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Control of Balance in Virtual Reality Interactions with a Galvanic Vestibular Stimulation

Master's thesis

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Abstract

This exploratory pilot study aims to gain insight into results a galvanic vestibular stimulation (GVS) would provide during a motion sickening (MS) (simulation sickness inducing) virtual reality (VR) interaction. GVS is proposed as a method which fights the sensory conflict by helping to sustain control over one's balance by sending very small currents through the head in order to selectively activate the vestibular system. Qualitative experiments are conducted in order to assess the severity of created simulation sickness, evaluate the application of a portable and automatic self-made GVS device (Appendix 1) and receive feedback about the experience. A thorough analysis of the results demonstrates that GVS as a method to fight instability in such scenarios is not only insufficient but also tends to increase the sensory conflict during such interaction.

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Introduction

Video games have become our everyday life as a popular leisure activity and are used by an increasingly wide range of age groups (McConville & Milosevic, 2014). Virtual reality (VR) is a field that has been lately growing and with it, the popularity of head-mounted displays (HMD) (Google Trends, 2018). The market for HMDs has been growing as fast as the amount of VR games and applications and with it a rise in the number of brands offering HMDs. The numerous brands allow for a wide range of variety and price which make it even more affordable, convenient, and enticing for a person to own one. VR has come a long way since its beginning and is used today in a diversity of applications encompassed within an industry, education, public and domestic settings. However, the use of HMDs in VR have been known to induce negative symptoms and effects in a person. This is known under the umbrella term as "simulation sickness" (Lin *et al*, 2002; Sharples *et al*, 2007). Simulation sickness, also known as cybersickness, induces symptoms similar to that of motion sickness although the difference is that simulation sickness is caused by the visually-induced perception of self-motion and not the actual self-motion of a person as in motion sickness (LaViola, 2000). Irwin (1881) notes that explanations of motion sickness have remained fundamentally unchanged for over 100 years and the most widely known account of motion sickness is the sensory conflict theory (Riccio & Stoffregen, 1991).

Soffel *et al* (2016) say that in virtual environments, balance studies are often related to symptoms of motion sickness, where the instability of subjects is used as a symptom indicator. The ability to maintain spatial orientation and balance is the result of synchronization of neural inputs from the vestibular, visual, and proprioceptive systems Cevette *et al* (2012). One of the main sensory inputs to postural balance is the vestibular system in the inner ear, which senses angular and linear acceleration movements of the head (McConville & Milosevic, 2014). Well enough there is a way to control this system from the outside of the body. It is called galvanic vestibular stimulation (GVS). GVS is a simple and safe way of affecting one's balance by applying a small current (from 1.0 mA to 3.0 mA) to the vestibular system (Fitzpatrick & Day, 2004). Although known about for 100 years or so, galvanic vestibular stimulation attracted relatively little interest until some 15 years ago. This is partly because oculomotor control has dominated human vestibular research, says Day (1999).

There has been a good amount of visual evidence online of people falling while using VR interactions. Having your eyes covered by an HMD gives you no visual clues, as well as a wrong effect of a self-motion in a VR interaction, causes motion sickness, which in order amplifies disorientation and postural instability. It all pours out into a loss of balance and potential physical damage for the person using VR as well as for surroundings. As an example, another case where solution system like GVS might be useful is for any VR installation (e.g. museums, malls, funfairs, etc.) because to this day these installations are usually operated by professionals, who tend to control the participant. To be more exact, their balance, by holding the person in case of any postural instability. Any external control of the person who's experiencing VR simulations diminishes the effect of immersiveness.

Research questions & hypothesis

VR experiences are designed around the illusion of movement, a conflict will exist between the visual experience and the inner ear experience (Akiduki et al, 2003). In the real world, this conflict is the basic source of motion sickness and loss of balance (Johnson et al, 1999).

With this exploratory pilot study, I target the primary research question with a qualitative experimental approach to understand what results a galvanic vestibular stimulation would provide if used as a balance controlling device during a sickening VR interaction.

I hypothesize that GVS can mask, diminish or even remove the sensory conflict completely by helping to sustain control over one's balance which would result not only in a straight posture of the user but also in a decreased amount of simulation sickness.

Expected outcomes

The overall plan of the whole research work consists of multiple parts. An initial step to kickstart the study is to do a thorough literature review in order to get a good grasp of multiple correlated topics at once. This part is going to take most of the time but it is vital to complete it in order to proceed to next steps. Once literature review is done it will generate a lot of necessary material for understanding how does the GVS process work, what is needed in order to create a device yourself, what things can be additionally developed for it to address secondary problematic aspects of that realm, understand how exactly could it be interconnected with VR and based on that design the experiment. Understanding of VR and processes of the vestibular system will provide enough information about the things to aim for – e.g. what questionnaires and interview questions would fit us best in order to get a fair understanding of the outcomes and how to analyze and what to look for from the results. In essence, goals of this research are to successfully conduct experiments that would use a well-made stimulation device whereas both experiments and the device would be designed and completed based on the knowledge obtained from the theory of previous researchers.

1. Theoretical background

This chapter aims to provide both brief historical overview on some subjects as well as a good background on previous researches and try to dig out specific nuances that could be beneficial in this research. In short, this chapter will look into specifics of a vestibular system, virtual reality, motion sickness and galvanic vestibular stimulation in order to combine the findings later on in the study.

1.1. Vestibular system

One of the main sensory inputs to postural balance is the vestibular system, a nonauditory component of the inner ear, which senses angular and linear acceleration movements of the head (McConville & Milosevic 2014). In other words, it is essentially a human inertial motion sensor, which is able to detect rotational changes (equivalent to a gyroscope, sensed via the semicircular canals (SCC)) and acceleration (equivalent to an accelerometer, sensed via the otolith organs). Due to the fluid mechanics of the canals, the SCC neural output actually closely matches angular velocity (Fernandez & Goldberg, 1971; Hullar & Minor, 1999; Hullar *et al*, 2005; Sadeghi *et al*, 2007). There are three orthogonal canals, the horizontal, superior, and posterior SCCs which sense angular velocities in the approximately pitch, roll and yaw motion planes. Because the otoliths are by their nature accelerometers, notes Einstein (1916), they are unable to differentiate between changes in gravitational and inertial accelerations so they cannot distinguish between tilt and linear translation without additional information and processing from the CNS. To be specific, the input is carried to the brainstem (as coded signals), where this information is distributed to several areas of the central and peripheral nervous system (Viirre & Furness, 2001). This information is used together with cues from the visual system and the somatosensory system (e.g. proprioception and motor actions) to determine a perception of self-motion (McGill *et al*, 2017).

Vestibular system provides sensory information about equilibrium, motion and spatial orientation, says Parel & Traskinaite (2012). According to Gaerlan *et al* (2012), balance system consists of multiple sensory inputs, making it difficult to assess as a single measure, because the performance depends on many factors. Also, human balance control, in general, is based on the combined inflow of different sensory systems. Proprioceptive, visual, haptic, and vestibular sensors are considered the most important sources of information (Fitzpatrick, 1994). In many situations, these sensory systems provide largely redundant information so that loss of one is not critical. In situations where one sensory channel becomes critical for balance or another becomes false or unreliable, the CNS might selectively deal with or ignore specific channels through a process of "reweighting" (Dilda *et al*, 2014; Kitazaki & Kimura, 2010; Oie *et al*, 2002; Cenciarini & Peterka, 2006; Pasma *et al*, 2012).

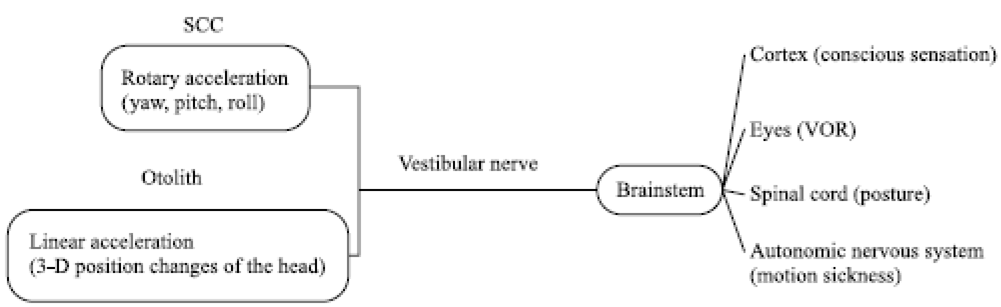

Figure 1 Connections between the vestibular system and the nervous system

The connection with the eye movement system (the vestibulo-ocular reflex; VOR) stabilizes vision during any head movement. The connections with the spinal cord play a role in maintaining the posture through controlling signals to the muscles of posture (Viirre & Furness 2001). Gaerlan *et al* (2012) have found that the visual system is the predominant sensory system for maintaining postural balance. Decent balance performance involves clear vision while moving, determination of direction and speed of movement, orientation recognition with respect to gravity, and automatisation of postural adjustments to maintain posture and stability under different circumstances (Parel & Traskinaite, 2012).

As Morasso & Schieppati (1999), try to explain, another good perspective to have on how the vestibular system works is that the underlying systems involved in balance control interact within a closed loop. When the body is disturbed by internal and/or external disturbances, it needs to react to these disturbances. The sensory information is combined and integrated by the nervous system with a specific time delay. Subsequent motor system action in the form of corrective, stabilizing joint torques is generated. This changes body position, which is again perceived by the sensory systems. Thus, in daily life cause and effect are interrelated in a continuous process within a closed loop (Morasso & Schieppati, 1999).

Interestingly enough, repeated actions on the balance system teach to optimize balance control. When the vestibular apparatus on both left and right sides of the head are well functioning, they send symmetrical impulses to the brain (Parel & Traskinaite, 2012). In the past, as mechanical techniques to induce vestibular sensations by moving the human body, there have been motion platforms such as the Stewart platform (Nagaya *et al*, 2005). Today, and already for a long time, a method called Galvanic Vestibular Stimulation has been used both in medicine and in research.

1.1.1. Posture instability and balance disturbance

Posture is defined as the overall configuration of the body and all its segments (Norkin & Levangie, 1983) and postural control as the coordinated stabilization of all body segments (Riccio & Stroffregen, 1988). Lee & Lishman (1975) state that overall body posture is strongly influenced by optical stimulation. Whereas uncontrolled eye movements interfere with a pickup of the relevant information, says Riccio & Stoffregen (1991) and so can induce instabilities in body posture. Actions that minimize uncontrolled movements require effort, such that in the absence of effort many postures are unstable. The longer you are unstable, the greater the likelihood and intensity of symptoms. When changes in dynamics are large or abrupt, or when we attempt a behaviour for which we lack control strategies, we may lose control entirely, says Riccio & Stoffregen (1991).

Riccio & Stoffregen (1991) also tried to explain, that in many common situations (e.g., vehicular travel, amusement park rides, or the workplace) we are unwilling or unable to terminate our interactions with the environment, even when the dynamics of these interactions are disturbingly unfamiliar. In such situations, there is not an outright loss of postural control, yet the unadapted animal is unable to terminate their state of instability. This can occur if we fail to perceive the new dynamics or if we are unable to assemble and execute the control actions that are appropriate for the new dynamics. In such situations, we maintain performance at a degraded level, and we are exposed to a prolonged instability that we normally would not tolerate. Another reason why we may tolerate instability, especially if it is subtle, is that it may provide information about the underlying dynamics of our interaction with the environment (Riccio & Stoffregen, 1991).

Pasmaa *et al* (2014) represent balance control as a closed loop. Using external disturbances the balance control can be disturbed at different places in the loop (e.g. by external pushes, ankle rotations, visual scene movement or galvanic stimulation) and the reaction to the disturbances can be established in different places by measuring muscle activity, ground reaction forces (i.e. center of pressure movement) and body sway (i.e. center of mass movement).

There are actual methods that are specifically dedicated to measuring posture changes. For example, Yang *et al* (2015) were using a Footscan 0.5m Plate (RSscan, Olen, Belgium) with resistance and pressure sensitive sensors. I decided to avoid this kind of method due to the challenge type (VR game) that was used, the unease of getting a hold of them and not mentioning the lack of skill to use them and their software.

One way of controlling your body sway is to consider that on stationary surfaces, muscular action at the ankle joint is effective for the control of body sway (Riccio & Stroffregen 1988). One effect of muscular action at the ankles is to stiffen the ankle joints. During experiments, it turned out that it is quite hard to notice such symptom directly, but it was assumed of happening when the person was barely moving their legs when the postural sway was happening.

