temporary and will disappear. The user should immediately stop using the AR/VR devices and stay still for a moment until the feeling goes over. The simulation or the used hardware can also cause simulation sickness. [Lackner, 2004; Johnson, 2005]

To minimize the risk of inducing simulation sickness several techniques are used in VR equipment. There is always base latency originating from the hardware and its limitations. One major source of latency is transfer latency from the central processing unit to the graphics processing unit. Current HMD devices try to minimize the time needed to transfer the provided image frame from the graphic processing unit to the display including the time required to update the display panel. The update rate for each pixel on the panel must be as fast to avoid tearing of the image. The rendered frame update rate should be synchronized with the display panel's update rate to avoid another source of image tearing. Usually the rendering implementation uses buffering to minimize stuttering that can occur when too much time is used while drawing one frame and the simulation moves forward in time. Another cause is if there is too much delay from the moment when the user provides input to the simulation and to the perceived result of the updated simulation. To reduce the latency and discrepancy to a non noticeable level the user's movements or actions can be predicted to some extent and calculated beforehand. The predicted state of the simulation can be utilized to render some frames beforehand.

In a situation where a static perspective is presented the user should avoid any head movements as the risk of inducting simulation sickness is high. This is common when cameras are used to provide different perspectives. In comparison, the risk is minimal when using cameras that are mounted onto the user's head, for instance as in AR equipment. A camera, or a pair of cameras can be mounted onto a motorized stand that provides movement in three axes to reproduce recorded head movements. Another option that does not require expensive motorized camera mounts is to accommodate the movement virtually. This can be achieved by displaying the static image on a plane in a virtual environment - like a virtual cinema. The eyes are represented by virtual cameras that move in the virtual space relative to the image plane. This provides visual queues of movement that reduce the risk of inducing simulation sickness. Still trick only works to mitigate small movements when using stereoscopic cameras as the static perspective will look distorted if the virtual cameras are not perpendicular to the virtual plane.

2.3 The immersive experience

The term immersion is often used when describing the level of absorption or submersion a gaming experience provides. Metaphorically, how much an entertainment source 'absorbs' the user into its world. Immersion can also be achieved when reading books or playing traditional board games. The traditional concept of immersion refers to a cognitive mechanism where one starts to ignore the surrounding environment while focusing on the media in question. However, HMD devices can provide a more absorbing experience while capturing the user's attention in a deeper sense. Additional sensory stimuli can be provided along with the modified visual stimulus. This increases the level of immersion. VR devices try to capture the user's whole attention by isolating the user from the surrounding environment, Immersive virtual reality (IVR) aims to provide the perception of being physically present in a simulated world by providing artificial sensory stimuli. [Slater et al., 2010]

The benefits of IVR experiences are not limited to pure entertainment as to escape reality. Its value for cognitive and behavioural research combined with neurophysiological measurements is immense alone. Serious gaming can provide educational content for practising or to prepare for a possible real-life event that can be cumbersome or dangerous to simulate in the real world. Artificial stimuli that mimics reality activates reflexes and affects emotions. Traumatic experiences and phobias can be confronted in a controlled environment using IVR. [Gerardi et al., 2008; Slater et al., 2010; Muller, 2013; Blom et al., 2014]

Augmented or virtual reality experiments produce varied results. Physiological responses can be recorded and psychological effects can be verbally evaluated. 'How was the experience?' 'What did it feel like?' are important questions when evaluating behavioural experiments. The described experiences are culturally biased as they are reflected upon the personal history of the teller. Neurological studies map autonomous physiological responses to neurophysiological mechanisms. These mechanisms can be analysed and altered using various techniques to identify cognitive processes. But to assess the effects on the cognitive level we have to rely on subjective verbal descriptions. The out-of-body illusion is one unusual experience that can be presented in IVR. The illusion is described in section 2.8. To understand what cognitive mechanisms the illusion utilizes the concept of the body image and the experience of its ownership need to be defined first.

2.4 The body image

Our brain has mechanisms to differentiate what is us and what is external to us. The self-conscious feeling, the feeling that we are surrounded by an environment, but that we are not the environment itself. If you close your eyes and think about your body you can visualize your own body to some extent. The body image represents the single, coherent whole-body representation of our body that is associated with the sense of selfhood. Selfood does not refer to the emotional layers of self-consciousness. [Lenggenhager et al., 2007; Aspell et al., 2009]

The phrase body image can refer to the perceived image of one's own body or to the structural schema that represents the body. Initially, both concepts were discussed together and referred to the same mental model of the body. Later, the concepts of an outer image and internal schema have been separated to differentiate between psychological and cognitive models. In psychology, the phrase body image refers to one's perception of the aesthetics, the emotional attitudes or beliefs, one has of one's own body. This emotional layer in self-consciousness concerning the perceived body image is associated with mental disorders. In cognitive research the phrase body image refers to the schema of the body concerning postural and motor control. Unfortunately, from early to recent publications both phrases have been used with terminological and conceptual confusion. Additionally, self-consciousness has mostly been studied in philosophical and psychological contexts leading to an overabundance of diverging models. The models lack empirical data-driven neurophysiological studies. [Gallagher, 2005; Aglioti and Candidi, 2011; Ionta et al., 2011]

Neurological research has provided means to map out the basic building blocks of the cognitive mechanisms. Still, the task of understanding the link between the neurophysiological building blocks and the cognitive regulation of the body is laborious. Non-invasive methods are mostly limited to brain imaging techniques and transcranial magnetic stimulation (TMS). These methods can reveal activity changes and provide limited stimulation of certain areas in the brain. [Lenggenhager et al., 2007; Aspell et al., 2009]

Invasive methods as direct electric stimulation of neurons in the brain using electrodes or the placement of sensors inside the skull require neurosurgery. The risk of infection or damage limits the usage of these invasive methods. They are mostly performed on terminal patients or to patients in need of brain surgery. Patients with lesions in the brain are often the only source of empirical information on cognitive mechanisms and their role in the human psyche. A confined lesion affecting a limited area in the brain can reveal the cognitive function of that area or details about the surrounding areas. This cognitive dysfunction can also highlight the computational mechanism of the affected area in relation to the connected neural networks. [Aglioti and Candidi, 2011]

2.5 The rubber hand illusion

Experimentation using rubber hands and fake bodies have given empirical results showing that the body image can be manipulated. These experiments are based on manipulated visual input and tactile stimuli. Temporally and spatially synchronized tactile stimuli alter the outcome of multisensory integration. The rubber hand illusion (RHI) is probably the first experimental technique that was proven to manipulate the body image. The rubber hand illusion is a simple experiment to perform. The participant sits on a chair next to a table. A rubber hand is placed on the table and the participant places his own hand next to it in an identical posture. The rubber hand should look similar or natural by its proportions and aesthetics. A sheet is placed between the rubber hand and the real hand to hide the real hand from the participant. An assistant strokes both hands, for example with a feather. The synchronous visual and tactile stimuli produces a feeling of ownership over the rubber hand. When the stroking is not synchronized the illusion vanishes. The RHI can be produced even without the sheet blocking the real hand from the view in a similar experiment setting. Participants have reported that a feeling of owning a third hand was present and it felt natural. [Halligan et al., 1993; Khateb et al., 2009; Slater et al., 2010; Newport et al., 2010; Muller, 2013; Blom et al., 2014]

Studies have shown that the aesthetics of the rubber hand does not need to match the real one as long as it has somewhat natural proportions and aesthetics. The amount of similarity increases the vividness of the illusion, but small deviations do not seem to influence the experience of RHI. Interestingly, the perceived deviations diminish when ownership is experienced over the rubber hand. Tsakiris highlights an important detail by stating that "ownership leads to perceived similarity, but perceived similarity does not lead to ownership.". Objects that do not resemble naturalistic limbs are not usually felt as part of the body. Also, if the rubber hand in the RHI is in an incongruent anatomical posture or has wrong laterality the illusion vanishes. [Haans et al., 2008; Tsakiris, 2010]

A study conducted by Moseley et al. showed that the temperature of the participant's hand decreased during the RHI. This only occurred if a sense of ownership was experienced over the rubber hand. This indicates that self-recognition that leads to ownership of a body-part has direct consequences in homeostatic regulation for body-parts that are experienced as replaced. The magnitude of change in the homeostatic regulation was proportional to the vividness of the illusion. [Moseley et al., 2008]

The RHI provides a way to study the conditions of self-recognition. A body-part can be objectified and presented on a screen to study the boundaries of agency and body-part ownership by testing if the projected body-part is judged as one's own or not. 'If I move my hand and a moving hand and I see a moving hand does it belong to me?'. This indicates of a cognitive mechanism that compares the visual stimuli and evaluates the relevance of the perceived objects during multisensory integration. This complex recognition process uses information from various cognitive sources and it is evaluated in a short time-window. The synchronous visuotactile stimulation provides a suitable neurological event, but the cognitive mechanism of self-recognition does not associate all perceived objects into the body image. [Tsakiris, 2010]

2.6 Multisensory integration

In neuroscience multisensory integration depicts a mechanism where the neural connections and neuronal populations in certain areas integrate information produced by the senses. Multisensory integration is involved when forming a coherent image from sensory stimuli. [Tsakiris et al., 2008; Ionta et al., 2011]

The RHI can be extended to a full-body ownership illusion. The cognitive mechanisms can be manipulated to take ownership over a different body or a virtual avatar. The multitude of stimuli needs to be congruent to form a coherent body image. Studies have shown that the mind is rather tolerant in taking ownership over perceived bodies as long as they are humanoid. A body-swap study by Petkova et al. utilized the full-body ownership illusion combined with functional magnetic resonance imaging to locate areas that are responsible for the multisensory integration. The putamen, the ventral premotor cortex and the intraparietal cortex were found to be responsible for combining sensory information from multiple sources. Petkova et al. state that the results of their fMRI study show that "a process exists that mediates the perceptual binding of the parts into a unified percept of a whole owned body.". This cognitive process is elaborated in the next section on the concept of body ownership. [Petkova et al., 2011a,b]

Neurophysiological studies on non-human primates have shown that neurons that integrate visual, tactile and proprioceptive information operate in reference frames centred on different parts of the body [Petkova et al., 2011a]. Temporally aligned stimuli (temporal synchronicity) are mapped spatially in body-part-centred coordinates and interpreted to belong to an identical event. The body image has its own body-centred coordinate system. The body's origo is mapped to a global context using the visual perspective perceived by the eyes. [Petkova et al., 2011a; Tsakiris, 2010; Petkova et al., 2011b]