1.2. Virtual reality

Virtual reality (VR) is a novel technology that allows players to experience three-dimensional (3-D) visual, auditory, and tactile environments. Specialized sensors and interface devices allow players to become immersed, navigate and interact with objects in a computer-generated environment. Most people associate VR with video games: however, researchers and clinicians are becoming increasingly aware of its potential benefits for people with disabilities and for individuals recovering from injuries, says Viirre & Furness (2001).

Viirre & Furness (2001) also studied, that the virtual world consists of a 3-D graphics program that uses a spatially organized, object-oriented database in which each object an object in the virtual world. For greater realism and increased immersion, these modelling programs apply state-of-the-art computer-graphic techniques to all of the objects in the scene - things like texture mapping and shading. The object database is manipulated using a real-time controller that specifies how objects behave within the world. In a virtual environment, we view images with a head-mounted display (HMD), which shows a virtual image corresponding to the current direction of gaze. The controller tracks the position and orientation of the user's hand and HMD - head.

VR includes the possibility of creating experiences that we would not normally have. These novel experiences may also include novel ways of generating illness (Viirre & Furness, 2001). They also specify that VR is motion illusion. Beyond what is being simulated, motion sickness in VR may occur because of the system itself. Such simple factors such as the weight and temperature and closed-in feeling of the HMD can exacerbate the symptoms. The motion of the head has to be detected, calculated and then converted into a new gaze direction by the VR system in real time to give the illusion of presence. There are two possible failures in this transformation: either the transformation can take too long, called transport delay or the transformation can be incorrectly done, called geometric distortion (Viirre & Furness, 2001).

1.2.1. Vestibular system & VR

The vestibular system interacts extensively with the visual system, and balance improvement has been demonstrated through static and dynamic visual stimuli in VR systems (Suárez, 2006). When a decrease in stability for the virtual environment happens, it is usually based on the fact that the anterior-posterior movement does not evoke any perceivable change in the virtual environment, which consequently cannot provide any visual cues to increase stability (Soffel *et al*, 2016).

Changes in body position with respect to gravity can influence performance in mental imagery tasks, notes Mast *et al* (2003). Mental imagery is being compared with the visual information when seen through the VR then it all is being compared to the body position and that's also where a sensory mismatch can occur. Merhi *et al* (2007) found that using an HMD with commercial console video game systems can provoke motion sickness preceded by instability in the control of seated posture. Postural loss of control is even possible during seated play!

1.3. Motion sickness

Motion sickness (MS) has been with us through the ages. Twenty-five centuries ago it was a problem for the ancient Greeks (Lawther et al, 1986) and even to this day due to being so hard to narrow down the definition for it having so many nuances and variables, explanations of motion sickness have remained fundamentally unchanged for over 100 years (Irwin, 1881).

The most widely known account of motion sickness by Ricco & Stoffregen (1991) is the sensory conflict theory. Sensory conflict is believed to interfere with the inductive inferences that animals make about their interaction with the world. Motion sickness is believed to be a byproduct of this interference. The primary symptoms of MS include nausea, vomiting, wanes, and cold sweating (Bosser et al. 2006). These symptoms come from visual, vestibular, and proprioceptive cues of motion and probably alert the body towards the potential danger of homeostasis. Conflict sensory input evokes physiologic disorders that are even similar to venom effects and leads to nausea and vomiting (Treisman, 1977; Crampton, 1990).

Reason & Brand (1975) defined three components of motion sickness: the total time of exposure, the characteristics of the stimulus and the susceptibility of the person. The result is that anyone with a functional vestibular system can suffer from motion sickness, given the right prerequisites and if the exposure is continuous over a long period of time (Dahlman, 2009). People without a working vestibular apparatus do not experience motion sickness, as observed by Viirre & Furness (2001). Hosseini et al (2015) noted that motion sickness typically occurs during unusual body movements and when there is a conflict between sensory-motor signals, such as messages from motion in an environment, it becomes compatible with reality. The greater the discrepancy between the sensory information and the expected sensory information, the greater the chance of motion sickness occurring, and the greater the severity of the sickness becomes (Oman, 1990; Bles et al, 1998). Studies by Owen et al (1998) have demonstrated that motion sickness can occur due to postural sway even without visual cues.

Another way how to put things about the appearance of motion sickness is that awareness of motion may not align with what the vestibular system is suggesting regarding the magnitude of motion, says McGill et al (2017). Several studies indicate that self-motion signals from the vestibular system are sent to the same brainstem nuclei that are stimulated by visually induced self-motion cues (Waespe & Henn, 1979). Visual and vestibular self-motion systems differ in response latencies to sudden stimuli (Wong & Frost, 1981). For moderately intense inertial stimuli (velocity changes), vestibular responses occur with latencies less than 1 s. By contrast, self-motion perception occurs with latencies on the order of seconds after scene motion onset, mentions Wong & Frost (1981). When there is a mismatch among these signals or when input patterns from different senses do not correspond to stored expected sensory patterns, spatial disorientation may occur.

Gonzalez (2015) defined two different types of intersensory visual-vestibular conflicts produced by a variety of provocative environments: a) both vestibular and visual systems simultaneously give contradictory or uncorrelated information, b) the vestibular system signals are received in absence of the expected visual signals. It has been proposed by Flanagan et al (2004) that, there is an interaction between eye movement, sensory conflict, and postural instability in the symptomatology of MS. Additionally, a theory by Riccio & Stoffregen (1991) stated that motion sickness results from prolonged instability in the control of the posture, so losing equilibrium is the cause of motion sickness. So far there is a strong relationship between how a person is standing and the amount of motion sickness they are possible to experience. There is evidence to suggest that posture may play an important role in the development of disorientation and nauseous symptoms (Golding, 1998). Also, stability has been shown to diminish motion sickness, through aligning the body with changes in the environment and minimizing head movements (Golding & Gresty, 2013, 2015; Bittner & Guignard, 1985).

Even though, as Mast et al (2014) specify, we are bound to physical space, we are able to represent objects and movements mentally in order to optimally predict actions, react to events, and solve problems. Brain areas dedicated to the processing of real body motion are also in the service of mental imagery when whole body motion is merely imagined but not executed (Mast et al. 2014). Viirre & Furness (2001) give an example about being inside a boat, where there is no access to windows, there is cue conflict because the visual system detects and apparently stable environment, but the vestibular apparatus is sending information to the brain indication motion. When out on the deck the horizon can be viewed, giving the visual system information of self-motion relative to gravity, the cue conflict is reduced and correspondingly, motion sickness is reduced.

Just to show how unstable the topic is Riccio & Stroffregen (1991) hypothesized in their research that motion sickness results from prolonged instability in the control of posture. They began by examining, and rejecting, the hypothesis that stimulation of perceptual systems is ambiguous with respect to the world. They argued that changes in sensory stimulation do not cause motion sickness. This leads them to consider a new approach to motion sickness; one that concentrates on the control of action.

1.3.1. Sensory conflict theories

Stoffregen & Ricco (1991) have emphasized in their research that the existence of sensory conflict is hypothetical; it is an interpretation of facts, rather than a fact itself. Yet they participated in defining one of the theories.

In the first, also called ecological, postural instability theory Ricco & Stoffregen (1991) define postural control as the coordinated stabilization of all body segments. This theory holds that when an animal encounters a destabilizing environment, it must try to regain and maintain postural control. If the animal does not possess or cannot learn a strategy to maintain postural control and the instability continues, sickness results (Ricco & Stoffregen, 1991). While learning/encoding a new sensory arrangement as “normal” is a part of this adaptation, modification of behaviours could also play a role. At a minimum, by modifying their behaviours people could potentially reduce the conflicting inputs (Jones, 2011).

The second theory is sensory conflict theory. Sensory conflict theory by Reason & Brand holds that sickness arises when the visual, vestibular, or proprioceptive system receives input that does not match with the “normal” expected situational norms that have been encoded in the brain. In essence they identify a variety of motion cue mismatches related to the vestibulo-ocular reflex (VOR), stressing the concept that the brain combines the sensorial information from the vision and the inner ear with the internal expectations from previous experiences, as part of all the needed information to determine where the body is at all times. (Reason, 1970, 1978; Reason & Brand, 1975). In other words as McGill *et al* (2017) described, if the motion perceived by the visual system conflicts with that perceived by other sensory systems there is a likelihood of motion sickness being induced.

The final theory of motion and simulator sickness is the evolutionary hypothesis of motion sickness. Treisman (1977) bases this theory on the fact that humans have evolved to use input from their visual, vestibular, and proprioceptive systems (or a subset thereof) to move their eyes/head to a target or their body about an environment. However, because this system uses none of the three inputs in isolation when one of the inputs is at odds with another sickness results. Unlike the sensory conflict theory, this conflict is not between the present and previous experience. It is a conflict between two or more senses in a situation that requires close monitoring of input for motor control purposes (Treisman, 1977).

As Jones (2011) mentions there are some problems with the work done on these theories thus far. To begin, all of the theories started as theories of motion sickness and were later adapted to cover simulator sickness. Because the symptoms are so similar it is easy to see how parallels could be drawn. One main problem with using a motion sickness explanation for simulator sickness is that in many simulators there is no motion at all.

1.3.2. Simulation sickness

Stanney *et al* (1998) notes, that when in a simulator, whether it is a VR game or a surround screen monitor setup for pilots, some individuals experience Simulator Adaptation Syndrome (SAS), which may include one or more of the following symptoms: nausea, disorientation, dizziness, headache, and/or difficulty focusing. Research has shown that these symptoms can sometimes linger for several days after the virtual environment exposure (Ungs, 1989; Stanney & Kennedy, 1998).

The illusion of self-motion is often referred to as vection. This illusion, in the absence of any congruent physically perceived motion, is primarily the cause of Visually Induced Motion Sickness (VIMS), often a significant component of simulator sickness/cybersickness (Keshavarz *et al*, 2015). Jones (2001) noticed that when a participant in a research study or a trainee experiences simulator sickness, it can have severe ramifications to the person involved, the simulation session, and the continued use of the simulator for that individual. In research, simulator sickness can skew experimental results by becoming itself a distractor to the task under examination (Kolasinski 1995; Lawson et al. 2002; Stanney et al. 2002). In addition, it can waste time for both participants and experimenters and also squanders experimental resources.

This is why it is best to diminish any possible simulator sickness by using a state-of-the-art computer to provide the best simulation possible, especially image frame rate, response time and graphics wise. It solely depends on the virtual environment/simulation that is planned to be used. If it is not very demanding of processing power then even a carton head mounted display with an inserted smartphone is a solution. Sometimes the symptoms are so severe that the experiments or interactions have to be terminated and data is lost (Stanney *et al*, 1998). One theory is that SAS occurs due to the visual perception of self-motion, induced by the virtual environment (VE), conflicting with the perception of a static situation from the vestibular system (Flanagan *et al*, 2004). It is good to mention that vestibular deactivation has been reported repeatedly during visually induced self-motion (Brandt *et al*, 2002).

One thing is overlooked in much of the simulator sickness research, is that people who have vestibular loss do not show classic motion sickness. To Jones' (2011) knowledge there has been little in the way of explicit testing to see if this holds for simulator sickness as well. In practice, only some people actually get sick in simulators while others seem to be immune. This is a problem because there are marked individual differences in how people react to simulations, and it is important to predict who will get sick before they step into a simulator. It has been thought, as Stanney et al. (1998) point out, that up to 95% of any simulator users show some level of simulator sickness. Individuals with a history of motion sickness are at increased risk, and those that have had an emetic response to a carnival ride have double the risk (Stanney et al., 2002). Factors such as drug and alcohol consumption, fatigue/sleeplessness, and current ailments (such as a cold or flu) have all been associated with higher levels of simulator sickness (Stanney & Kennedy, 2009).

1.3.3. VR & GVS effects on posture, balance and sickness

Reed-Jones *et al* (2008) mention if the natural reaction to adaptation following exposure to a VE simulator is to reduce the weight of visual information for spatial orientation, visual contributions to posture control should remain predominant with the application of vestibular and cutaneous stimulation (which would reduce the visual conflict). The natural reaction to the visual conflict presented by the VE simulator results in a decreased weighting of visual information in postural control activity. However, when a secondary sensory stimulus is given during the simulation (e.g. GVS), visual contributions to postural control actually increase, suggesting that application of an additional sensory perception of motion reduces conflict and attenuates sensory recalibration.