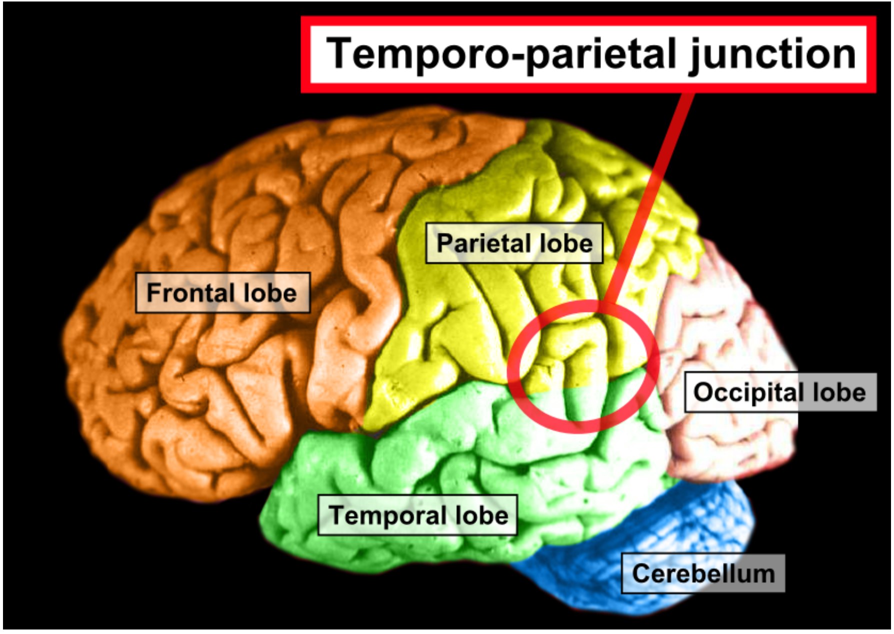
Experiments using brain imaging or direct electric stimulation have revealed that the temporo-parietal junction (TPJ) has a vital role in the formation of the body image [Tsakiris et al., 2008]. In particular, at the right hemisphere of the temporo-parietal junction (rTPJ). The location of the left TPJ is depicted in figure 2.1. In a study where the rTPJ was disrupted using TMS this mechanism of self-recognition was impaired [Tsakiris et al., 2008]. This mechanism involves matching external sensory events with the internal body image [Tsakiris, 2010]. Tsakiris writes that “Based on a meta-analysis of neuroimaging studies [...], Decety and Lamm (2007) suggested that the rTPJ may underpin a single computational mechanism that is used by multiple cognitive processes;”. [Tsakiris, 2010; Ionta et al., 2011]

2.7 Body ownership

The feeling of being in control, having agency, of ourselves gives us an experience of body ownership. Tsakiris has formed a neurocognitive model on how body ownership arises based on a comprehensive review on neuroscientific research. Tsakiris describes body ownership in his article by stating that “Body-ownership refers to the special perceptual status of one’s own body, which makes bodily sensations seem unique to oneself, that is, the feeling that ‘my body’ belongs to me, and is ever present in my mental life.”. [Tsakiris, 2010]

How the body image is created and maintained has been theoreticized for a long time. Earlier models have proposed that the body image is genetic in its nature or that it emerges during ontogeny (the sensitive phase of neuronal development). The RHI depicts a weighted interaction between vision, touch and proprioception. The first explanation was a bottom-up approach that suggested that intermodal matching between visual and tactile stimulation is sufficient for self-attribution of the rubber hand. The first studies made it clear that it was a necessary condition for self-attribution. The challenge was to find out if temporal synchronicity was both necessary and sufficient for a body ownership experience. This would indicate that ownership should occur over non-natural objects when the conditions are right. A complementary model took top-down regulative mechanisms into consideration along with the bottom-up model. Top-down mechanisms refer to more complicated processing that can be said to occur on the cognitive level. These alter the neural networks on the lower levels of signal processing affecting the bottom-up regulation. [Tsakiris, 2010; Guterstam and Ehrsson, 2012; Blanke and Metzinger, 2009]

Figure 2.1: The location of the temporo-parietal junction (TPJ) on the left hemisphere. The location is identical on the right hemisphere. Image author: John A Beal. Licensed under CC BY 2.5 via Commons.



Studies have shown that not all objects will produce an experience of ownership. There is a cognitive mechanism that evaluates the relevance of presented suitable stimuli. It has been noted that the recalibration of the coordinate systems is not sufficient for the induction of the experience of ownership. Tsakiris has formulated a neurocognitive model on the body ownership mechanism during the RHI. It involves three neurocognitive comparison steps.

The first comparison is computed in the rTPJ and it evaluates the visual form of the perceived object against the pre-existing anatomical and structural properties of some stored body image. Interestingly, this stored body image operates ‘off-line’ in a sense that external objects can be considered to be part of the body, for example a third hand. It does not seem to directly check the current state of the body image. If this step does not associate the perceived object as a body-part the cognitive ownership evaluation does not continue to process the current visual input.

The second comparison evaluates the postural state of the body-part against the current postural configuration in the body image. Incongruence in the postural position or in the laterality of the recognized body-part will not provide the processed input to the next comparison.

The third comparison is between the seen and felt stimuli. Their congruency is evaluated by comparing the reference frames of the tactile and visual events. If the temporal asynchrony between the respective reference frames is too large the seen touch and felt touch will not be associated. This will not induce an experience of ownership over the perceived body-part.

The debate is still ongoing whether there are stored body representations that are formed during ontogeny by frequent reoccurring sensory input in addition to mechanisms like multisensory integration. These affect the nature of the bottom-up approach. The 'off-line' model in the first comparison indicates that some previously stored body image is available that is not altered by the later top-down mechanisms. [Tsakiris, 2010]

The purposefully crafted out-of-body illusion is a major tool in neurological research on self-consciousness and body ownership [Blanke and Metzinger, 2009]. This illusion is presented in the next section.

2.8 The out-of-body illusion

In 2007, Ehrsson presented an experimental set-up [Ehrsson, 2007a] that could be used to induce an out-of-body like illusion in a controlled environment. The experimental set-up consists of a stereo camera and an HMD device. The person wearing the HMD device sees himself from a third person perspective. An out-of-body illusion is a purposefully crafted version of a similar phenomenon known as an out-of-body experience (OBE). An OBE can be described as a sensation of being or floating outside one's own body. OBEs include autoscopic elements, e.g. seeing oneself from a different perspective, often from an elevated perspective. OBEs have been reported since time immemorial. Spiritual or near-death experiences often contain similar elements and they can be seen as similar phenomenon. Documented descriptions of OBEs often describe them as real experiences filled with details of the surroundings including other persons and objects in the room. The lifelike properties of the experience often give a spiritual feeling as one's "soul" or consciousness would drift out from the body. This third person perspective can feel as a near death experience (NDE) or a proof of a spiritual world. [Aspell and Blanke, 2009; Blanke and Metzinger, 2009; Guterstam and Ehrsson, 2012]

OBEs are characterized by disembodiment of the self to an extracorporeal or external location with an extracorporeal visuospatial perspective and seeing one's own body from this perspective. The feeling of a self-conscious affection for an extracorporeal virtual body. OBE is an phenomenological experience that challenges our self-consciousness, the cognitive feeling of unity between our mind and body. [Blanke and Metzinger, 2009; Aspell and Blanke, 2009; Guterstam and Ehrsson, 2012] Patients with constant or repeated occurrences of an extracorporeal perspective, heatoscopy, have variable experiences of external localization. The heautoscopic experiences are similar to OBEs. They often identify an illusory body and partly transfer selfood to this virtual body, even if visual detail is lacking in the seen body. Still, none of the patients with heautoscopic experiences report overt disembodiment that is central in OBEs. [Lenggenhager et al., 2007; Blanke and Metzinger, 2009]

OBEs are hard to study and to verify due to their rare and seemingly random pattern of occurrence. It has been estimated that they occur in about 5 percent of the population. The cause of OBEs is not yet fully understood. Several factors have been reported to induce or cause OBEs, including brain tumours or lesions at specific areas, abnormal neural activity caused by medical conditions, extreme stress or fear, psychedelic drugs [Wilkins et al., 2011] and direct electric stimulation of neurons in certain areas of the brain. [Saavedra-Aguilar and Gómez-Jeria, 1989; Wilkins et al., 2011]

Experiences similar to out-of-body experiences seem to share neurophysiological mechanisms. Recent studies have found out that the cortex at the temporo-parietal junction (TPJ) is integral to the occurrence of OBEs [Lenggenhager et al., 2007; Ionta et al., 2011]. The TPJ is activated when the perception of the location of the body is changed [Ionta et al., 2011]. Lesions in the rTPJ are often the source of OBEs reported by patients. The left hemisphere TPJ may be less reported due to potential interference with the language cortex present at the left TPJ [Ionta et al., 2011]. Electrical stimulation of the rTPJ has resulted in an external perspective for the patient. [Tsakiris et al., 2008]

The out-of-body illusion is not remotely as vivid as an OBE. In most cases only a feeling that the seen perspective feels natural is induced. Still, the physiological change in the body is much larger. A study showed that memory store problems are present under the illusion. The episodic memory is disrupted. The theory is that the abnormal perspective that is viewed and processed on the cognitive level changes the internal coordinates that are somehow associated in the memory footprints. The memory storing mechanisms may store memories in the normal first person perspective. This altered perspective disturbs this process. [Bergouignan et al., 2014]

A recent fMRI study by Guterstam et al. showed evidence that the illusion is visible in the brain in a live imaging session using a similar experimental set-up as described by Ehrsson. The illusion produced changes in the hippocampus. Guterstam et al. pinpointed that the body image and its origo is stored in the hippocampal area. This is the first live evidence stating that the illusion exists and produced changes that are associated with body ownership and the body image. [Guterstam et al., 2015] Previously, the descriptions of the illusion have relied on subjective narratives and the similarities between OBEs and the illusion have not been verified. Still, the narratives and reports of OBEs, NDEs and purposefully crafted illusions are important when evaluating the cognitive effect on the psyche. Even in controlled situations the narratives vary greatly. This phenomenon is explained in the next section.

2.9 Cognitive dissonance

The narrative reconstructed from memory produces great variation in a similar or an identical experience across individuals. The individual's own beliefs and cultural background affect the narrative of an experience. Saavedra-Aguilar and Gómez-Jeria describe that according to Gazzaniga [Gazzaniga, 1985] the verbal system is a central part when describing experiences to the individual's own mind to find "logical, coherent, and explicative hypotheses". Saavedra-Aguilar and Gómez-Jeria state that "These hypotheses can sometimes be completely erroneous, but they are taken as absolute truth.". NDE narratives from patients from different cultures produce varying descriptions of similar events. The narratives can contain elements that are never mentioned by other patients from other cultural backgrounds. Saavedra-Aguilar and Gómez-Jeria use as an example a trans-cultural comparison of NDE reports among Americans and Indians [Pasricha and Stevenson, 1986]. Saavedra-Aguilar and Gómez-Jeria write "In their study, 62% of the Indians were 'sent back' because of 'mistake,' compared to none of the American cases, while 81% of the Indian respondents were brought back from 'other realms' by 'messengers,' again compared to none of the Americans.". The conceptual differences caused by different cultural backgrounds in NDE or OBE reports are in line with the theory of cognitive dissonance. [Saavedra-Aguilar and Gómez-Jeria, 1989]

Cognitive dissonance (inconsistency) occurs when an individual's beliefs, opinions or attitudes are in disagreement with something experienced or as a result of the individuals own actions. The theory of cognitive dissonance characterize the psychological stress or discomfort that an individual experiences while striving for internal consonance (consistency). Cognitive consonance is required for the individual to function and the disagreement is resolved by changing the prior values or beliefs [Egan et al., 2007]. An recent fMRI study conducted by Jarcho et al. on cognitive dissonance confirmed that rationalization occurs during emotion regulated decision-making. Behavioural studies have shown that one tends to rationalize decisions and alter the argumentation behind the decisions. Neuroimaging results show that the change of attitude is fast and occurs within seconds after the decision. This process changes the prior attitudes that are emotionally bound. Jarcho et al. discusses that similar cognitive processes have been identified that are associated with evaluation of stimuli in general. To the outside this appears like disingenuous rationalization on behalf of the individual, but it seems to occur without explicit intention. [Jarcho et al., 2011]

The surrounding events are described to the individual using his own internal language to form a hypothesis that the individual understands. In reference to cognitive dissonance, Saavedra-Aguilar and Gómez-Jeria state that “Within this view, it is the verbal system that is the final arbiter of our multiple mental systems (Gazzaniga and LeDoux, 1985).” [Gazzaniga and LeDoux, 1985; Saavedra-Aguilar and Gómez-Jeria, 1989]. This highlights the importance of physiological measurements in cognitive research as the models based on behavioural research alone have tendencies to be culturally biased.