This altered relationship between sensory systems would be maintained immediately after exiting the simulator until re-adaptation to the natural environment occurred Reed-Jones *et al* (2008). This altered aftermath state can be easily used for probing a person on how they feel by using the Simulator Sickness Questionnaire (SSQ; Kennedy, Lane, Berbaum & Lilental, 1993), the current standard for evaluating SAS in simulator research.

Providing a vestibular motion stimulus through GVS, as Kemeny (2003) proposes, may help reduce the conflict between the perception of a static (vestibular) and a perception of a dynamic (visual) situation, resulting in reductions in SAS in fixed-base simulators. Reed-Jones *et al* (2007) also noticed that reductions in SSQ scores due to the application of GVS were observed. This suggests that, as they have hypothesized, the application of GVS during a simulation can help reduce symptoms of SAS. Not only did GVS reduce overall symptoms of SAS (as measured by Total SSQ), but GVS significantly reduced disorientation symptoms. Typically, in static VE simulators, disorientation scores are greater than oculomotor discomfort scores, which are in turn greater than nausea scores.

1.4. Galvanic vestibular stimulation

In the late 1700's Luigi Galvani, an Italian physicist and biologist was studying the nervous system of the frog and discovered that distant electrical discharges of the lumbar nerve would cause the muscles of a dead frog's legs to contract (Galvani, 1791). This first display of bioelectricity became known as galvanism and has been used extensively since then to study the form and function of the nervous system (Galvan-Garza, 2016). Galvanic vestibular stimulation (GVS) has since been defined as the transcutaneous delivery of electric currents to the vestibular afferents (Fitzpatrick & Day, 2004) associated with both semicircular canals and otolith organs (Cathers *et al*, 2005).

As individuals can have a different level of skin impedance it is necessary to calibrate the GVS system. In other words, one person could be affected at a much lower current than another (Byrne *et al*, 2016). The need for a larger current for another person may be due to the lower sensitivity of the vestibular system to GVS (Yang *et al*, 2016). The central nervous system could mistakenly consider GVS as a head movement and then the whole-body responses can be evoked (Fitzpatrick & Day, 2004). Some studies have discovered that the amplitude of sway varies from person to person (Balter *et al*, 2004a, 2004b; Rinalduzzi *et al*, 2011; Tax *et al*, 2003). The larger body deviation may be due to a weaker ability to suppress vestibular illusions induced by GVS (Yang *et al*, 2016).

GVS is a simple and safe way of directly affecting the person's vestibular system via electrodes placed on the mastoid bones behind each ear, in other words by inducing sensations of vertigo within the inner ear (Byrne *et al*, 2016). The resulting effect is that wearers feel a pull or sway towards the positive electrode and thus the system affects one's sense of balance in that direction. Repeated use of GVS results in no deterioration to global function (Wilkinson *et al*, 2009), and only minor itching from electrode placement (Utz *et al*, 2011).

Designers have considered the possible applications of GVS, for example Nagaya *et al* (2006) investigated altering a person's visual perception and balance based on the playback of music tuned to the GVS stimulation, whilst Maeda *et al* (2005a) adapted a

GVS system to allow one person to affect another's balance via remote control. Maeda *et al* (2005b) have also investigated GVS in VR environments, finding that in a VR setting, GVS can increase one's sense of self-motion. GVS has also been explored as a practical training tool, for example, Moore *et al* (2001) used GVS as a training tool for astronauts to simulate post-flight effects.

There have also been many studies where GVS has been used as an acceleration interface. "Radio-controlled walking" is an attempt to mimic human walking using GVS-induced vestibular information (Maki *et al*, 2003).

Balter *et al* (2004a, 2004b; 2004c) discovered that postural responses to GVS reduced after the first GVS stimulus and the reduced response could be maintained for at least 2 weeks, meaning that people could be habituated to GVS within minutes and maintain this habituation over an extended period of time.

Lund & Broberg (1983) discovered a key principle when they showed that the direction of the evoked movement was always in the direction of the anodal ear. No matter how much a person changed their posture by twisting their body and/or neck about a vertical axis, the current always made them sway towards the anode.

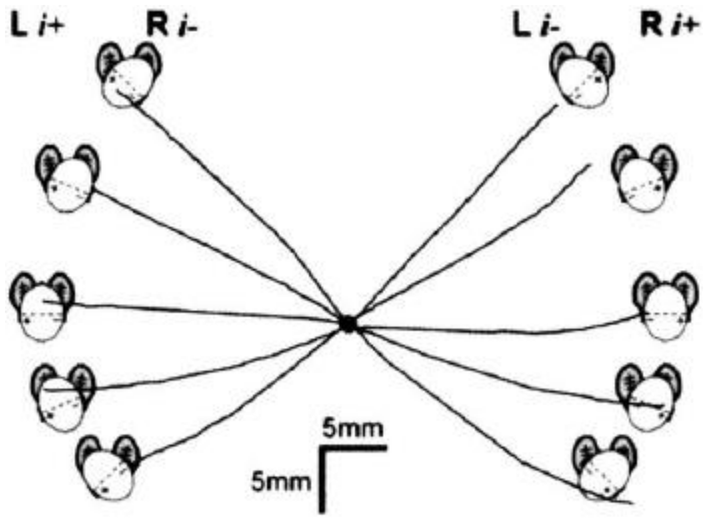

Figure 2 The whole-body sway trajectories were always along the head interaural line and towards the anodal electrode; the direction of sway induced by bilateral bipolar GVS is dependent on head position (from Fitzpatrick and Day, 2004; redrawn from Pastor et al, 1993)

This is an important aspect to consider when dealing with VR. When a person is using VR for gaming, they can have their feet looking in one direction and head turned into another at all times due to observing feature availability in VR games (look around yourself to see what is happening). The question occurs where to put the GVS device with the accelerometer during tests, because if a person will be losing their postural balance and leaning towards one of the sides, the received angles by the accelerometer might differ whether it's placed on the head (which can be turned) or the body.

Bilateral bipolar GVS application (most commonly used), the model predicts a primary signal of acceleration toward the cathodal electrode and tilt response toward the anode. Whole body responses to GVS seem to be organized by the balance system that interprets the GVS-induced afferent firing as a real head movement in space resulting from an unplanned body movement. The greater the stimulus level, the greater the virtual tilt that the subject feels.

Previous research has shown that Assistive Vestibular Stimulation reduces simulator sickness (Reed-Jones *et al*, 2007, 2008, 2009). The original explanation for this result was that stimulation replaced the missing vestibular input and in turn removed the conflicting situation.

1.4.1. Stochastic vestibular stimulation

Stochastic resonance is a phenomenon in which the response of a non-linear system to an input signal is benefited by the presence of a particular non-zero level of noise.

The application of subsensory mechanical noise to the feet has been shown to improve balance through the reduction of sway in young and elderly subjects (Priplata *et al*, 2002, 2003;Dettmer *et al*, 2015) and gait variability in elderly fallers (Galica *et al*, 2009).

Lobel *et al* (1998) set their stimulus level 0.5 mA below each subject's pain threshold while Geraghty *et al* (2008) used 90% of sensory threshold (in their case was the level at which nystagmus began). Samoudi *et al* (2015) used the lowest level of SVS with which subjects exhibited rhythmic sway measured by a force plate. SVS has been found to improve ocular stabilization reflexes in response to whole-body tilt (Geraghty *et al*, 2008) and postural balance performance on an unstable compliant surface in Parkinsonian patients (Samoudi *et al*, 2015; Pal *et al*, 2009).

Galvan-Garza *et al* (2016) have found that the application of low level, noisy electrical current to the vestibular system via electrodes placed behind each ear can improve the human vestibular perception of low-level physical motion stimuli. They believed that this improvement in sensory performance is due to the exhibition of stochastic resonance, in which added noise enables better transfer of information through the nonlinear system (Galvan-Garza *et al*, 2016).

1.4.2. FES & electrical stimulation overview

One of the additionally questionable things that needed at least some research were electrodes, and in particular, how does the electrical stimulation actually happen. Since for GVS parameters of electrodes used were important in order to gain an appropriate result, it was decided to research in depth on that topic before purchasing the ones that were used later on in the experiment.

As an example, I took functional electrical stimulation (FES) due to its simple yet straightforward methodology. FES itself is a technology that uses electrical currents applied to the peripheral nerves. Those electrical currents are established between two surface stimulation electrodes (Bajd *et al*, 2008). The electrical currents across the nerve influence the transmembrane potential and can generate an action potential. In case the FES the action potential propagates along the nerve causing contraction. In case of GVS, it affects the vestibular nerve, which transmits sensory information transmitted by vestibular hair cells located in the two otolith organs. As ions create a current in the tissues the current is going through not just the bone or just the skin (Bajd, 2006).

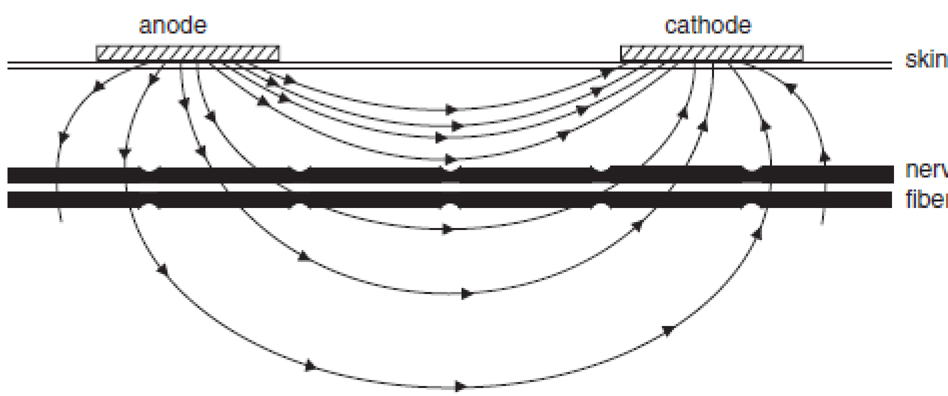

Figure 3 Electric field between a positive and negative electrode (Bajd, 2006)

When we are talking about different stimulation types regarding electrode placements, their size – there are things to consider. With a unipolar stimulation, one electrode is often considerably smaller than the other, whereas the electrodes used in bipolar stimulation both have the same size (Bajd, 2006). Larger electrodes are used to stimulate the nerve endings spreading all over the underlying tissue, whereas smaller electrodes are applied to influence the nerve when the latter comes closer to the skin. By larger electrodes, stronger contraction is obtained along with a reduced current density and a likewise less pronounced unpleasant sensation on the skin. However, large electrodes permit no selective choice of a desired movement of the stimulated paralyzed extremity.

An electrode is usually made of metal (Bajd *et al*, 2008). However, it may be made of a nonmetal, commonly carbon. The simplest of the surface electrodes consists of a metal plate or metal wire mesh coated with fabric or sponge. The design criteria for surface stimulation electrodes are as follows: physical comfort to the skin, sufficient electrical surface area preventing skin irritation, use of hypo-allergenic materials, flexibility to follow body surface, ease of attachment and ability to remain in position for the duration of at least one active day, reusable, low cost, reliable means of connection to stimulator, resistant to medical solvents and electrode gels, low and stable electrical resistance (Bajd *et al*, 2008).

Another important property of electrical stimulation is the impedance between the electrode and the skin. It is desirable that the resistance should be as low as possible to avoid energy losses before the stimulation has reached the neuromuscular tissue (Bajd, 2006).

The contact conduction is increased by moistening the electrodes with water or special conductive electrode gels. Bones are also very bad conductors of electric current; the greatest current density appears at the skin-electrode contact and tends to decrease with distance from the electrodes as the flow spreads out over a larger area. If the skin between the electrodes is too moist, this causes the current between the electrodes to flow to the skin, which results in a burning sensation (Bajd, 2006). A too thinly or unevenly spread gel increases the current density at certain points, thereby bringing about a danger of burns. Small differences in size and shape of clinically available electrodes do not seem to affect the patient’s tolerance to electrical stimulation (Bajd, 2006).

1.4.3. GVS stimulation specifics

There are some conditions which should be taken in the count when the galvanic vestibular stimulation (GVS) is happening. In short, they are a current threshold, length of the stimulation, skin to electrode resistance and the electrode size. The most compact benchmark characteristic was proposed by Hanes & McCollum (2006) similarities to which are seen throughout almost every GVS related publication. The most common type of the GVS is referred to as bilateral bipolar GVS and consists of 2 electrodes placed on either side of the head on the mastoid processes and a current of about ~1 mA is supplied for 1 to 2 seconds, through the electrodes with 600-900 mm2 contact surface and generous amount of electrode gel (Hanes & McCollum, 2006).