Chapter 3

Experiment methodology

In this thesis we will conduct a study to investigate if immersion can be measured physiologically. An experimental set-up is constructed using equipment intended for consumers. This chapter is divided into three main sections. The aim of this study is described in the first section. In the second, the outline and procedure of the study are presented. The experimental set-up to be constructed for the study is examined in detail in the last section of this chapter.

3.1 Aim of this study

In this study we will manipulate the participant's experienced level of immersion and analyse how a change on the cognitive level alters the physiological response to a threatening visual distraction. To investigate if a change can be measured in the level of immersion a participant experiences we create an experimental set-up that enables the induction of an out-of-body illusion by presenting synchronized visuotactile stimulation. This experiment is based on Henrik H. Ehrsson's study [Ehrsson, 2007a]. This study uses Ehrsson's methodology as a basis to the experiment procedure and to the analysis of the results. Ehrsson's study and methodology is presented in more detail in section 4.5.

The aim of this study is to examine the psychophysiological response to a visual threat under an illusory state of the mind. The hypothesis is that this visuotactile stimulus induces an out-of-body illusion as a psychophysiological response. The illusion alters the perceived location of the body image. A visuotactile event is evoked when the visual stimulus of a touching object and the sensory stimulus of a physical touch are aligned temporally and spatially. Sensory integration combines the temporally aligned stimuli and overrides the spatial discrepancy between the perceived location and felt location of the touch that is projected spatially on the current body image. The resulting psychological interpretation is a feeling of being outside one's own body. A repeated synchronous visuotactile stimulus maintains the illusion, an illusionary state of the mind.

The participants' EDA signal and head movement will be recorded during the experiment to evaluate if the illusion can be measured physiologically. The presented visual threat is the key event that is studied quantitatively in this study. Both experiments will include a questionnaire at the end of the experiment to evaluate the participant's subjective experience of the hypothesized out-of-body illusion.

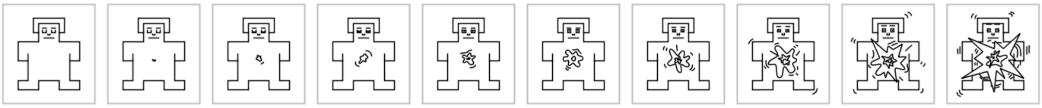
3.2 Experiment procedure

This study consists of two separate experiments with different voluntary participants. Both experiments are carried out in an office room and are accompanied by a research assistant. A chair is placed in the middle of the room. Behind the chair at approximately two meters distance a stereo camera is stationed on an adjustable camera mount. The stereo camera (camera rig) points towards the chair. The stereo camera provides a live video feed that is presented on a HMD device. During the experiment the participant will see himself from a third person's perspective, as somebody would sit behind the participant and look at him. The assistant will produce repeated visuotactile stimuli to induce the out-of-body illusion. The participants' electrodermal activity (EDA) biosignal will be recorded during the experiment for quantitative data analysis. The experiment is recorded with a video camera to provide timing information for the visual threat events.

The participant will first be allowed to familiarize himself with the room while the experiment procedure is explained briefly. The participant will be asked to sit down on the chair and to fill out a short personal data inquiry and to sign the written consent form. The participant will then be presented with the HMD device and aided to put it on. First, the participant's interpupillary distance (IPD) value is measured using the provided software tool of the HMD device. The IPD value will be temporarily stored on the computer running the experiment set-up.

The height of the camera rig is adjusted to match the seated participant's eye level. The participant is enquired if the presented view feels 'natural'. When the height of the camera rig, the virtual image settings and optical (focal) adjustments are in order the EDA biosignal recorder is attached. The participant is instructed not to move unnecessarily during the experiment.

Figure 3.1: The 10-step anxiety scale visualized using Self-Assessment-Manikin (SAM) arousal figures. The value one stands for 'no anxiety at all' (leftmost figure) and the value ten stands for 'the strongest possible anxiety imaginable'.



Moving the head can cause simulation sickness as the presented view from the cameras is stationary. The EDA signal quality is checked before starting either experiment one or two. The details of the experiments are explained in their own subsections.

Before the start of the experiment the assistant ensures that the participant understands that at no occasion will he be hurt nor will he feel any physical pain or danger during the experiment. The participant is free to abort the experiment at any time at his own will. The participant is also introduced to the anxiety scale that will be presented during the experiment. The 10-step scale is depicted in figure 3.1. The scale is based on Self-Assessment-Manikin (SAM) figures for arousal.

During the experiment the assistant stands next to the participant's chair facing the chair from the side. The assistant's arm closer to the camera is visible to the participant from the camera's perspective while the assistant's other arm is blocked from view by the assistant's own body, as he is facing the camera sideways. The assistant will hold two rods of the size of thick pens in his hands. The assistant pokes the participant's chest with one of the rods. The assistant brings the other rod towards the camera as he would be poking a virtual body represented by the camera. The participant only sees the rod closer to the camera. The assistant moves the rods repeatedly at a constant pace either synchronously or asynchronously. When the rods are moved synchronously the participant will see a rod coming towards him from the camera's perspective while simultaneously feeling a touch on his chest. When the rods are moved asynchronously the rods are moved one at a time with an alternating pattern so that the visual stimuli is not synchronized with the tactile stimuli.

After the experiment the EDA recording is stopped and the participant is asked to fill out a questionnaire. The questionnaire contains ten statements that are evaluated on a seven-point scale. The statements are presented in English and Finnish. The ten statements are listen in table 3.1. The first three statements support the hypothesised illusionary experience. The following seven serve as control statements and are unrelated to the illusion.

The participant is asked to rate the applicability of the statements to his own experiences over the whole experiment. The questionnaire is filled out on a desktop computer. The statements are presented in a randomized order.

3.2.1 Experiment one

In this experiment two conditions are defined for inducing the out-of-body illusion. An 'illusion condition' (1) is represented by moving the rods synchronously and a 'control condition' (2) is represented by moving the rods asynchronously. The two conditions are performed in a pseudo-random order [(1,2,2,1,1,2) or (2,1,1,2,2,1)]. The order of conditions is balanced across the participants.

In each condition the visuotactile stimulus is repeated by the assistant for a random time between 40 to 80 seconds to facilitate the illusion. The visuotactile stimulus is repeated at a constant pace of 1 Hertz. In the end of each condition the assistant swings a hammer towards the camera to induce a lifelike threat event. From the participant's point of view it looks like the participant would be hit in the face by the hammer. In reality the participant is not threatened or harmed physically.

Immediately after the presented visual threat the participant is asked to judge the feeling of anxiety induced by the threat on a scale from 1 to 10. The given number is recorded by the assistant. A 10-step SAM image is shown on the HMD to aid the participant to rate the magnitude of the evoked anxiety. The shown image is depicted in figure 3.1.

3.2.2 Experiment two

The second experiment is similar to the first experiment except for the control condition (2). The second experiment uses a different control condition to out rule conditional learning that could evoke after the repeated sequences. The asynchronous visuotactile stimulus in the control condition is changed to a spatially identical synchronous stimulus. The assistant moves only one of the rods repeatedly and location of the touch is the participant's shoulder. The visual and tactile stimuli are congruent and directed at the physical body even if the visual perspective comes from the projection of the stereo camera. The participant experiences this as a life-like situation where he sees his body being poked from a third person perspective. This new control condition tries to eliminate conditional learning that can affect the physiological response on the neurophysiological level.

Table 3.1: Statements in the Questionnaire

Nr.	Original statement *and the Finnish translation*
1.	I experienced that I was located at some distance behind the visual image of myself, almost as if I was looking at someone else. *Koin, että sijaitsin jonkin matkan päässä oman kuvani takana, aivan kuin katsoisin jotakuta muuta.*
2.	I felt as if my head and eyes were located at the same place as the cameras, and my body just below the cameras. *Tuntui siltä, kuin pääni ja silmäni olisivat olleet kameroiden kohdalla ja kehoni aivan siinä alla.*
3.	I experienced that the hand I was seeing approaching the cameras was directly touching my chest (with the rod). *Koin, että käsi, jonka näin lähestyvän kameroita, kosketti rintakehääni (sauvan kautta).*
4.	I felt that I had two bodies. *Tunsin, että minulla oli kaksi kehoa.*
5.	I experienced that my (felt) body was located at two locations at the same time. *Koin, että kehoni sijaitsi kahdessa eri paikassa samaan aikaan.*
6.	I experienced a movement-sensation that I was floating from my real body to the location of the cameras. *Tuntui siltä kuin olisin irtaantunut kehostani ja leijaillut kameran kohdalle.*
7.	I felt as if my eghead and body was at different locations, almost as if I had been ‘decapitated’. *Tuntui siltä, kuin pääni ja kehoni olisivat olleet eri paikoissa, miltei kuin minut olisi ‘mestattu’.*
8.	I did not feel the touch on my body but at some distance in space in front of me. *En tuntenut kosketusta kehollani, vaan jonkin matkan päässä edessäni.*
9.	I could no longer feel my body, it was almost as if it had disappeared. *En voinut enää tuntea kehoani - aivan kuin se olisi kadonnut.*
10.	The visual image of me started to change appearance so that I became (partly) transparent. *Näkemäni kuva minusta alkoi muuttaa muotoaan niin, että minusta tuli (osittain) läpinäkyvä.*

3.3 Experiment set-up

This section describes the components to be used in the experiment set-up. The main idea is to use commercially available hardware and solutions that are affordable for the consumer. The experiment set-up uses a purely digital solution compared to the set-up described in the supplementary online material [Ehrsson, 2007b] provided by Ehrsson for the original study [Ehrsson, 2007a].

3.3.1 Hardware

Ehrsson's experiment set-up is replicated using a consumer level HMD device and a stereo camera consisting of two DSLR cameras and a mirror box. The camera images are shown on the HMD using a custom made software solution. The participant's electrodermal activity (EDA) is measured using a biosignal recorder. Initial EDA tests will be performed with a Q sensor by Affectiva. If the signal-to-noise ratio (SNR) is not good enough a Varioport biosignal recorder by Becker Meditec will be used instead. A webcam is placed in the room to record the experiment. Timestamps for the visual threat events are collected from the recorded video for the EDA analysis. The recorded video is discarded after the study is completed.

3.3.1.1 Head-mounted display

The head-mounted display device (HMD) is a Oculus Rift Development Kit 2 (DK2) virtual reality headset [VR, 2014] by Oculus VR, LLC. It is a developer version of the upcoming Oculus Rift consumer version. The DK2 uses a separate infrared camera to track the location of the HMD device in world space. The infrared camera provides a tracking frustum with a depth range of 0.4 – 2.5 meters in front of the camera. The DK2 has a horizontal FOV of 84°. It uses two spherical lenses in front of the eyes to distort the image shown on the display panel. This is done to achieve a larger FOV than the display could physically provide. The lenses produce heavy chromatic aberration and a fish eye distortion effect. To minimize the user's perceived distortion the displayed image is programmatically adjusted to counteract the physical distortion. The used techniques are described in section 3.3.2.2.