The vaguest aspect in GVS is the current consumption amount, which is measured in mA. This is the variable that defines how mild or potent the effect of GVS is going to be. There are some conditions which should be taken in the count when the stimulation is happening. The 9V battery basic GVS experiments with home-made electrodes (soaked in salt water) and a couple of wires were popular only on the web and that was the place where people were advocating that the current that will be going through one's head whilst accommodating the natural skin impedance and electrode contact surface dimensions, would be around 1.0 – 1.2mA. This shows that in essence, the methods are more-less universal, noting the usage by Hanes & McCollum (2006).

Yang *et al* (2015) et al. were suggesting that the need for these kinds of large current numbers may be due to the lower sensitivity of the vestibular system. That being said 1.0 mA does provide quite a wholesome effect for a noticeable body sway. This amount really depends on the amount of sway that is necessary for a particular experiment. If the stimulation effect has to be minor and create only mild postural sway then the needed current has to be lower. This was achieved by Yang *et al* (2015) where they were trying to find the threshold by starting from 0.0mA and increasing the current by 0.1mA until the definitive visible body sway was judged by the experimenter (Bent *et al* 2000; Inglis *et al* 1995). The threshold was then confirmed by reducing the intensity of GVS current by 0.3mA as well as GVS thresholds were determined for the anode on the right and the left sides Yang *et al* (2015). As Yang (2015) *et al* mentioned that the sensitivity of one's vestibular apparatus may be different it should be better to calibrate the threshold before ensuring the comfort of the experiment.

Yang (2015) *et al* were maintaining resistance between two electrodes between 2 and 5 kΩ. The Correlation Between et al. noted that it is important to avoid connecting electrodes to hair since they are an insulator for the electrical impulses that are going to be sent through. Galvan-Garza (2016) mentioned that to promote consistency between stimulation applications, she required the impedance between the two electrodes to be less than 1 kΩ before applying stimulation. Before electrodes were placed, the surface of the skin was lightly scrubbed using Nuprep skin prep gel. Alcohol wipes were used to clean the skin before and after the application of the scrub. Although the electrodes were manufactured to include a layer of Multistick gel, an additional, generous layer of Signagel electrode gel (Parker Labs) was added to the electrodes before adhering to the subject's head for improved conductivity and to ensure subject comfort (e.g. avoiding tingling, itching, or pain during stimulation) (Galvan-Garza, 2016).

Galvan-Garza (2016) was using 0.5mA current, 3 cm in diameter electrodes and time of stimulation for 2 seconds. Electrode size is a factor, but for most subjects and studies, this threshold is around 1 mA (Fitzpatrick *et al*, 1994; Wilkinson *et al*, 2008; Cevette *et al*, 2012). Current levels around and above 1 mA can also elicit tingling and itching at the electrode site, depending on the size of the electrode, amount of electrode gel used, and resistance across the electrodes. Increasing the stimulus level further, to around 2-3 mA, can cause moderate heating sensations on the skin at the location of the electrode and a metallic taste in the mouth, while levels around 4 mA can cause pain to the subject (Fitzpatrick *et al*, 1994; Lobel & Kleine 1998). None of these studies mention subject discomfort from high amplitude stimuli but they do state that their use of large area electrodes allowed them to use higher stimulus amplitudes than before. For reference, Fitzpatrick *et al* (1994) used electrodes 6-8 cm2 Moore et al. (2006) and MacDougall *et al* (2006) used larger 10 cm2 electrodes, and Mulavara et al. (2011), used electrodes with a 50 cm2 area. Lastly, it has also been found that suprathreshold GVS (>1 mA) can cause degradation in some cognitive measures (Dilda *et al* 2012).

After a couple of measurement tests, I’ve decided to have our device create around 1.0 mA current. I chose this number since besides already mentioned work, additional related work indicates good performance from 1 mA – 2.5 mA, and it is far less than the recommended maximum of 5 mA.

2. The study

This chapter will focus on the practical aspects of the thesis. Mainly it will talk about the process of building the GVS device, programming its automation, finishing it up. Additionally, the methodology of the experiment will be looked at as well as results from the experiment – analyzed, followed by a conclusion of the work.

2.1. Building the device

Based on the theoretical material found mostly from other research papers I've built the GVS device by hand. To accommodate the device for a better use during our designed experiment I've set some goals for the device to do. The decision concentrated on it being compact, efficient and automated. That meant it had to fit in a relatively small wearable enclosure that could be worn by any person and not constrain their movement while doing its job correctly no matter the circumstances. The automation part was defined as it having all the functionality it needs in order to operate like any other GVS device done in previous researches but also being able to provide stimuli automatically (without manual control) by reacting on the predefined scenarios. Automating the device allowed to drastically improve its portability – the device ended up having every working part it needed in one place within the wearable bag thus avoiding the need for any external parts, externally wired connections, etc. and especially avoiding the manual remote control.

Our initial tests of the method itself to understand how it actually works and whether it is as easy as people claim it to be were done by using a very simple but straightforward prototype. This same idea was found on multiple online forums of people discussing GVS. It consisted simply out of a 9V battery as a source of current, two wires that on one end of each had a home-made electrode made out of spongy kitchen cloth that is used e.g. to wipe tables and a small aluminium cutout. Other ends of the wire were held in hand and placed on the battery to create an electrical circuit and toggle the current on or off. Polarization changes were simply done by placing same wires to the different poles of the battery (e.g. first red goes on plus, black on the minus, then the other way around). In order for these electrodes to work, they were soaked in a salty water and held behind each ear by a medical elastic headband. It was not measured but later on compared to the output of our complete GVS device the current amount was significantly greater, altering your balance so much that it was possible to make yourself fall if used for more than 2 seconds, it was zapping your skin quite hard and in some cases your vision started to have barely noticeable flashes (increase-decrease of brightness). All the initial tests of the first prototype testing, as well as semi-complete and complete versions of the final device, have been conducted by the principal investigator of this research at his own risk.

After the initial idea has been grasped and enough confidence for next iteration of the prototype development has been obtained, I began to design the device schematically. I initiated the process by sketching out the design idea and then finalizing it after multiple iterations in a software called Fritzing. It is an open-source hardware initiative developed by FH Potsdam and Friends-of-Fritzing foundation. As it can be seen on the final scheme (Appendix 1) I have ended up using one Arduino prototyping platform (Uno R3 AtMega328P), herein referred to as "Arduino", one gyroscope (Flora LSM9D50 Adafruit 9DOF), two relays (Songle SRD-05VDC-SL-C), one voltage display and a potentiometer. I have used an additional 9V battery to power the Arduino in order to avoid external cables but it is possible to do it with a micro USB cable as well. Later on, when the device was being built the breadboard was not being used – everything got connected with wires directly in order to make the device much more compact and firm. The breadboard was used only as a reference point during visual and physical prototyping.

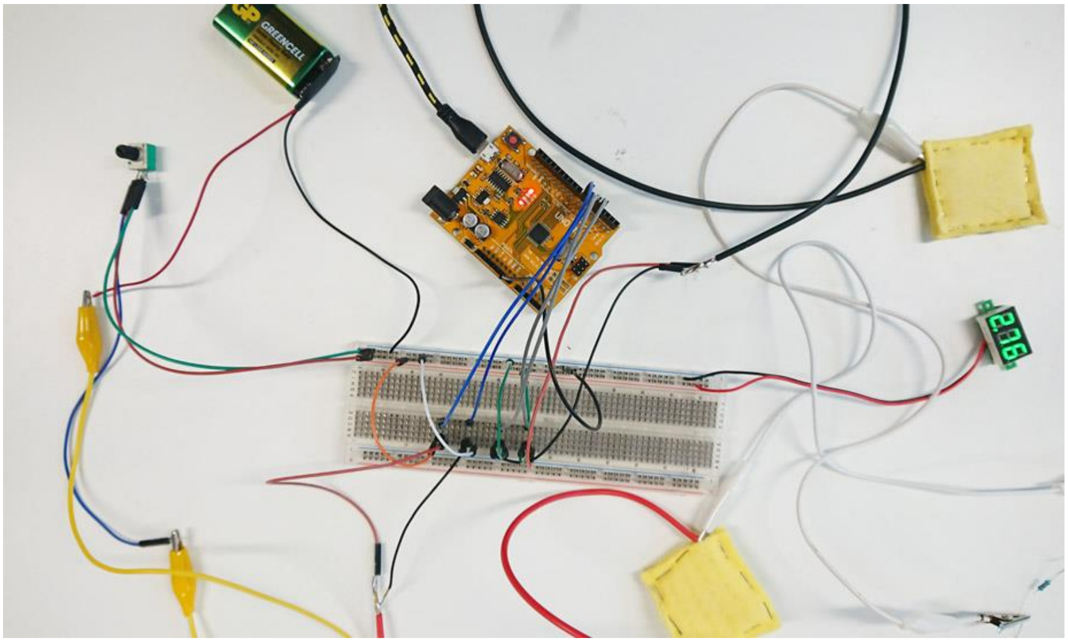

Figure 4 One of the initial prototypes of the device

Full prototype scheme can be found in Appendix 1.

The overall circuit design was that the device has two separate circuits: first is the one that is providing the stimulation to the vestibular system and another is responsible for how the stimulation is being provided. This automation part was mainly done by programming the Arduino. The default state of the device was set not to send any signal onto any relay by turning off signal pins, named “right” and “left” on the Arduino.

```
.void setup() {

 …
 pinMode(right, OUTPUT);
 pinMode(left, OUTPUT);
 digitalWrite(left, LOW);
 digitalWrite(right, LOW);
 …
 }
```

Code example 1. Disabling of both pins

The Arduino was set to react to two specific thresholds provided by a calibrated gyroscope. If the gyroscope rotated in its Y-axis and stayed between -6° and -70° (if tilted to the left) or 6° and 70° (tilted to the right) then Arduino would send a corresponding signal for the relays.

```
void loop() {

  …
     if (orientation.pitch > -70.0 && orientation.pitch < -
6.0 ){
   leftToRight();
   }
  …
}
void leftToRight(){
 digitalWrite(right, LOW);
 delay(200);
 digitalWrite(left, HIGH);
 delay(200);
 …
}
```

Code example 2. Left threshold

When a device user was standing still and not entering thresholds, then the device would keep everything turned off like it was by default.

```
void loop() {
  …
   if (!(orientation.pitch > 6.0 && orientation.pitch < 70.0)
   && !(orientation.pitch
   > -70.0 && orientation.pitch < -6.0 )){zeroItOut();}
  …
}
void zeroItOut(){
 digitalWrite(left, LOW);
 delay(200);
 digitalWrite(right, LOW);
 delay(200);
}
```

Code example 3. Setting the device to default null settings

The full code can be found in Appendix 2.

The minimal amount of -6° and 6° was chosen during premature tests where the device was calibrated. This amount of degrees showed that there was enough space for a person to have while playing the game in order not to trigger the device without a reason. If the device would start noticing postural instability where the yaw degrees would be equal or more than 6 for both sides (left and right) – then the reaction would happen. -70° and 70° were set as ends of thresholds in case if a person would fall the device would stop sending stimulation to the body.

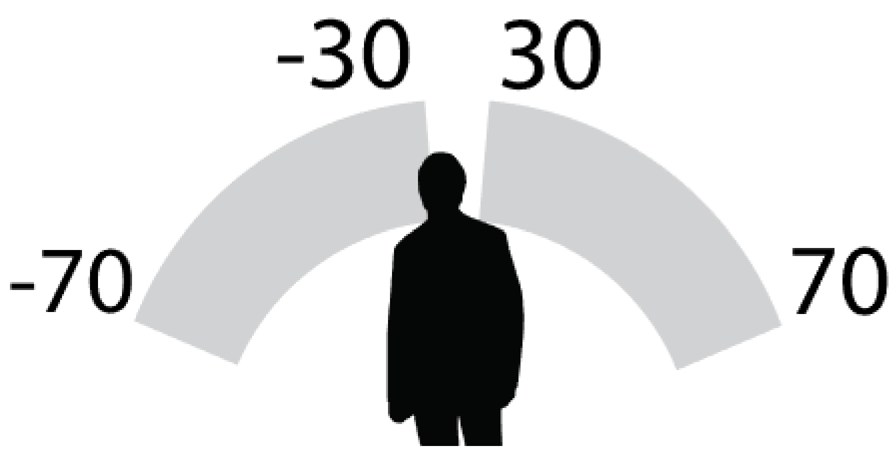

Figure 5 Illustration of chosen thresholds

When the signal that was triggered by the data from the gyroscope being in the range of the threshold, the corresponding relay would open. This would enable the second circuit of the whole system. By the default, both relays are powered from the Arduino which makes them work, but in order to create the right polarity for the current that goes through electrodes then need to be opened. While they stay closed both electrodes stay as negative in the circuit (cathode) and the current can't flow from one to another. For example, when the signal from Arduino reaches the relay which has the right electrode connected to, the relay opens and this right electrode becomes positive (anode). This lets current from the battery flow from the right electrode into the left electrode and then to the ground of the circuit, in other words – close the chain. This is, in essence, how the stimulation was being provided every time. Additionally, the system had a potentiometer and a voltage display, which were a part of the stimulation circuit. This would let calibrate the amount of voltage the device would use for the stimulation for every participant’s needs.

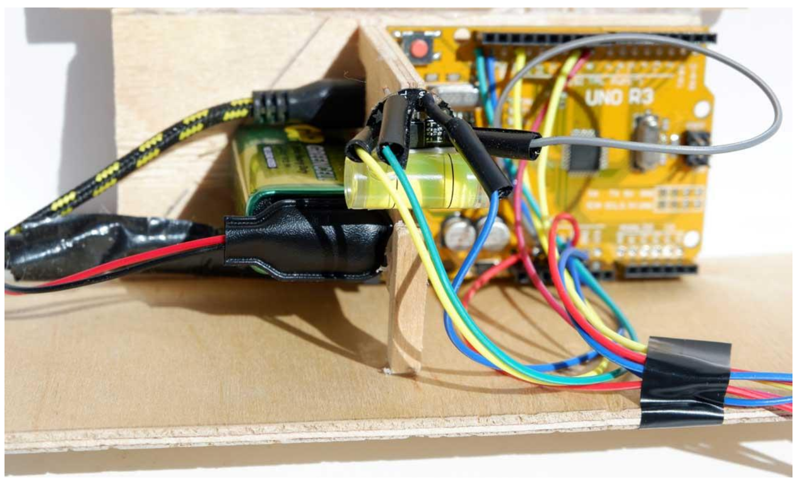

Figure 6 Final version of the hardware

When the whole hardware part of the device was completed, it was put in a pouch waist bag in order to make the device wearable. The bag was firmly fixed around the chest – firm enough not to fall but loose enough to allow to breathe and move hands around. The idea was to put the device as close to the head as possible in order to synchronize with the body movement. The head is the top of the whole body thus the body swaying angles are the highest the closer to the top you get. There was also added an additional strap the bag that was going over the neck to give more stability to the device and to better synchronize with the movements. Inside the bag, the device was supported by a couple of lightweight wooden planks to avoid wobbling inside the bag and increase stability. One more trick to ensure proper calibration was done by using a bubble level which was attached next to the gyroscope. Because gyroscope calibrates itself zero degrees as soon as you power the device – the task was to level the device on participant's chest before plugging the battery in. The whole setup was not heating up in any way so the bag could be closed to preserve the device, because after calibration of the device was done there was no need to touch it anymore till the end of the experiment.

Figure 6.1 Final version of the device

2.2. Methodology

For this experiment I have decided to go with a qualitative approach due to this topic, as a combination of two moderately researched topics, being quite new, specific and full of nuances. Ideally, to see proper results for questions addressing the efficiency of GVS as a method of controlling ones balance compared to VR interactions without the help of GVS – a quantitative study would be a much better idea. Due to limited resources and general lack of information, an exploratory and experimental approach was chosen in order to gain a general overview of the idea, hypothesis and feedback on the implemented results.

The purpose of this study was to investigate the work of a method called Galvanic Vestibular Stimulation (GVS) in Virtual Reality (VR) interactions that invoke a loss of balance. Participants beforehand signed a consent form (Appendix 3) where they were introduced to a brief description of the project, their tasks during an experimental procedure, what was expected from them before the experiment (e.g. what not to consume, what to consider about your physical state and weaknesses), benefits and risks of the experiment and information about investigators, voluntariness of the participation, confidentiality of the data.

Figure 7 The room where the experiments have taken place; since there was a chance of a participant falling I decided to provide soft mats as a support

The whole experimental procedure consisted out of five parts. After signing a consent form, ethical aspects of which were supported by Declaration of Helsinki (World Medical Association, 2013), participants were asked to complete a short balance test called FICSIT-4 (Rossiter-Fornoff *et al*, 1995) (Appendix 4). It has 7 static balance oriented tasks and results with an index out of 28 points that were assigned for each participant and was used later on in analysis as a reference when personal balance ability was being questioned during a comparison with other results from other questionnaires.

After defining their balance index, the participant was asked to sit and got prepared for the game. I put the GVS device on his chest, firmly fixing it in order to synchronize its movement with the upper body, but leaving enough room for the person to breathe and freely move hands around. It was worn as close to the top of the chest as possible in order to get a similar centre of rotation as the head has in relation to the waist. A fresh pair of electrodes were lubricated with the electrode gel and firmly placed onto the skin behind ears on top of mastoid processes, and then got fixed with a medical headband.

After that part was done, I've explained the basic controls for the game, its objective, how to complete it and where I defined an end in the game in order to stop that part of the experiment. Then an HMD with a launched VR game was placed on the participant's head, calibrated and provided with connected headphones for hearing the in-game sound, the main intention of which was to mask triggering sounds of the GVS device to create less distraction for the participant.

Figure 8 Final look of a calibrated (active) device and a working HMD

I've chosen a PC game for VR developed by Anshar Studios called Detached (Steam, 2018). This is a puzzle game with a first-person viewpoint, where a player is flying in and between space stations solving puzzles in zero gravity with a full six degrees of freedom

(6DoF) movement ability in order to progress with challenges and complete all the tasks and the game. Our precursory tests showed that this kind of movement creates enough disorientation for a standing player in order to invoke enough postural sway and chances for a complete loss of balance during the gameplay. As it was mentioned before, I've defined a short task for participants to complete in the game. I didn't ask them to complete the whole level in order to avoid getting them sicker than needed. Their whole task was situated within a first room where they needed to interact with the door at the other end of the room (opposite from where they start), fly into a different room to interact with an object and come back to that door to open it. Every participant was asked before entering the second room about how they are feeling and was let to proceed only it not feeling bad in any way.

Once they were done with the task both HMD and GVS were taken off the participant, electrode gel leftovers cleaned from the back of their head, they were seated and given two final questionnaires. First was the Simulation Sickness Questionnaire (SSQ) (Kennedy *et al*, 1993) (Appendix 5) to get feedback from participants on how they feel after this VR experience. The very last part was an interview with participants to get their feedback on the experience with the GVS device and this type of stimulation in general, how well it behaved and how efficient they thought it was in the result (Appendix 6).

2.3. Analysis

The whole experience, from start to end, of every participant, was being recorded by a camera that was placed in front of them, to see their movements and reactions during the experiment, and also a screen recorder – to capture their gameplay. Later both videos for each participant were combined, synchronized and analyzed. I've also provided video timelines from the editing software to give a better overview of the whole experiment (e.g. how often have things happened that I describe in the analysis). As shown in every timeline figure before every textual video analysis - I've been marking specific events with DA, SS & PI.

DA – device activation, usually, for every device trigger unless if it has been active for a long time then indicating just the start; if there have been a lot of short ones in a small period of time then also just once. SS – simulation sickness, usually when the participant was indicating verbally that they are experiencing weird feelings like getting disoriented, thinking they are losing their balance or starting to feel certain sickening symptoms. PI – postural instability, when the participant was noticeably tilting their body, momentarily losing control or increasing activity of their leg support by displacing them in order to ensure the best posture and add the control to the balance.

Additionally, for each participant, I've done an analysis of a post-experimental interview, where they have answered a SSQ questionnaire as soon as they taken off the HMD and GVS devices followed by the interview and a balance test. These are the results.

2.3.1. Participant 1

Video analysis:

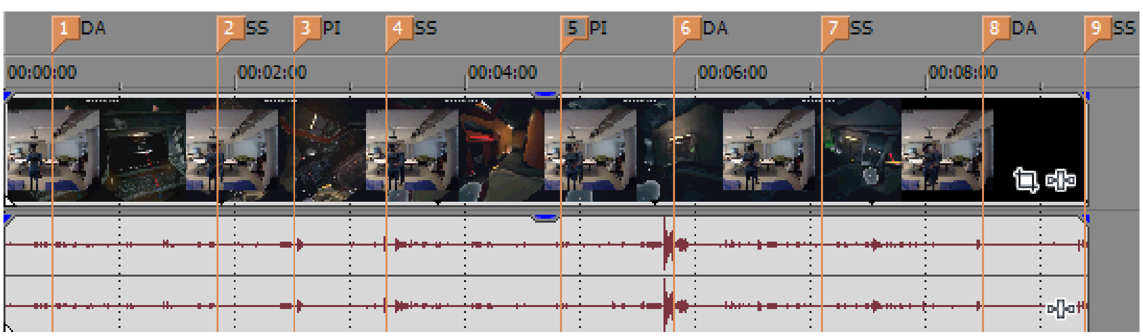

Figure 9 Video analysis timeline for the first participant; total time 09 min 25 sec; Legend: DA – device activation, SS – motion sickness, PI – postural sway

From the very start, our first participant was flying in the game very slowly and steadily. He was avoiding sharp turns, tried to stay in one orientation plane as much as he could.

You could tell that his priority was to have the room's floor stay as a floor and not become a ceiling. He was trying hard not to fly upside down, was commenting on motion sickening moments from any amount of rotation but not so much about forward acceleration (he wasn't trying to fly backwards or to the side). Occasionally he was stretching his shoulders presumably to feel how he's standing but later during the interview, it turned out that he was straining his every muscle in order to feel the body, to be in control. As he was playing he was trying to align his in-game point of view (reference in the game was the helmet that the character was wearing) to how straight he's standing in real life. Also, he had just a couple of times when he was not paying attention how he is standing outside the game (the head was looking a bit to the left and up + tilted about 10 degrees to the side). I believe in that situation you usually stop paying attention to how the ambient objects that represent player are placed (in this case it is a helmet). This is a very similar technique that Whittinghill (2015) proposed in their study on adding an image of a human nose inside the virtual environment as a reference point for the player in order to reduce simulation sickness. It looked like when he used the ability to look around in the game and as soon as he saw the object/place where he had to go he was not trying to align his character with the direction where he is going but rather set the movement of the character in air to the new direction and stay in real life as he was at the time of decision making. This was mainly due to the in-game mechanics – the helmet was turning just slightly when you were doing basic head movements in order to create the illusion that it is attached not to your head but to the suit you are wearing in game. This helmet was rotating with the head movement more than usual only if your head movements were much more distinct and aggressive (e.g. you wanted to displace yourself in real life by turning 90 degrees to the left thus changing your point of view with it). His whole interaction was 9 minutes long and during first 4 and a half minutes he had 5 occasions where he was excessively using yaw rotation in the game. Two times it was even combined together with pitch movement followed by him commenting that "These kind of movements are just the worst!". After every case like it was taking him a bit of time to notice that his head is not looking straight and that made him change his character's movement together with his head position back to default (looking straight in the in-game helmet as well as in real life). In spite of his comments on the sickening nature of the movement, he gave a positive answer on his state before moving into the second room. It was very noticeable throughout the whole interaction that the only part of participant's body that was swaying was his head. That was happening only in moments when yaw, pitch or roll rotation was used. Starting from the second room participant seemed like he adjusted and understood how exactly he needs to hold his posture, head and move in the game in order to stay completely stable. Nevertheless, it was occasionally noticeable that after using breaks to stop the forward acceleration or any sort of rotation, he was momentarily and slightly swaying forth and back, sometimes diagonally. I believe this could be some sort of calibration of the body – involuntarily his body was making these brief movements in order to send information into the vestibular system to alert the brain with the image of how he is standing in relation to the ground in real life. Shoulder stretches were still present 5 minutes in. It was also occasionally noticed that when any in-game interaction was happening where the participant had to stretch his hand out and touch an object, whether he was in motion or not, he was standing a bit more stable than usual. I assume stretching out your hands in such situations provides you with spatial information (e.g. what is happening around you what you can't see right now), also it has to have the same effect as when you are losing your balance and you decide to stretch your hands out to the sides and add additional control over your body. In case of this game, most of the interactions required just one hand to be stretched and only in front of you (not necessarily fully extended also). Another action that this participant did a couple of times closer to the end – he was intentionally moving his head around, in every direction, looking around with circular motions – looked up, down and then a full quick circle. None of the participants has tried doing that from the very start of the game. I assume you can decide to do that when you are at least moderately confident in how you are standing, in how the game behaves and most likely when you have adapted to the simulation enough in order to receive previously mentioned perks. Also, one more thing was noticed – once he was in game floating under any degrees that were different from the ordinary position, if he gave a quick look to the side or slightly behind the back and returned to his initial point of view, then his head got into the slightly tilted position (as soon as he turned back) and that position was somewhat similar to the angles his in-game character was floating with. Throughout the whole interaction participant stood very straight and the GVS device has triggered only a couple of times, when he was laughing or turning around observing the environment. The stimulation impulses that it was providing at those times were so brief (about 1 second each) that it didn't affect his posture at all.