The inter-pupillary distance (IPD) varies from person to person. Nearly all of the available HMD devices including the DK2 have a non-adjustable distance between the lenses. This is a problem that can affect the IVR experience. The depth parallax is distorted if the stereo view presented via the lenses do not match the user's IPD. Fortunately, this can be alleviated by adjusting the distance between the left and right images that are shown on the HMD. The location of the centre points of the images on the panel will match the left and right eye through the lenses. This will produce a correct depth parallax.

3.3.1.2 Stereo camera

Ehrsson's original experiment [Ehrsson, 2007a] used two CCTV cameras as described in the supplementary online material for the study [Ehrsson, 2007b]. In this study the CCTV cameras are replaced with two Canon EOS 5D Mark II DSLR cameras. One drawback is that DSLR cameras are larger in size than the used CCTV cameras. When the DSLR cameras are placed side by side the distance between the lenses is much wider than the average human IPD. To overcome this problem the cameras are mounted to a mirror box, as shown in Figure 3.2.

The mirror box enables the cameras to be placed in different planes so that the distance between the lenses accommodates the users' IPD. The distance between the centre point of the lenses do not need match the user's IPD exactly. The perception of depth will not be affected noticeably when the targeted depth range is small. The mirror box is described in section 3.3.1.3. Lenses with a focal length of 28 millimetres and horizontal FOV of 65° were chosen for the cameras due to the constraints of the mirror box. The captured view has a smaller FOV than the HMD used in this study as described in the previous section (3.3.1.1).

3.3.1.3 Mirror box

The mirror box that will be used in this study is lent from the department of Computer Science. The mirror box has been used for stereo imaging in previous research projects at the department. The mirror box consists of a $33.5 \times 18 \times 18$ centimetre wooden box with one side open. A one-way mirror is placed inside the box in a 45° angle with the mirror side upwards and facing the opening. The cameras are fastened onto separate rails located above and behind the box. Behind the mirror on the back side of the box is a wide opening. The camera that represents the left eye is placed behind the box and looks through the one-way mirror. The second camera representing the right eye is fastened to the top rail with the lens pointing downwards and looking at the mirror through a hole. The cameras are mounted to Manfretto 454 micro-positioning sliding plates. The sliding plates are fastened onto the rails. The sliding plates enables accurate IPD adjustment. The calibration is described in section 3.3.1.2.

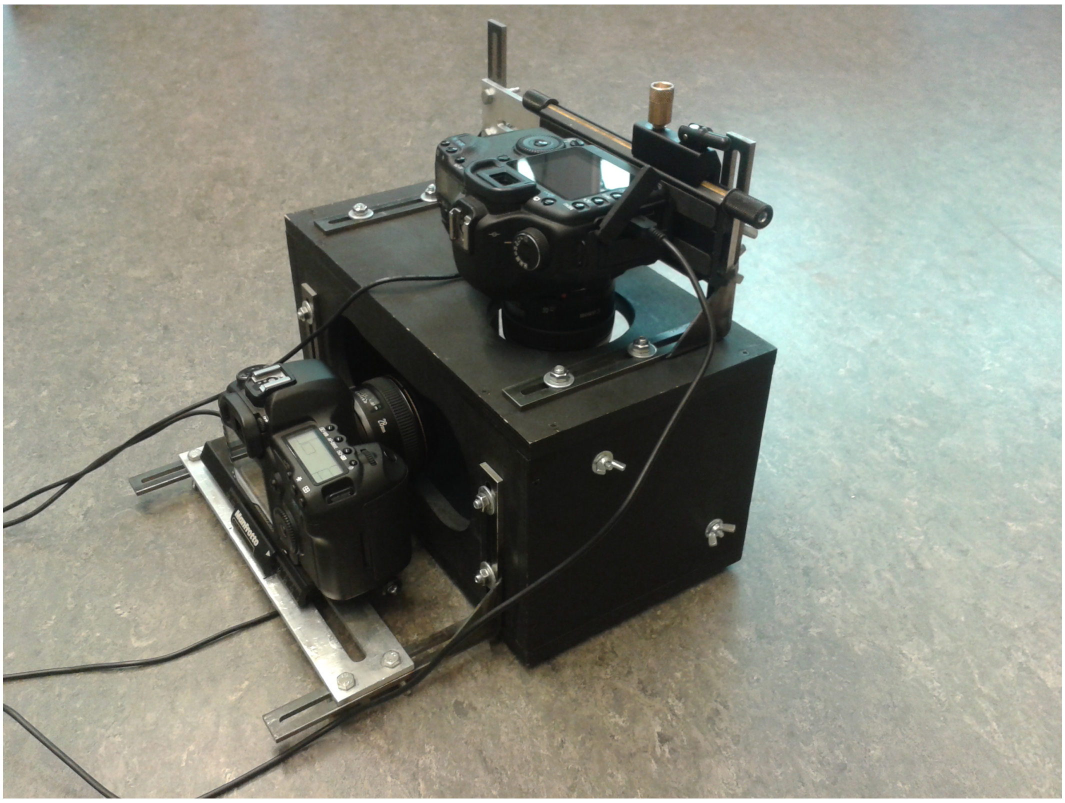


Figure 3.2: The mirror box with two Canon EOS 5D Mark II cameras attached depicted from behind.

The mirror box is suitable for 50 millimetre lenses. A lens with a shorter focal length will show the walls of the box. The left camera image is a bit darker due to the one-way mirror affecting the incoming light. The right camera image is mirrored and needs to be flipped horizontally.

3.3.2 Software

An open source software solution titled ‘StereoScopica’ is created for this study [Juslin, 2015]. StereoScopica communicates with the cameras, shows their images on the HMD and records sensor data from the HMD. The result is displayed on the HMD so that the user’s left and right eye only see the corresponding view. StereoScopica transfers the camera images onto a virtual image plane in a three dimensional VR environment and takes care of required image adjustments. This virtual image plane approach is used to mitigate the risk of inducing simulation sickness. The perspective would be to static

Figure 3.3: The mirror box with two Canon EOS 5D Mark II cameras attached. Left image: the mirror box depicted from front. Right image: the one-way mirror reveals both cameras.

if the camera images would be presented directly on the HMD. Now the user can move his head and see a change in the perspective even if the camera images show a static view.

StereoScopica provides several settings that can be adjusted to configure the stereoscopic image and to suit the users' varying physiological properties. It also includes a calibration mode to help the tedious task of aligning the cameras to achieve a parallel projection. The image and VR scenery settings can be adjusted via keyboard shortcuts. The distance and orientation of the cameras can be verified by using a physical print of a check-board pattern. The distance between the squares should match the intended IPD value.

3.3.2.1 Platform

StereoScopica is built upon the .NET Framework using the C# programming language. Camera communication is handled via Canon's own EDSDK library [Canon, 2015]. The rendering is done with DirectX 11.0 using the SharpDX library [SharpDX, 2015a]. Oculus Rift SDK interaction is handled via the SharpOVR library [Godin, 2015]. The platform and used libraries are portable except for the Canon's EDSDK library that requires 32-bit support and Windows as the operating system. The software is designed so that the camera library can be easily replaced or a custom image provider class can be implemented instead.

3.3.2.2 Architecture and implementation

The Visual Studio solution package contains two project directories named StereoScopica and CanonHandler (see [Juslin, 2015]). These two projects produce their own binaries that communicate with each other over local one-way anonymous memory pipes. StereoScopica is based on the MIT licensed [MIT, 1988] SharpDX Toolkit API Game class [SharpDX, 2015b]. The StereoScopica application contains the main logic and user interface (UI). The CanonHandler application takes care of the camera communication and image retrieval.

This separation was made due to the limitations of the EDSDK camera library allowing only one active camera to be used at a time. The .NET platform automatically loads a referenced native library statically into the memory space of the process. This limits only one camera to be used per process. The separate binary and two running instances of it makes it possible to use two cameras at the same time since only one camera can be used per EDSDK library instance. By separating the library instances in their own process spaces the implementation becomes cleaner and it circumvents the limitation imposed by the architecture of the .NET platform.

The StereoScopica class instance handles the main event loop and UI interaction. StereoScopica initializes the Renderer class, two TexturedPlane class instances as image planes and two CameraHandler class instances as image sources for the image planes. The Renderer takes care of the DirectX and Oculus Rift HMD handling via the SharpDX [SharpDX, 2015a] and SharpOVR [Godin, 2015] -libraries. The camera images are converted to textures that are drawn using a shader. The TexturedPlane class represents a textured plane drawn using a given TextureShader instance. It extends the Plane class which is based on a C# version [‘PavelB’, 2015] of Rastertek DirectX 11 C++ tutorial 5 [RasterTek, 2015]. The Plane class takes care of the vertex updates and the TexturedPlane transfers the image to a texture resource on the GPU. The plane vertices are updated to accommodate the aspect ratio of the camera image. The image update mechanism is thread safe as the acquired images from the cameras are read and updated in a separate thread for each camera. To avoid a race condition a lock is used for thread safety. Image effects are implemented on the shader level and they can be adjusted independently to the left and right image. The shaders can be externally modified, recompiled and reloaded at runtime.

One TextureShader instance is shared between the two planes to support a calibration mode that blends both images together. This calibration mode aids the adjustment task of the camera position and lens alignment to minimize unwanted perspective differences between the cameras. Both images are subtracted from each other separately on the left and right view. Identical pixels will be black while non-aligned pixels will result in some colour. This can be utilized while the cameras are near the origo configuration with a IPD value of 0. Now the resulting image should be close to black when the orientation of the lenses is parallel. When the cameras are moved to a 64 millimetre separation (IPD) a 64 millimetre check-board pattern can be filmed and the edge of the squares should align nicely when the cameras are in proper alignment.

The program state is defined by the CameraSettings and TexturedPlane class instances and the UISettings class instance. The state is loaded from the .NET user settings file at start up. If the file doesn't exist the classes are initialized with default values and they will be serialized into the settings file on exit. The user's IPD value is read from the current user profile provided by the Oculus Rift SDK. The relative distance between the image planes is adjusted to match the user's IPD value.

The captured images are not synchronized due to the lack of support for hardware level synchronization in the cameras. The captured frames per second (FPS) fluctuates a bit between the cameras. The FPS value is mostly dependent on the exposure settings of the camera. A FPS value of 30 is desirable and it can be achieved by adjusting the room lightning and exposure settings accordingly. The Universal Serial Bus (USB) 2.0 connection between the cameras and the computer does not get filled up from the image data flow of 30 JPEG-images per second. The computing power needed for the bus operation is also minimal with current chip-sets. This does not produce noticeable latency or delay in the image stream.

StereoScopica launches the CanonHandler processes automatically during start up and passes camera configuration setting to them as command line arguments. The CanonHandler class utilises an open source wrapper class that encapsulates Canon's native EDSDK library. The wrapper class code is MIT licensed [MIT, 1988] and copyright to Johannes Bildstein [Bildstein, 2015]. The CanonHandler listens for events produced by the Canon EDSDK when a camera is connected to or disconnected from the system. The connected cameras are presented as a unordered list. The EDSDK library does not provide a way to uniquely identify the cameras. The CanonHandler tries to establish communication with a default camera device number, passed as a command line argument from the calling application. If the camera is already in use it tries to connect to an another camera or waits until more cameras are connected. This design automatically connects plugged-in cameras and tolerates a situation where two or possibly more library instances compete for camera access.