Questionnaires & interview:

SSQ results have shown that our first participant when leaving the VR game was feeling slight general discomfort, fatigue, sweating, the fullness of the head and dizziness with eyes open; moderate salvation increasing, nausea, dizziness with eyes closed and burping; severe stomach awareness. His average SSQ score is 1.00 out of 3.00 (the closer to 3.00 the worse). His FISCSIT-4 balance test score was 27out of 28 (the closer to 28 the better).

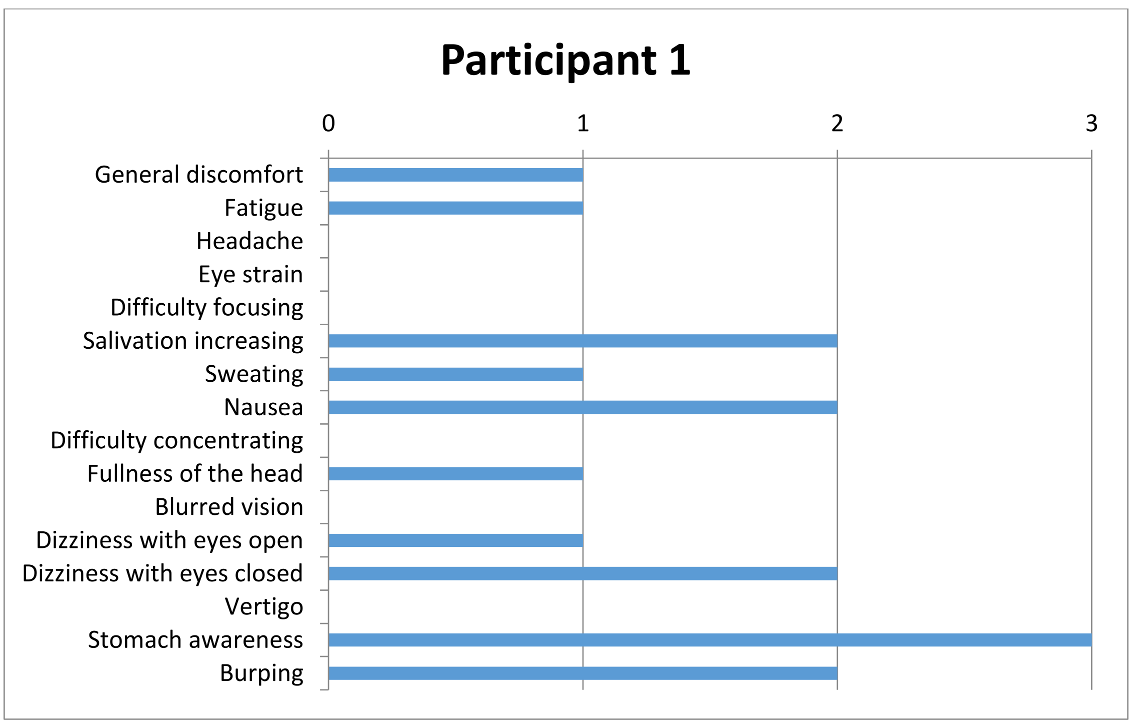

Figure 10 Results from a Simulator Sickness Questionnaire by the first participant; Legend: 0 – None, 1 – Slight, 2 – Moderate, 3 – Severe

During the interview, it was known that this participant has never done any electrical stimulation before and the only proper VR experience he has had was several times using Google Cardboard (Questions 2, 3). The most disturbing or discomforting experience to him was the roll movement in the game (Question 4). He said that he has experienced a moderate amount of disorientation and a slight loss of balance (Question 5). Additionally, he was feeling like he was being dragged back when playing. Commented that it was possibly due to being fully immersed in the game. Our participant felt like most of the times he has had enough control over his posture although occasionally felt like at some point he's going to fall back (Question 6). He thought he was standing very straight throughout the whole experiment but he overall was very stiff, especially legs (Questions 7, 8). Mentioned that he wasn't forcing himself to stand so stuff, believed it was an unconscious action. He absolutely wasn't concentrating on how he is standing (Question 9). He felt fully immersed and was bothering more about how was he positioned in game. He has not felt like something was assisting him in controlling his balance and he believed that the GVS device didn't even trigger once (Questions 10, 11). Finally, he said that he wouldn't use such device to support his balance unless it would be a built-in feature in the headset (Question 12). Otherwise, he wouldn't bother and would just play such kind of games in a seated position.

2.3.2. Participant 2

Video analysis:

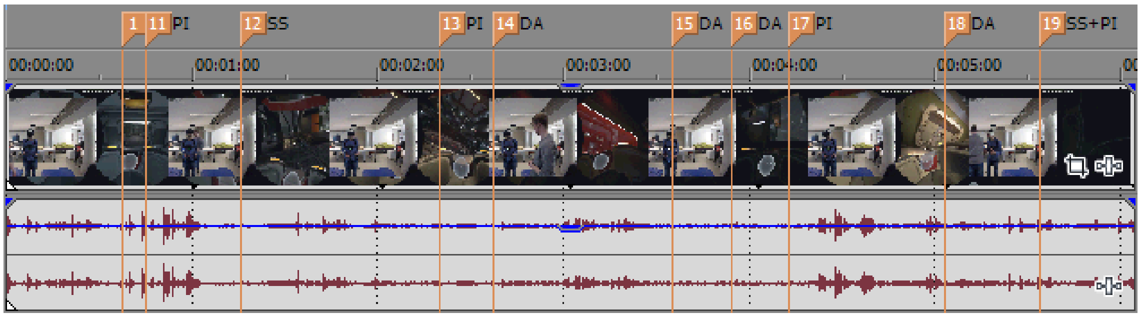

Figure 11 Video analysis timeline for the second participant; total time 06 min 05 sec;

Legend: DA – device activation, SS – motion sickness, PI – postural sway

As every person is different, the second participant had a totally different approach compared to the first. Different approach caused different reactions. Right away when the movement started he was smiling and telling how good it feels. A good sign that he felt immersed right away meaning the high-end computer and state-of-the-art graphics were doing their job well. When the need came and he tried the pitch and roll movements in the game his straight posture has let go. He started swaying together with the in-game rotations he produced, notifying us how weird it feels, but not mentioning anything about the fact that he was moderately swaying to each side. After this practical introduction to the movement, it seemed like he more-less understood the mechanics, adjusted to the environment at least to some extent and continued the task with confidence. His next task was to go from the main door towards the orange corridor where he would continue his assigned task. He rotated, aimed at the corridor from afar and accelerated. His flight between those two points took 8 seconds whilst he was not showing any signs of disbalance. Once he reached the designated point he quickly decided to yaw to the side and in order to adjust himself to the related plane the corridor was built, in addition, a roll rotation was needed to be added, thus it was. This change of spatial orientation in two axes almost simultaneously has created a slight disorientation which in turn made the participant slightly but noticeably lean forward and tilt to the opposite of where he has just been rotating. This tilt was quite bold, not severe enough to induce a major disbalance but quite on point in order to trigger the stimulation device. The stimulation lasted roughly two seconds and it was discontinued by participant's correction of posture to almost a perfect state. At least perfect enough to leave the trigger threshold of the stimulation. While the device was doing its job our participant was smiling and quietly giggling. I'm fairly certain that his change of posture wasn't due to hearing the device click because the headphones had in-game sounds at a decent volume – participants had trouble hearing me, so GVS device clicks are not the case. Possibly the participant has felt the shock thus that made him question his orientation and try to adjust it. He did mention in the interview that the only stimulation he actually felt was at the very start of the interaction and later he was just very concentrated on the game and ignoring stimulations completely. This one, in particular, was not his first stimulation but it was the longest one. Previous shocks were very brief and happened due to moving around while getting prepared, so it's not entirely the case. Anyways, even if he has felt the stimulus and decided to analyze his posture during the game and reposition himself so precisely, then it happened quite fast and efficiently which is a good thing to consider. His laughter, that I've mentioned previously, actually started before the GVS has triggered and most likely it was about the experience of the rotation in the game and nothing else (a good example are his initial comments of amazement at the beginning of the game). This participant's whole interaction lasted for 7 minutes and only the first room was completed due to him dying at the very end of it (he forgot to use breaks and crashed into the wall on a high speed). The last checkpoint was at the very start of the level which meant he would have to complete the whole course from the very start. Because of that, I decided to stop there as it is in order to spend less time to avoid increasing motion sickness, especially with the fast and aggressive type of flying manoeuvres this participant was playing the game with. Previously explained scenario of sway and stimulation happened on 2:20 of the interaction. For a minute he has been standing straight, not showing any signs of disorientation no matter how he was moving in the game. From thereafter his body posture got tilted to the side a couple of degrees, after some strong rotations in the game, and stayed on the edge of GVS device's activation threshold. Which started continuously retriggering. Judging by his later feedback he was so concentrated on the game that he didn't feel those repeating at all. He wasn't correcting his posture either because the stimulations were very brief and had pauses in between. Another thing that was noticed and in almost every participant at least to some extent, that when they focus too much on something in game they don't notice how their posture is continuously in a wrong position until they feel when their muscles that support this potion get tired or just take their mind off the game and decide to think about how they are standing.

Questionnaires & interview:

SSQ results have indicated that our second participant when leaving the VR game was feeling slight general discomfort, fatigue, eye strain, nausea, blurred vision, stomach awareness and burping; moderate difficulty focusing, salivation increasing, difficulty concentrating and vertigo; severe sweating and fullness of the head. His average SSQ score is 1.31 out of 3.00 (the closer to 3.00 the worse). His FISCSIT-4 balance test score was 28 out of 28 (the closer to 28 the better).

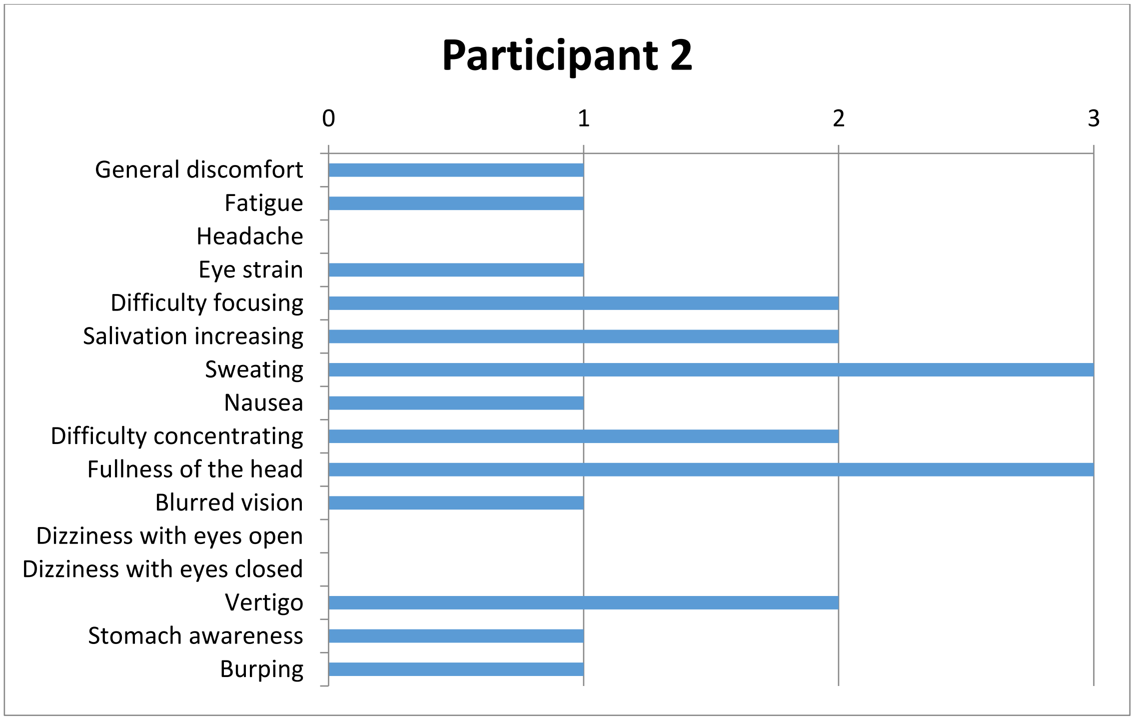

Figure 12 Results from a Simulator Sickness Questionnaire by the second participant;

Legend: 0 – None, 1 – Slight, 2 – Moderate, 3 – Severe;

During the interview, it was known that this participant hasn't had tried electrical stimulation before but has played VR games before (Questions 2, 3). At some places he said he couldn't stop rotating, going upside down was giving him nauseating feelings in his stomach and he started to feel hot (Question 4). He felt some disorientation but he believed it was due to the GVS device. While playing he felt like he needs to move his body (Question 5). Nevertheless, he has felt like he had enough control over his posture. At first he believed he was standing quite straight, thought dedicating a lot of effort for doing it, but as soon as he got the hang of controls and became flying more freely it started to overload his brain (referring to thinking about how does he stand, how he should stand, processing in-game movement, etc) and it was hard for him to focus on dedicating effort for controlling his posture (Questions 6, 7, 8). He felt first stimulations from the device but later forgot about them because was concentrating on the game but occasionally was noticing a difference in stabilization (Question 10, 11). He was thinking about using this kind of device in the future, especially for using FPV drones (Question 12).

2.3.3. Participant 3

Video analysis:

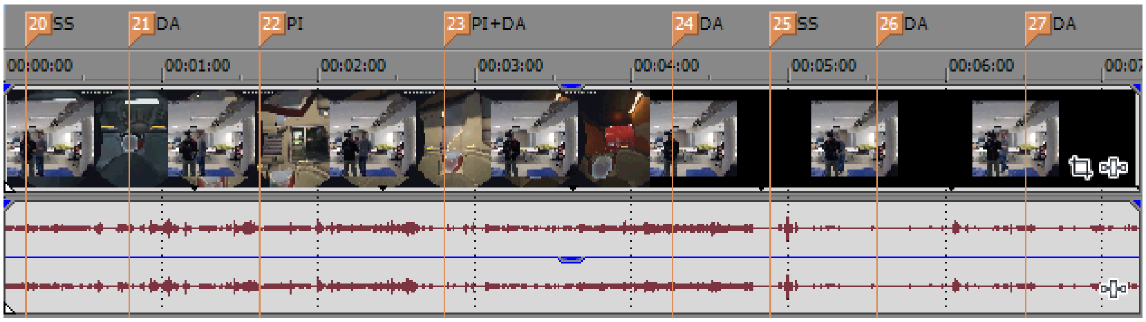

Figure 13 Video analysis timeline for the third participant; total time 07 min 14 sec; Legend: DA – device activation, SS – motion sickness, PI – postural sway

Our third participant turned out to be the most stable (posture wise) out of all five. He wasn't really expressing a lot of emotions regarding the things happening in the game and about the stimulation device affecting him. He was most of the time quietly following the assigned tasks, occasionally clarifying movement mechanics and task order or location. The only time he commented on the sickening aspect of the in-game movement was when I've clarified how to use it in game, then he tried to do a full circle of pitch rotation, stopped and said that his vestibular system is very confused. Other than that the rest of the interaction was completely smooth. No matter how much the participant was moving or rotating in the game his posture was staying constantly straight. No swaying, head tilting or any sorts of stance analyzing body movements were noticed throughout the whole interaction. The participant was completely confident in his surroundings while wearing an HMD, was freely observing the in-game environment and doing any in-game movement that was necessary in order to progress through the tasks. The device has triggered minimal amount of times and very briefly during each time, mainly during observational movements of the body and head rotations. There was no need to control the balance and the effects of GVS were not noticed also due to one more reason. When calibrating the device before VR interaction I had to set the voltage more than three times lower than for other participants due to this participant's skin being quite sensitive to electric shock. Full voltage was causing discomforting pain as well as burning sensations and I decided to tone it down to the point that it was still present but much more bearable. This most likely has diminished the effects of a balance control ability of the stimulation device but has left the electric feedback that could have worked as a placebo effect. When the participant was feeling the shock there was no stimulation of the vestibular system but was information for the brain that could associate with inquiries about postural changes. Another possibility is due to low current our GVS device became SVS device instead. It is hard to assign these possibilities to this participant in particular due to the low amount of GVS triggers, but overall it could take place in some shape or form. One barely noticeable reaction from the participant was discovered after analyzing recorded footage a couple of times. Although he was stable and relaxed throughout the whole interaction, I've noticed that whenever there was a moment in the game that was usually described by other participants as a motion sickening, that is movement or a character rotation, then this participant was briefly tightening his whole body. It was very slight but it was happening multiple times. Not exactly sure whether this was voluntary or not but this method of fixating your whole body has worked nicely. It is quite similar to the body state our first participant had, where he was fully tightened, not relaxed and getting tired from that.

Questionnaires & interview:

SSQ results have shown that our third participant when leaving the VR game was feeling slight fatigue, eye strain, difficulty focusing, salivation increasing, the fullness of the head, blurred vision, dizziness with eyes open and vertigo; moderate general discomfort, dizziness with eyes closed and stomach awareness. His average SSQ score is 0.88 out of 3.00 (the closer to 3.00 the worse). His FISCSIT-4 balance test score was 27 out of 28 (the closer to 28 the better).

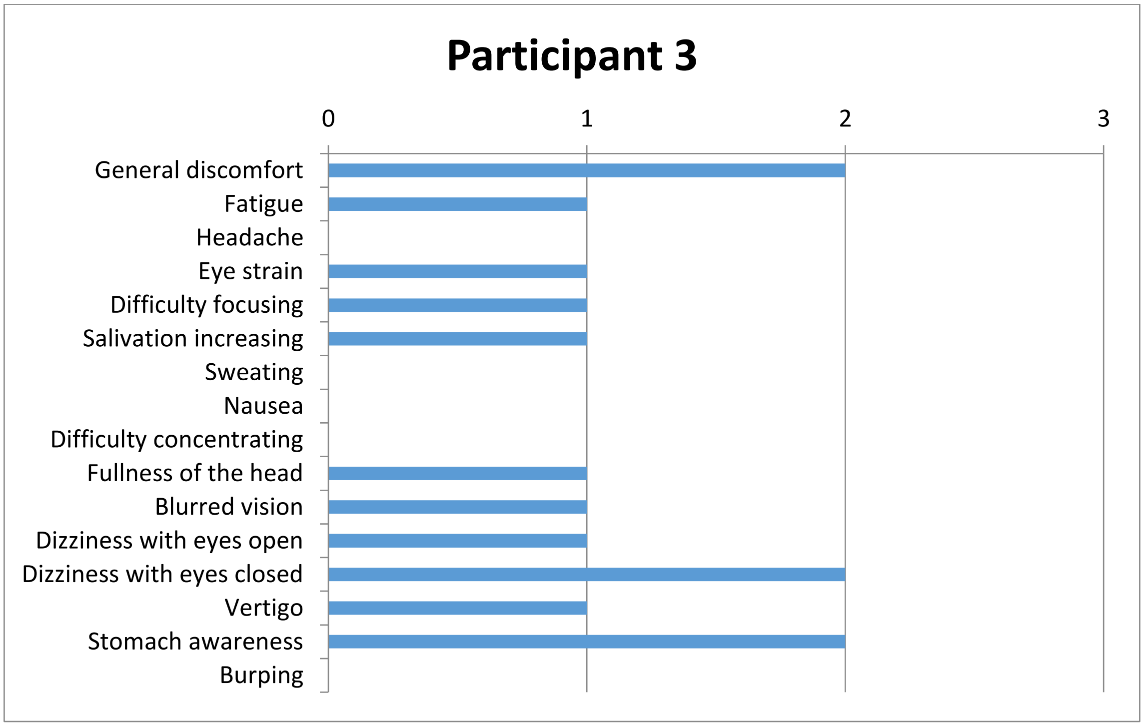

Figure 14 Results from a Simulator Sickness Questionnaire by the third participant;

Legend: 0 – None, 1 – Slight, 2 – Moderate, 3 – Severe;

During the interview, it was known that our participant has had a similar VR experience before but hasn't done any electrical stimulation ever (Questions 2, 3). His most disturbing experiences turned out to be the in-game rotations. He didn't feel disoriented but when he was accelerating in the game too fast it was making him dizzy because he was relying on the information through eyes (Questions 4, 5). Nevertheless, he felt like he had enough control over his posture and he has managed to stand as straight as possible throughout the whole thing (Questions 6, 7). He was dedicating a lot of effort for standing straight when experiencing rotations he wasn't concentrating a lot on his posture throughout the rest of the interaction (Questions 8, 9). He was constantly questioning whether the device is doing anything because he wasn't sure and said that doing the tests without the device could've helped clarify that (Question 10). He did feel the shock from stimulations but not the effects. The whole stimulation, as he said, seemed really fake to him (Question 11). Due to these shocks, he believed the body was trying to numb them down because there were more important things to do. He commented that he would never use this device to assist him (mainly due to pain and discomfort) unless its effects could be proven.

2.3.4. Participant 4

Video analysis:

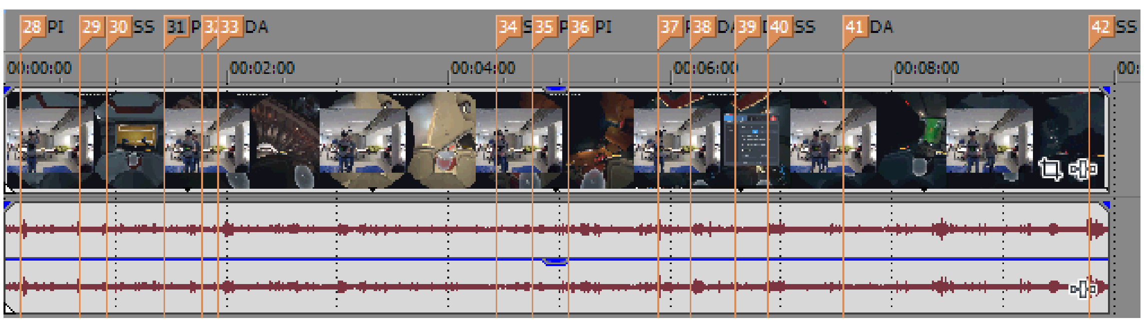

Figure 15 Video analysis timeline for the fourth participant; total time 09 min 57 sec; Legend: DA – device activation, SS – motion sickness, PI – postural sway

Our fourth participant had a similar way of experiencing the interaction as our very first one. Most of the time he was stiff and constrained and it was noticeable that he was trying his best to stand as straight as possible by moving just his head and hands in quite minimal motions. When the motion sickening movement started to be practised within the game, this approach of a forceful straight posture started to give way. On a very first rotational movement in the game, our participant lost control of the character and started spinning until he stopped. This spin created a spontaneous reaction – he started swaying from side to side, back and forth, heavily and rapidly breathing, swearing and then laughing when he remembered the controls for stopping the rotations. This obviously was very stressful and unexpected for him. On a second try to get the hold of these controls when he started spinning he made nauseating sounds a couple of times (as if he is about to throw up) but indicated that he is alright. Over time he got used to the sickening nature of the controls but not the controls mechanics. This resulted in him spinning more than the necessary amount of times when doing any sorts of manoeuvres, which undoubtedly amplified his SSQ results. Interestingly enough, when he was experiencing a rotation from a new angle due to controls being so clunky and with a lack of understanding – unpredictable, he always started slowly falling forward, then noticing his posture sway, getting scared (because the reaction was similar to when you jump when being scared) and trying to rebalance himself. This is where a GVS setup that evokes virtual head pitch motion would come in handy. Our participant wasn't swaying to the sides a lot during the whole experiment. It has happened only a couple of times when he was getting totally disoriented. There were a couple of moments when he was concentrating so much on the game that his head was looking almost for 90 degrees to the side for a long period of time. During those periods there was no loss of balance taking place, no vestibular stimulation either. This orientational mismatch has been occurring quite often in participants and the only disadvantage of such thing is if postural sway would be present and it would trigger GVS, then the stimulation would sway the person towards the anodal electrode thus creating a motion either diagonally to the back or to the front. This is a very subjective matter but gladly it hasn't happened during our experiments with participants. One last thing to notice, and at least two times it was quite obvious when the participant started to feel disoriented, began to sway and entered the stimulation threshold he corrected his posture quite quickly and almost at the same time as soon as the triggering has happened. If to assume, that the participant has been reacting to the shock from the stimulation and it was his immediate reaction to correct his posture, then there is a question – how he might know in an instant towards which direction he has to sway back in order to center himself so perfectly with such not just limited but also altered visual information, sensory mismatch and constant general disorientation. It also couldn't be the ideal effect of the stimulation, because first of all it’s not that extreme (and I am talking about the participant who sprung back up from an angled posture into aligned and centered state within 1-1.5 sec) and second of all as our premature testing of the very early GVS prototype have shown that when the stimulation reaches its peak where there is maximum effect from the provided amount of current, if the stimulation stops at this peak, the vestibular apparatus will keep “pushing” you in the direction you were going for a short period of time.