The CameraHandler class instance in StereoScopica creates an inbound

Anonymous Pipe Server Stream object into a separate thread and passes its handle via the command line arguments. CanonHandler uses this string as a handle to initialize the client stream that flows towards the calling process. CanonHandler uses a MIT licensed [MIT, 1988] Command line parser library [Scala, 2013] to read the command line arguments to a settings class. The images are retrieved using the Canon's LiveView feature found in their EOS camera series. This feature limits the dimensions of the captured image to a Canon's pre-defined value depending on the camera model. The LiveView mode provides a steady stream of JPEG-compressed images. The LiveView mode provides processed 'preview' images when Depth Of Field Preview setting on the camera is enabled. The aquired images are transferred as byte streams over the memory pipe to minimize latency and processing overhead.

The spherical lenses in the HMD device produce chromatic aberration that can be seen as separated colours near edges of the image. The lenses also produce barrel distortion due to their physical form. Spherical lenses are used to widen the perspective and make the view visually bigger for the user. To minimize the visual artefacts that chromatic aberration and barrel distortion produce image manipulation techniques can be applied. The Oculus Rift runtime includes post-processing shaders that automatically process the displayed content using algorithms that produce an approximate inverted result. The perceived distortion is thus minimized.

Brightness and mirroring can be adjusted separately for both images. The virtual head position and orientation in the scenery are updated using real-time data from HMD. The Oculus Rift DK2 produces small jittering, stuttering and lag when moving the virtual head on the basis of the provided data. This is not a noticeable problem if the user does not move around a lot.

3.3.2.3 EDA analysis

The EDA amplitude is defined as the difference between the extreme values in a short time window (trough-to-peak). In the through-to-peak method the baseline (minimum) value is usually taken a second before the stimulus (event). The maximum value is taken from a predefined response time window of about 1-5 seconds after the stimulus. The collected EDA measurements will be analysed by extracting continuous phasic activity from the data using the Ledalab [Benedek and Kaembach, 2015] software. Ledalab is used to extract the phasic driver response as it eliminates the cumulative effect of temporally close EDA events [Benedek and Kaernbach, 2010]. A window size of five seconds is used.

Chapter 4

Results and evaluation

This chapter presents the acquired results from the experiments. The hypothesis is that this visuotactile stimulus induces an out-of-body illusion as a psychophysiological response. Initial testing of the experiment set-up was performed using two volunteers from the Department of Computer Science. The initial tests provided insightful feedback and some changes were made to the planned experiment procedure (see 3.2). These changes are explained in the first section of this chapter with the description of the general arrangements. The results of the two experiments are presented in the next sections. The results were also combined to gather a larger data set for comparison. The combined results are presented in the following section. How the recorded data was processed and evaluated is described in the last section of this chapter.

4.1 Arrangements

The experiments were carried out in a small office room with some furniture. A generic adjustable office chair was placed in the middle of the room. The mirror box with two cameras attached, the camera rig, was placed on an adjustable mount 2 metres behind the chair. In front of the chair at a distance of 1.5 meters was an office table placed adjacent to the wall. The infrared head tracking sensor for the HMD was placed on the table. It would have provided spatial head tracking but due to some unknown interference between the sensor and the cameras on the operating system level the sensor did not produce any spatial data.

Initial testing showed that the brightness level of the room was not adequate. The one-way mirror darkens the image through the mirror and to brighten up the view two additional indirect light sources were placed in the room. Great care was taken to minimize the perspective differences between the cameras as initial tests showed that small differences in the perspectives between the cameras disturb the feeling of a ‘natural view’. The mount of the camera rig was not adjusted as the orientation of the mirror box was prone to change. Instead, the height of the chair was adjusted to accommodate the participant’s eye level. The participants reported that this solution corrected the perspective difference that is present if the ‘virtual eyes’ are at a different elevation. The focal distance of the camera lenses was adjusted to 0.5 metres in order that the focus point was between the camera rig and the back of the chair. This minimized the blur effect at the target depth between the chair and the camera. At the beginning of each experiment the focus of the camera rig was checked manually.

Two thick pens were selected as the poking rods. The repeated synchronous movement was found hard to replicate in an identical manner. The point of touch on the participant varied and the visual queue of the pen coming towards the camera gave sometimes the illusion that it touched at a different depth. These caused too much distraction for the participants during the first trials. To overcome these problems a ‘poking rig’ was constructed using thin black plastic rods. The black colour of the rods was ideal as it was least visible to the participant. The pens were attached to the plastic rods in a configuration that hid the rig from the participant’s perspective. The rig had a stem that went behind the assistant’s back and the rods holding the pens were held under the assistant’s arms. This rig was only used in the illusion condition (synchronous). Two identical pens were used in the control conditions, as in Ehrsson’s original experiment. The rig was hid during the switch between the two conditions.

4.2 Participants

In total nineteen participants participated, eleven men and seven women. The participants took part only in one of the experiments. The EDA measurements for the first seven participants were garbage and the results had to be discarded. These participants are not included in the results of this study. The participants were between 25 and 60 years old with different nationalities. The participants had some previous knowledge of virtual reality. Only three of the participants had tried VR equipment before.

Six participants’ results were analysed from the data recorded in the first experiment. Two of the six participants had tried some kind of VR equipment before, while none had tried AR equipment. Four of the participants were men and two were women.

Six participants' results were analysed from the data recorded in the second experiment. One of the six participants had tried some kind of VR equipment before, while none had tried AR equipment. Four of the participants were men and two were women.

4.3 Results

The EDA recordings for the first seven participants were garbage and the results had to be discarded. The first seven participants' EDA signal was recorded using a Q sensor (version 1) by Affectiva. The signal-to-noise ratio (SNR) was very low and the sensor produced various artefacts randomly into the data. The issue was not limited to a particular Q sensor as three different sensors were tested. Two additional sensors were available but they stopped responding after their firmware was upgraded. We tried to modify the reusable electrodes of the Q sensor by soldering cables directly onto them and by attaching pre-gelled single-use EDA electrodes to the cables. The signal-to-noise ratio was still low and the strange artefacts remained. A VarioPort biosignal recorder by Becker Meditec was configured and taken into use instead of the Q sensor. The VarioPort provided a good EDA signal using the same pre-gelled single-use electrodes. The sampling rate was set to 1000 Herz.

Due to the small sample size the results of both experiments were also combined to provide a statistically sufficient (barely) sample count. The acceleration data from the sensors in the HMD was not analysed in this study. Due to the small sample size the variation in the participants' reactions to the threat event were too broad for meaningful statistical analysis. Some of the participants did not even flinch noticeably while some did react boldly by moving the head rapidly as a sign of being genuinely startled.

In the figures 4.1-4.9 the black bar in the gray box depicts the median value. The dotted line leading to the small bar indicates the outer range of the analysed values. The small circles depict outliers. Outliers are values that were not included in the result set due to being too far away from the median.

In the EDA figures 4.1, 4.4 and 4.7 the left and right boxes depict the standard deviation of the the illusion and control conditions. The phasic driver response was extracted from the EDA measurements and is presented on the y-axis on a logarithmic scale $(1 + Log(\mu S))$.

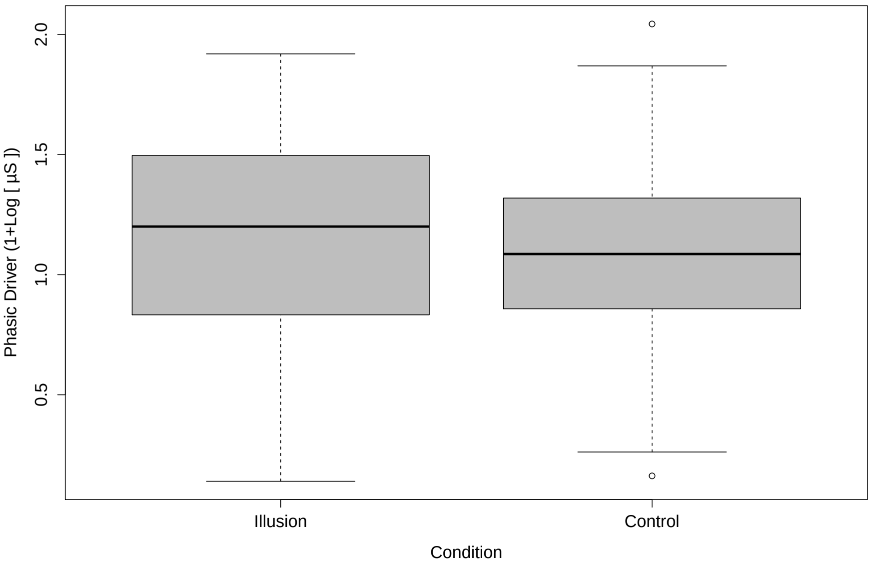
In the anxiety rating figures 4.2, 4.5 and 4.8 the left and right boxes depict the standard deviation of the the illusion and control conditions. The level of anxiety was rated on a scale from one to ten. The value one stands for no anxiety at all and the value ten stands for the strongest possible anxiety imaginable.

In the questionnaire figures 4.3, 4.6 and 4.9 the statements marked Q1-Q3 supported the illusion condition and Q4-Q10 served as control statements. The statements are listed in table 3.1.

4.3.1 Combined results of both experiments

The EDA phasic driver response contrast between the illusion condition and the control conditions was $p < 0.212$, $d.f. = 11$, $estimate = 0.07066$, $std.error = 0.05659$, $z - value = 1.249$. See figure 4.1.

Figure 4.1: EDA results of both experiments combined (12 participants)



Anxiety ratings contrast between the illusion condition and control condition was $F(1, 70) = 1.339$, $p < 0.2512$; illusion condition 3.14 ± 1.69 (value ± SD), control condition 2.69 ± 1.93. See figure 4.2.

Questionnaire results with the difference in ratings between the illusion and control statements (ANOVA): $F(9, 120) = 17.964994$, $p < 0.001$. Contrast comparison with the three illusion statements to the seven control statements: $p < 0.001$, $estimate = 3.3492$, $std.error = 0.2844$, $z - value = 11.78$. See figure 4.3.

Figure 4.2: Anxiety ratings of both experiments combined (12 participants)

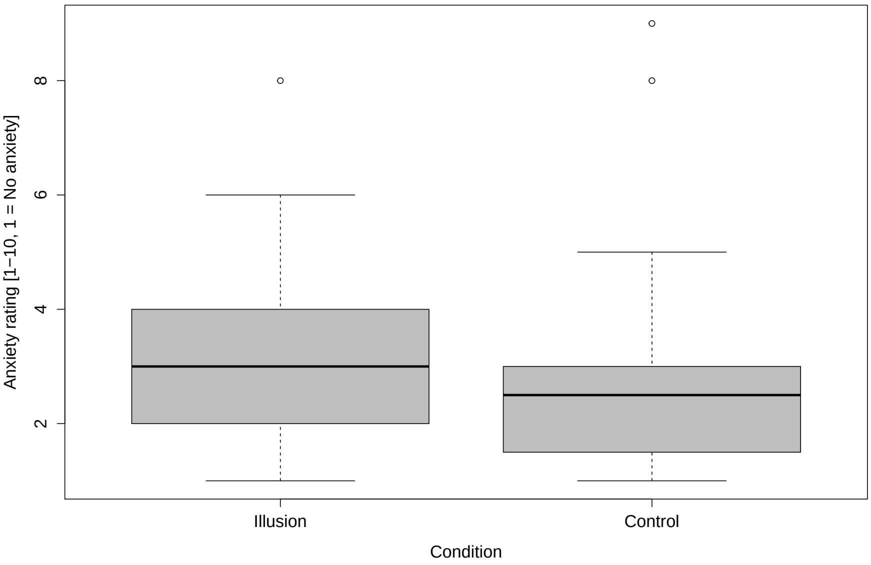
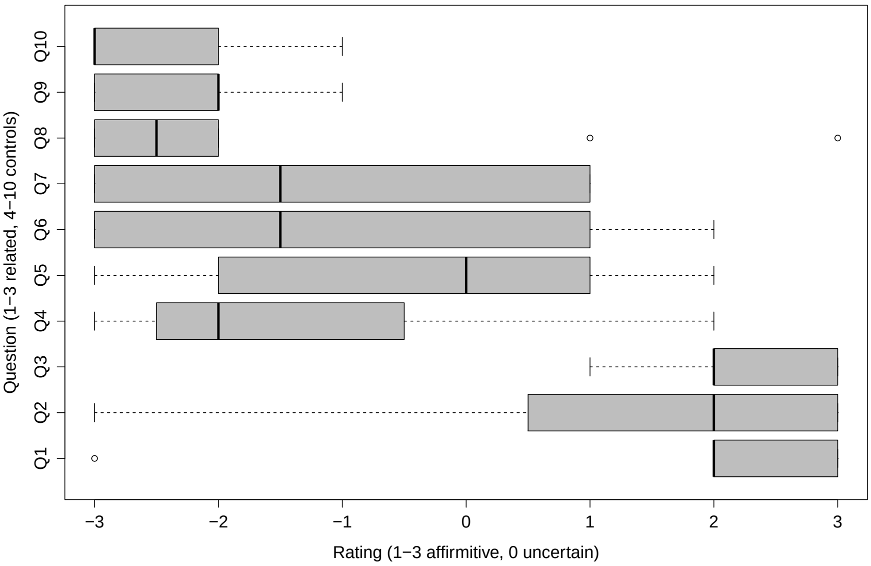


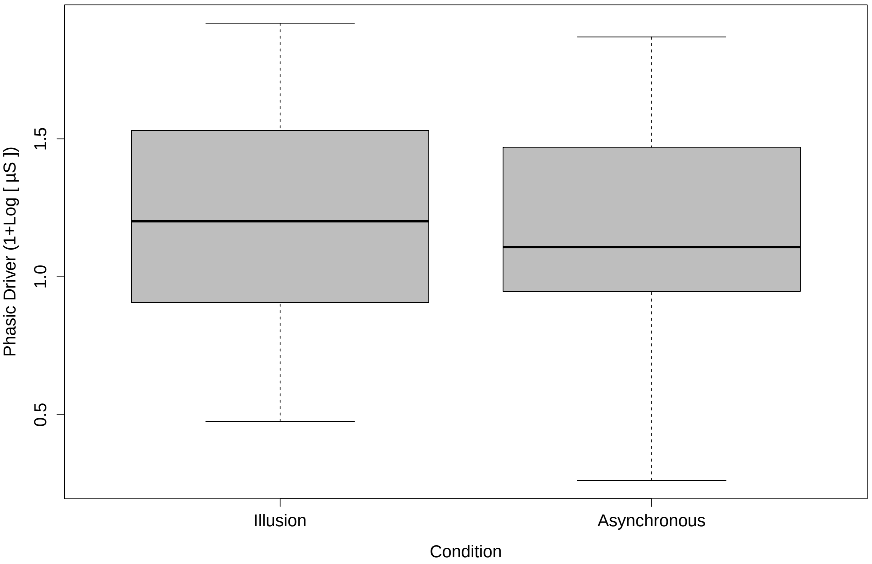
Figure 4.3: Questionnaire results of both experiments combined (12 participants)



4.3.2 Results of experiment one

The EDA phasic driver response contrast between the illusion condition and the control condition was $p < 0.37$, $d.f. = 5$, $estimate = 0.06196$, $std.error = 0.06904$, $z - value = 0.897$. See figure 4.4.

Figure 4.4: EDA results of experiment one (6 participants)



Anxiety ratings contrast between the illusion condition and control condition $F(1, 34) = 1.876$, $p < 0.18$; illusion condition 2.89 ± 0.98 (value ± SD), control condition 2.44 ± 1.32. See figure 4.5.

Questionnaire results with the difference in ratings between the illusion and control statements (ANOVA): $F(9, 60) = 4.392243$, $p < 0.001$. Contrast comparison with the three illusion statements to the seven control statements: $p < 0.001$, $estimate = 2.5238$, $std.error = 0.4665$, $z - value = 5.41$. See figure 4.6.

4.3.3 Results of experiment two

The EDA phasic driver response contrast between the illusion condition and the control condition was $p < 0.371$, $d.f. = 5$, $estimate = 0.08597$, $std.error = 0.09618$, $z - value = 0.894$. See figure 4.7.

Anxiety ratings contrast between the illusion condition and control condition $F(1, 34) = 0.4051$, $p < 0.5287$; illusion condition 3.39 ± 2.21 (value ± SD), control condition 2.94 ± 2.43. See figure 4.8.

Figure 4.5: Anxiety ratings of experiment one (6 participants)

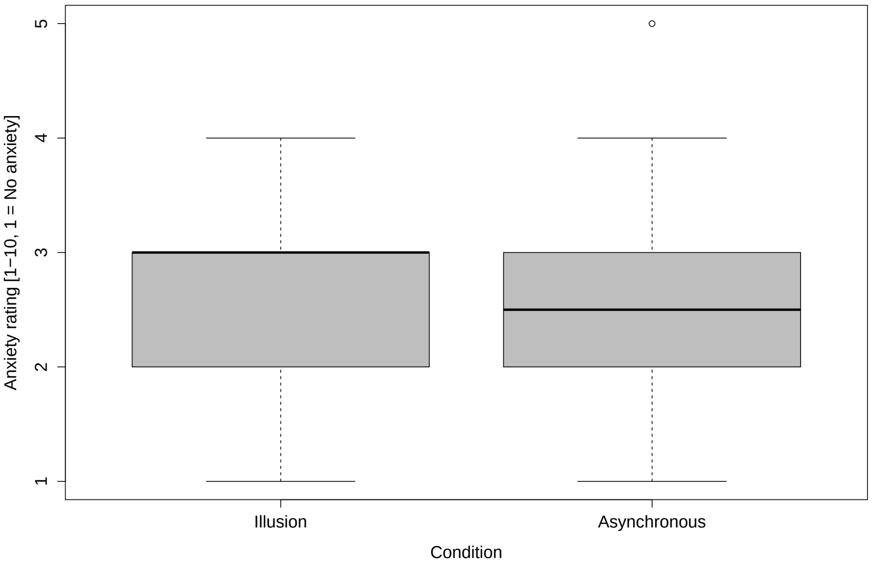


Figure 4.6: Questionnaire results of experiment one (6 participants)

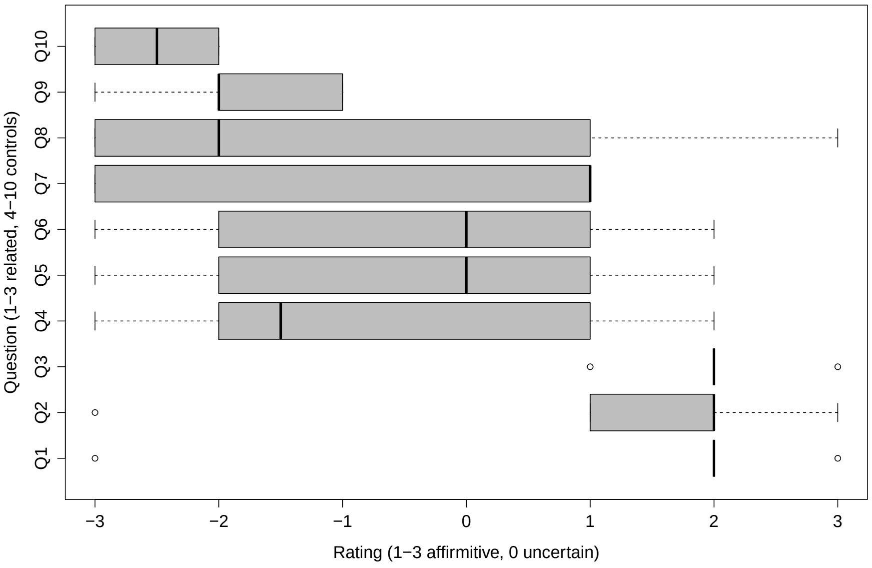


Figure 4.7: EDA results of experiment two (6 participants)

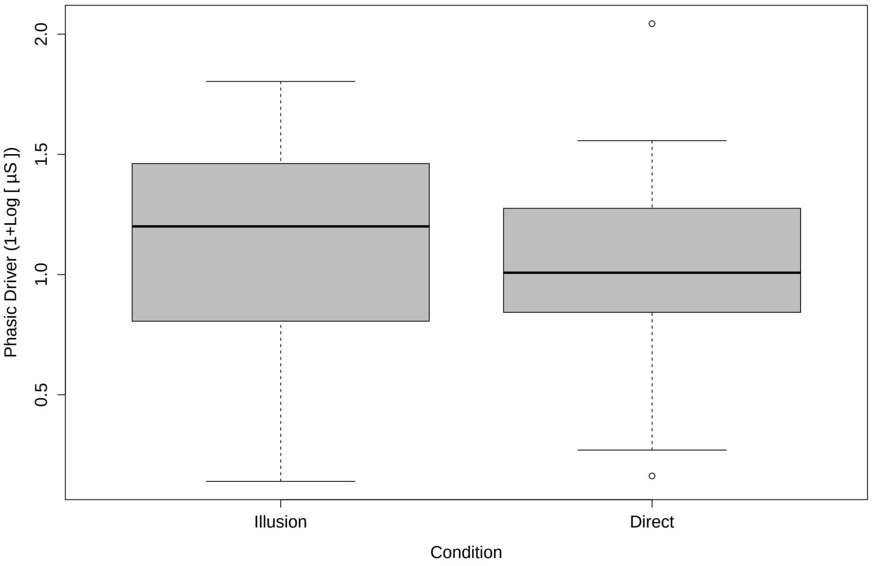


Figure 4.8: Anxiety ratings of experiment two (6 participants)

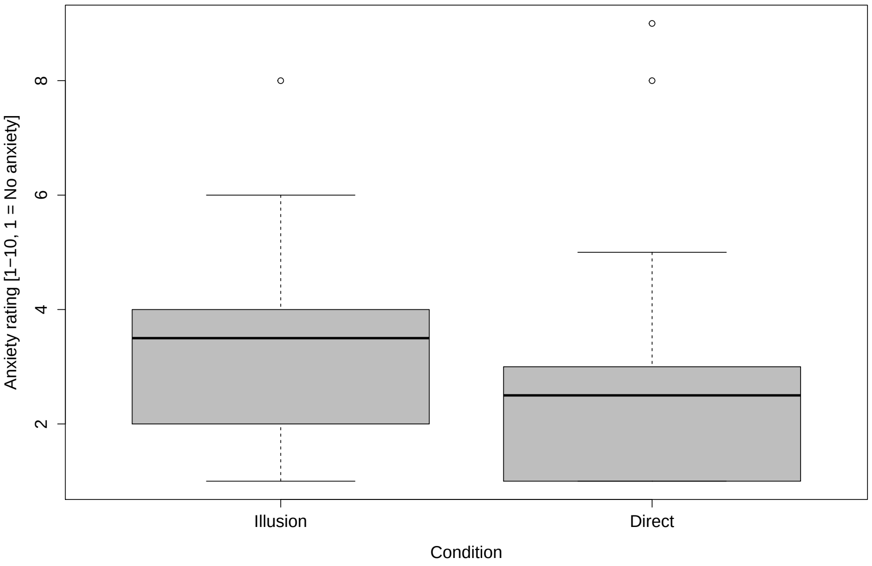
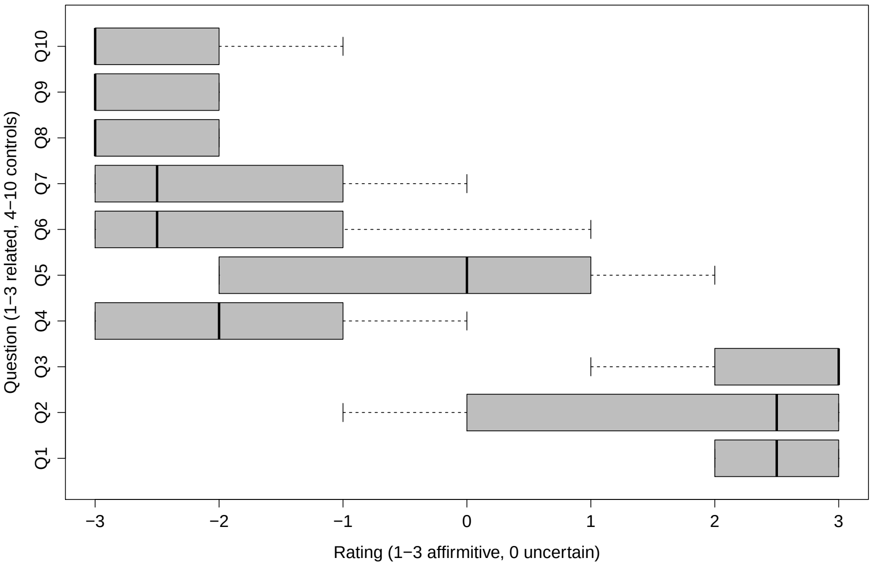


Figure 4.9: Questionnaire results of experiment two (6 participants)



Questionnaire results with the difference in ratings between the illusion and control statements (ANOVA): $F(9, 60) = 25.060249$, $p < 0.001$. Contrast comparison with the three illusion statements to the seven control statements: $p < 0.001$, $estimate = 4.1746$, $std.error = 0.2964$, $z - value = 14.09$. See figure 4.9.

4.4 Evaluation

Statistical analysis showed that the results did not have statistical significance except for the questionnaire. However, the p values from the EDA and anxiety ratings were not that far away indicating that there is a possibility that a confirming result could be achievable with a larger sample size.

The constructed set-up did not provide temporally synchronized images between the left and right camera image due to the lack of support for hardware level synchronization in the digital cameras. Generally, DSLR cameras due not support hardware synchronization. In comparison, Ehrsson's set-up used synchronized analogue CCTV cameras. It could have been possible to synchronize the images with some kind of analogue clock signal that would have been visible to both cameras. This clock signal would then be processed on the software level using pattern recognition to only show the images that would have the same synchronicity. This solution was deemed too time consuming to implement and initial tests showed that this effect was not noticeable to the user. The images from the cameras could even have different focal settings and that would not be evident to the user. The dominant eye is the primary source for our vision and masks the differences between our eyes.

However, there is some indication that the illusion was achieved with the constructed set-up. The participants reacted very differently to the visual threat. We noted that some participants reacted naturally to the visual threat by wincing or being graphically startled while others showed no visible reaction whatsoever. It was evident that the participants were most startled during the first presented threat regardless of the condition that was used with the repeated visuotactile stimulation. The 'freshness' of the presented threat vanished during the next threat events. This verifies at least that the visual threat evoked a spontaneous reaction as intended. The measurements showed an attenuating trend (see figure 4.10) in the magnitude of the physiological responses. This is presumably the result of habitual learning. The visual threat does not result in any tactile stimuli so no danger is associated with the threat. This was hypothesized and the order of the conditions in both experiments was varied between the participants.

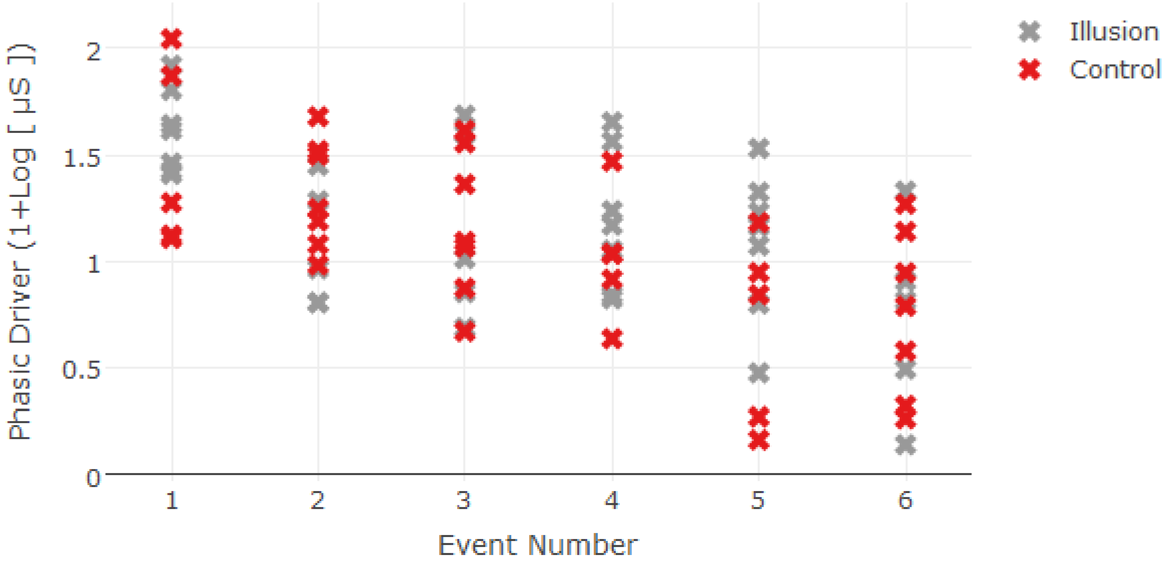
The comparison between the acquired results and the results of Ehrsson's study is discussed in the next section.

4.5 Comparison to Ehrsson's study

In Ehrsson's study three separate experiments were carried out. Our study fused elements from these three experiments into the two as described in section 3.2.

Ehrsson's first experiment was designed to evaluate if the illusion of an out-of-body experience is inducible. Only the illusory condition (see section 3.2.1) was repeated for two minutes after which the visual threat was presented once. To evaluate the experience the participants were asked to fill out a questionnaire immediately after the presented threat. The questionnaire contained ten statements that described different emotional states. The participants were asked to evaluate each of them on a seven-point scale to judge if the description fitted their perceived experience. The questionnaire had three statements that supported the illusionary experience and seven control statements that were designed to describe experiences that should not be present in the study. They tested for suggestibility and compliance with demanded task. The statements were the same as the English ones used

Figure 4.10: The attenuation of the EDA responses over the six threat events (x-axis). The figure depicts the measurements from both experiments distinguishing the illusion (red marker) and control (light gray marker) conditions. The phasic driver response was extracted from the EDA measurements and is presented on the y-axis on a logarithmic scale $(1 + Log(\mu S))$.



in our study (see table 3.1). The statements were presented in a randomized order.

The second experiment recorded EDA data to quantitatively gather data over the illusion and control conditions and to evaluate is there a measurable difference between the two conditions. Two EDA electrodes were attached to the second and third fingers. In our study the electrodes were attached to the index and the middle fingers. The execution of the second experiment was very similar to the first experiment in our study (see section 3.2.1).

The third experiment was designed to rule out habitual learning that could affect the differences between the two conditions in experiment two. The execution of the second experiment in our study was very similar to the Ehrsson's third experiment (see section 3.2.2).

The main difference between Ehrsson's study and the study conducted in this thesis is that the questionnaire in Ehrsson's first experiment was used in both the second and third experiment. The purpose of the questionnaire was to evaluate a visual threat that was presented once after the visuotactile stimulation. The procedure in our study changes the evaluative nature of the questionnaire as it addresses all six repetitions of the conditions. The participants were asked to judge all the experiences in their short time memory. The combined questionnaire results were in line with the hypothesis of the supportive and control statements.

In Ehrsson's study the subjective rating of the evoked anxiety was requested in experiments two and three. The participants were presented a 10-point visual analogue scale where 1 meant 'no anxiety at all' and 10 meant 'strongest possible anxiety imaginable'. The participants reported the average anxiety across the three threat events for each condition, whereas in our study the anxiety rating was queried after each threat event.

In Ehrsson's study the measured EDA values were evaluated by applying the through-to-peak (described in the end of section 4.3) method directly on the raw data. In our study we chose to use the Ledalab toolkit to extract the phasic driver response. This method eliminates cumulative errors that can bias EDA signal changes. The obtained phasic driver response values cannot be directly compared with the ones in Ehrsson's study but the relative difference between the two conditions should be the same.

Chapter 5

Discussion

This thesis focused on replicating Ehrsson's experiment set-up using devices intended for the consumer market and freely available software. The HMD device used in this study, the Oculus Rift DK2, and most of the selected software components have been designed for game developers. The study conducted in this thesis did not produce results that are statistically meaningful as the amount of participants in the experiments was too small. Other studies have confirmed Ehrsson's hypothesis in similar experiments (see chapter 2). The participants' verbal reports often state that the illusion is not that noticeable on the self-conscious level but the results show that the illusion does change the physiological response. The existence of the out-of-body illusion was recently confirmed using functional magnetic resonance imaging (see the end of section 2.8). The illusion is truly achievable using simple visuotactile tricks. This offers the possibility that the results of this study are in line with the hypothesis even if the results are not statistically significant.

The constructed set-up had a marginal delay between the recorded view from the stereo camera and the perceived output from the HMD. The delay was not measured as it was only slightly noticeable when observing one's own intentional movement. The participants were instructed to stay still to avoid inducing simulation sickness since the perspective was stationary. This inhibited the direct observation of the delay. Also, the initial tests showed that the visuotactile stimuli averted the participant from noticing the delay. In the first experiment the touching rod and the assistant's arm were blocked by the assistant's body from the perspective of the camera. The constructed rig for the rods ensured that the pens moved the same amount and came to rest at the same time. The cognitive mechanism associating the seen movement of the approaching rod with the touch of the other rod seemed to tolerate some level of discrepancy as the visual motion should have been incongruent because of the delay in the equipment. In the second experiment this should have been more evident as the point of touch is visible (the participant's shoulder). Interestingly, direct comparison between the results of the first and second experiment seem to indicate the opposite. The illusion was more visible in the results of the second experiment. Unfortunately, the analysed results did not provide enough statistical support for comparing the values.

It is possible that the delay in the visual output of the constructed set-up inhibited the induction of the illusion in some cases. Another source of interference can be the vague changes in the repeated hand movements performed by the assistant. The incongruent repetitions were noticeable from the recorded video material. Still, the sample size is too small to justify any definite conclusions. From our gathered experience we suggest that in further studies any tactile stimuli should be produced mechanically to eliminate incongruence between repetitions.

In this study the recorded head movements were not analysed due to the small sample size. The magnitude of the evoked anxiety or arousal could be quantitatively identified from the head's acceleration data. This could be explored in further studies to identify a relationship between the EDA events and graphic psychophysiological responses. Additional sources to measure the physiological response could be for example recording face expressions using electromyography (EMG). The movements of the body could also be analysed from the video using computer vision techniques like motion analysis.

In general, the EDA measurements do not state anything as discrete values. A rapid change in a short time frame is said to indicate something. The rapid change is associated with changes in the emotional state. The most prominent theory is that the sweat glands react to hormonal changes and the secretion of water changes the conductance of the skin. The precise mechanism or process behind the emotional state change and the following change of skin conductance is not known. It is possible that the regulation of the sweat glands is coupled to a variety of physiological mechanisms such as homeostatic regulation and other emotional states than arousal. There is suspicion that these possibly independent mechanisms produce multivariate noise that generates random changes in the EDA signal leading to false positives that are by chance temporally aligned with the events we are looking for. This could lead to an error factor that is too large to give any statistical or neurophysiological value to the EDA measurements.

Chapter 6

Conclusions

Cognitive sciences are an interdisciplinary field combining neurological, physiological and psychological aspects. The neurological mechanisms can be linked to cognitive processes that shape our psychological behaviour. The ambiguous phrases like self-consciousness and body image have long been tackled from different scientific viewpoints to find probable definitions that cover the empirical findings. Fortunately, new experimental solutions from the entertainment industry have provided the means to discover new scientific methods of evaluating our current models and concepts.

The IVR experiences can alter cognitive processes on the neurophysiological level as observed with the out-of-body illusion. Full body swapping experiments have enlightened the possibilities of manipulating the senses using immersive virtual reality (IVR). Serious games have many new opportunities which scope we just now begin to grasp.

Fears can already be confronted using IVR simulations to reduce the associated emotional distress. The rubber hand illusion (RHI) has been used to spoof a feeling of owning a third hand. The sense of selfhood seems to be very lenient when adjusting the body image to new configurations. These findings give a positive outlook for prosthesis development. The mental process of taking ownership over artificial or 'bionic' body parts is wired in our favour.

Nonetheless, IVR experiences can have far reaching consequences that we might not yet be aware of. Artificial stimuli can change our neural processing and induce long-term effects that can disrupt our everyday life. Fearful experiences can create new fears and affect our mental well-being. Further studies should assess the risks of these new AR and VR devices and model preliminary boundaries for the equipment manufacturers and the game industry in general. The entertainment industry may have incentives on exploiting the possibilities of these devices.

Bibliography

Salvatore M Aglioti and Matteo Candidi. Out-of-place bodies, out-of-body selves. *Neuron*, 70(2):173–175, 2011.

Jane E Aspell and Olaf Blanke. Understanding the out-of-body experience from a neuroscientific perspective. Technical report, Nova Science Publishers, 2009. `http://infoscience.epfl.ch/record/154802/files/2009_Aspell(chap)_understanding%20the%20obe%20from%20a%20neuroscientific%20perspective.pdf`.

Jane E Aspell, Bigna Lenggenhager, and Olaf Blanke. Keeping in touch with one's self: multisensory mechanisms of self-consciousness. *PloS one*, 4(8): e6488, 2009.

Mathias Benedek and Christian Kaembach. Ledalab, 2015. `http://www.ledalab.de/`.

Mathias Benedek and Christian Kaernbach. A continuous measure of phasic electrodermal activity. *Journal of Neuroscience Methods*, 190(1-5):80, 2010.

Loretxu Bergouignan, Lars Nyberg, and H Henrik Ehrsson. Out-of-body–induced hippocampal amnesia. *Proceedings of the National Academy of Sciences*, 111(12):4421–4426, 2014.

Johannes Bildstein. Canon edsdk tutorial in c#, 2015. `http://www.codeproject.com/Articles/688276/Canon-EDSDK-Tutorial-in-Csharp`.

Olaf Blanke and Thomas Metzinger. Full-body illusions and minimal phenomenal selfhood. *Trends in cognitive sciences*, 13(1):7–13, 2009.

Kristopher J Blom, Jorge Arroyo-Palacios, and Mel Slater. The effects of rotating the self out of the body in the full virtual body ownership illusion. *Perception*, 43(4):275–294, 2014.

Canon. Canon edsdk, 2015. `http://www.usa.canon.com/cusa/consumer/standard_display/sdk_homepage`.

Louisa C Egan, Laurie R Santos, and Paul Bloom. The origins of cognitive dissonance evidence from children and monkeys. *Psychological science*, 18 (11):978–983, 2007.

H. Henrik Ehrsson. The Experimental Induction of Out-of-Body Experiences. *Science*, 317(5841):1048, Aug 2007a.

H. Henrik Ehrsson. Supporting online material, 2007b. `http://www.sciencemag.org/content/317/5841/1048/suppl/DC1`. Accessed 1 Sep 2014.

Shaun Gallagher. *How the Body Shapes the Mind*. Oxford University Press, 2005.

Michael S Gazzaniga. The social brain. *Psychology Today*, 19(11):28, 1985.

Michael S Gazzaniga and Joseph E LeDoux. *The integrated mind*. Plenum Press, 1985.

Maryrose Gerardi, Barbara Olasov Rothbaum, Kerry Ressler, Mary Heekin, and Albert Rizzo. Virtual reality exposure therapy using a virtual iraq: case report. *Journal of traumatic stress*, 21(2):209, 2008.

Guy Godin. Sharpovr, 2015. `https://www.nuget.org/packages/SharpOVR/`.

Arvid Guterstam and H Henrik Ehrsson. Disowning one's seen real body during an out-of-body illusion. *Consciousness and cognition*, 21(2):1037–1042, 2012.

Arvid Guterstam, Malin Björnsdotter, Giovanni Gentile, and H Henrik Ehrsson. Posterior cingulate cortex integrates the senses of self-location and body ownership. *Current Biology*, 2015.

Antal Haans, Wijnand A IJsselsteijn, and Yvonne AW de Kort. The effect of similarities in skin texture and hand shape on perceived ownership of a fake limb. *Body Image*, 5(4):389–394, 2008.

Peter W Halligan, John C Marshall, and Derick T Wade. Three arms: a case study of supernumerary phantom limb after right hemisphere stroke. *Journal of Neurology, Neurosurgery & Psychiatry*, 56(2):159–166, 1993.

Morton L Heilig. Stereoscopic-television apparatus for individual use, October 4 1960. URL `http://www.google.com/patents/US2955156`. US Patent 2,955,156.

Silvio Ionta, Lukas Heydrich, Bigna Lenggenhager, Michael Mouthon, Eleonora Fornari, Dominique Chapuis, Roger Gassert, and Olaf Blanke. Multisensory mechanisms in temporo-parietal cortex support self-location and first-person perspective. *Neuron*, 70(2):363–374, 2011.

Johanna M Jarcho, Elliot T Berkman, and Matthew D Lieberman. The neural basis of rationalization: cognitive dissonance reduction during decision-making. *Social cognitive and affective neuroscience*, 6(4):460–467, 2011.

David Johnson. Introduction to and review of simulator sickness research, 2005. `http://www.dtic.mil/dtic/tr/fulltext/u2/a434495.pdf`. Accessed 6 Jan 2015.

Niklas H. Juslin. Stereoscopica, 2015. `http://www.jz.fi/stereoscopica/`.

Asaid Khateb, Stéphane R Simon, Sebastian Dieguez, François Lazeyras, Isabelle Momjian-Mayor, Olaf Blanke, Theodor Landis, Alan J Pegna, and Jean-Marie Annoni. Seeing the phantom: a functional magnetic resonance imaging study of a supernumerary phantom limb. *Annals of neurology*, 65 (6):698–705, 2009.

James R. Lackner. Motion sickness. 2004. `http://www.brandeis.edu/graybiel/publications/docs/190_ms_encns.pdf`. Accessed 6 Jan 2015.

Bigna Lenggenhager, Tej Tadi, Thomas Metzinger, and Olaf Blanke. Video ergo sum: manipulating bodily self-consciousness. *Science*, 317(5841): 1096–1099, 2007.

MIT. The mit license (mit), 1988. `https://opensource.org/licenses/MIT`.

G Lorimer Moseley, Nick Olthof, Annemeike Venema, Sanneke Don, Marijke Wijers, Alberto Gallace, and Charles Spence. Psychologically induced cooling of a specific body part caused by the illusory ownership of an artificial counterpart. *Proceedings of the National Academy of Sciences*, 105(35):13169–13173, 2008.

Lavell Muller. *Investigating Perceived Ownership in Rubber and Third Hand Illusions Using Augmented Reflection Technology*. PhD thesis, University of Otago, 2013.

Roger Newport, Rachel Pearce, and Catherine Preston. Fake hands in action: embodiment and control of supernumerary limbs. *Experimental brain research*, 204(3):385–395, 2010.

Satwant Pasricha and Ian Stevenson. Near-death experiences in india. 1986.

'thiagodiaspastor' 'PavelB'. Rastertek's tutorials on sharpdx and in c#, 2015. `http://sharpdx.org/forum/7-documentation/52-rastertek-tutorials-in-sharpdx`, `http://sharpdx-examples.googlecode.com`.

Valeria I Petkova, Malin Björnsdotter, Giovanni Gentile, Tomas Jonsson, Tie-Qiang Li, and H Henrik Ehrsson. From part-to whole-body ownership in the multisensory brain. *Current Biology*, 21(13):1118–1122, 2011a.

Valeria Ivanova Petkova, Mehrnoush Khoshnevis, and H Henrik Ehrsson. The perspective matters! multisensory integration in ego-centric reference frames determines full-body ownership. *Cognition*, 2:35, 2011b.

RasterTek. Rastertek's directx 11 c++ tutorial 5, 2015. `http://www.rastertek.com/dx11tut05.html`.

Juan C Saavedra-Aguilar and Juan S Gómez-Jeria. A neurobiological model for near-death experiences. *Journal of Near-Death Studies*, 7:4, 1989.

Giacomo Stelluti Scala. Command line parser library, 2013. `https://www.nuget.org/packages/CommandLineParser`.

SharpDX. Sharpdx, 2015a. `http://sharpdx.org/`.

SharpDX. Sharpdx toolkit's game class, 2015b. `http://sharpdx.org/documentation/api/t-sharpdx-toolkit-game`.

Mel Slater, Bernhard Spanlang, Maria V Sanchez-Vives, Olaf Blanke, et al. First person experience of body transfer in virtual reality. *PloS one*, 5(5): e10564, 2010.

Ivan E Sutherland. A head-mounted three dimensional display. In *Proceedings of the December 9-11, 1968, fall joint computer conference, part I*, pages 757–764. ACM, 1968. URL `http://design.osu.edu/carlson/history/PDFs/p757-sutherland.pdf`.

Manos Tsakiris. My body in the brain: A neurocognitive model of body-ownership. *Neuropsychologia*, 48(3):703–712, 2010.

Manos Tsakiris, Marcello Costantini, and Patrick Haggard. The role of the right temporo-parietal junction in maintaining a coherent sense of one's body. *Neuropsychologia*, 46(12):3014–3018, 2008.

Oculus VR. Oculus rift development kit 2, 2014. `http://www.oculus.com/dk2/`. Accessed 22 Dec 2014.

Leanne K Wilkins, Todd A Girard, and J Allan Cheyne. Ketamine as a primary predictor of out-of-body experiences associated with multiple substance use. *Consciousness and cognition*, 20(3):943–950, 2011.