Questionnaires & interview:

SSQ results have shown that our fourth participant when leaving the VR game was feeling slight general discomfort, fatigue, eye strain, nausea, the fullness of the head, dizziness with eyes open, dizziness with eyes closed. His average SSQ score is 0.44 out of 3.00 (the closer to 3.00 the worse). His FISCSIT-4 balance test score was 26 out of 28 (the closer to 28 the better).

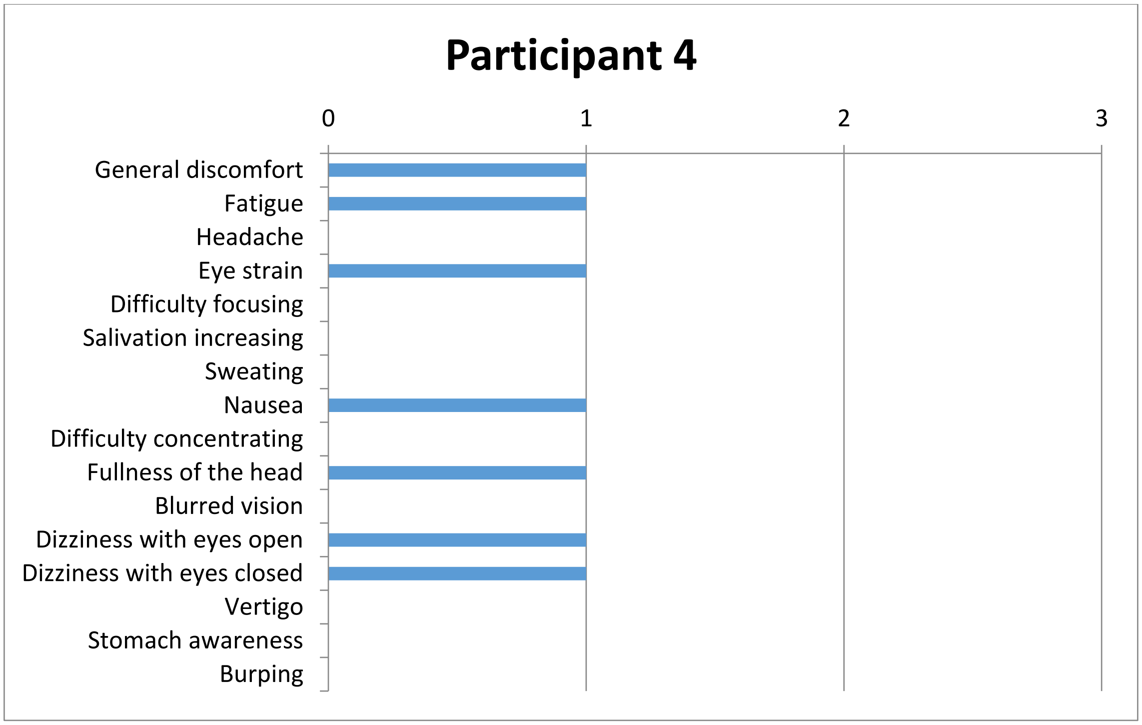

Figure 16 Results from a Simulator Sickness Questionnaire by the fourth participant;

Legend: 0 – None, 1 – Slight, 2 – Moderate, 3 – Severe;

During the interview, it was known that this person has tried VR applications before but never tried electrical stimulation (Questions 2, 3). The most discomforting part of the experience for him was the buildup during preparations (Question 4). He has felt disoriented and didn't feel like he had enough control over his posture (Questions 5, 6). He thought he did badly at trying to stand straight because at first he was always trying hard to be in control, but was getting distracted and then forgetting about how he's standing (Questions 7, 8). Basically, he was so immersed in the game that could barely concentrate on his posture (Question 9). It wasn't clear to him whether he was getting any sort of assistance from the stimulation and said it would get clarified if he would've tried playing without it (Question 10). He also got used to the electric shock after a couple of stimulations (Question 11). He wasn't also sure whether it is worth to have such device in similar scenarios to help with a loss of balance (Question 12).

2.3.5. Participant 5

Video analysis:

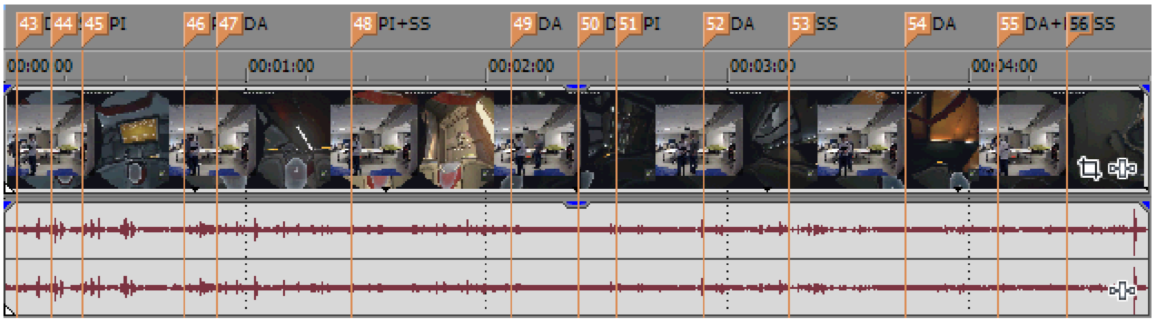

Figure 17 Video analysis timeline for the fifth participant; total time 04 min 45 sec;

Legend: DA – device activation, SS – motion sickness, PI – postural sway

Our fifth participant was exactly the reason why I have mentioned multiple times to our participants that they are free to withdraw from the experiment at any point if they are going to feel bad during the interaction. Overall he has handled the interaction very well but had to withdraw in the middle of the first room (on the way back in the orange corridor) due to feeling very dizzy. From the very start when he did his first rotational movements he has commented how crazy it feels, that he is feeling quite dizzy and thus began breathing heavily and occasionally holding his breath - a really obvious sign of stomach awareness and nausea. This participant turned out to be the most sensitive towards simulation sickness out of all five but nevertheless did great because the game's difficulty setting named "Simulation" was called this way for a reason. Besides doing the usual and already mentioned things other participants did, like swaying during rotations, holding their head fixed under a certain angle due to focusing hard on the game, he was doing two more things. Better to say he was doing familiar to us things but a bit more distinctively. Whenever there was a horizontal acceleration used as well as breaking – his body was swaying accordingly. What is meant by that can be reimagined by the movement a person does when sitting in a car and it starts to accelerate and then break. When accelerating your body starts swaying backwards and forwards when the car breaks. The same movement patterns were noticed from our fifth participant. These movements were not disturbing or disbalancing to him like they were for our fourth participant, but they were present nevertheless. Another way he was controlling his balance was by using his legs. He was changing the pivot point for his body depending on the situation by displacing feet to support the body. Others who have been trying to stand as straight as possible were moving all the physical work onto their back to keep being stiff and centred. This participant was making his legs work for him thus leaving his upper body moderately relaxed and more active and engaged in playing the game compared to some previous participants. Regarding the vestibular stimulation – it was working most of the time. In the beginning, it was disabled but as soon as our participant got accommodated with in-game control mechanics and adjusted to the simulation as well he got more relaxed and presumably let his body handle the disorientation. GVS was getting briefly triggered during the first half of the interaction with similar reasons like with previous participants. But it started working almost non-stop once our last participant loosened up and started standing a bit askew. I have assumed that there was a slight probability when I was calibrating the device on him, initial launch that set default degrees for the gyroscope, he was standing unnaturally straight. What is meant by that is that he possibly had slight scoliosis also known as uneven shoulders that started affecting the device’s angles on his body. It started happening once he got comfortable with the environment, began taking comfortable and active stances while playing the game thus his body took its natural shape. Of course, I am not ignoring the fact that I could just be a similar occasion of fixed disbalance described in previous participants. Nevertheless, stimulation was making him change how he is standing but after rebalancing it was still kept being toggled possibly due to the previously described reasons.

Questionnaires & interview:

SSQ results have displayed that our fifth participant when leaving the VR game was feeling slight difficulty focusing, blurred vision and burping; moderate general discomfort, sweating, difficulty concentrating and fullness of the head; severe fatigue, eye strain, salivation increasing, nausea, dizziness with eyes open, dizziness with eyes closed, vertigo and stomach awareness. His average SSQ score is 2.19 out of 3.00 (the closer to 3.00 the worse). His FISCSIT-4 balance test score was 27 out of 28 (the closer to 28 the better).

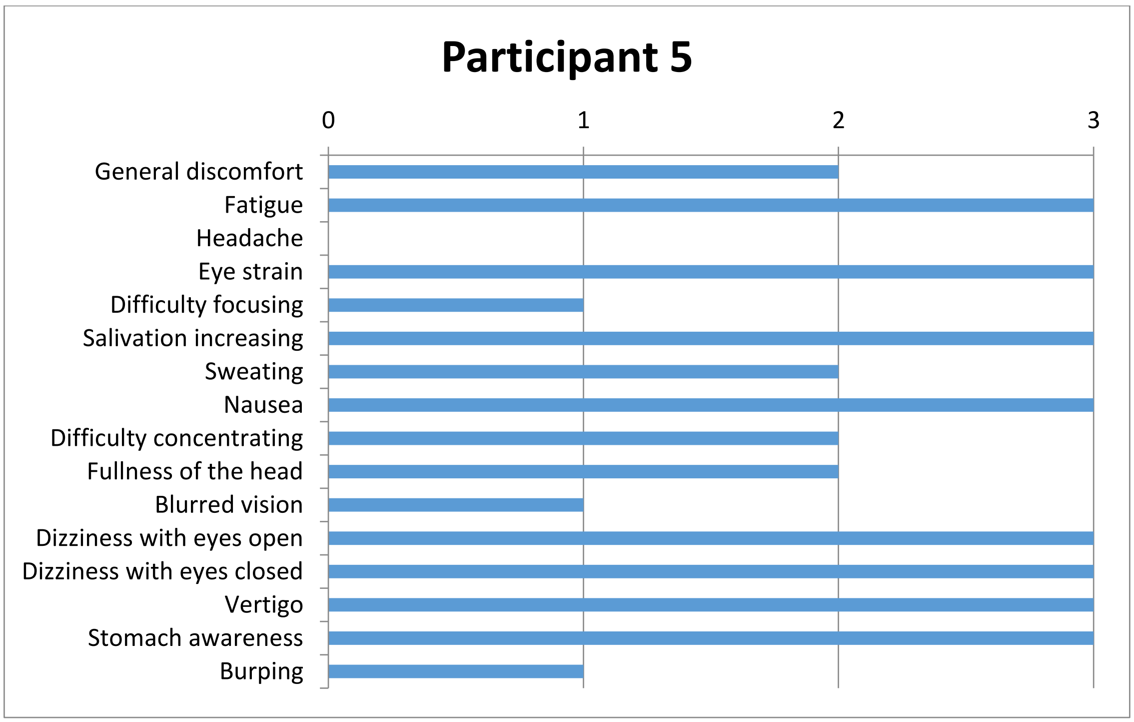

Figure 18 Results from a Simulator Sickness Questionnaire by the fifth participant;

Legend: 0 – None, 1 – Slight, 2 – Moderate, 3 – Severe;

During the interview, it was known that our participant has had this kind of, as he called it "serious", VR experience for the first time but he has tried other casual VR games before (Question 2). He has never done any electrical stimulation before (Question 3). The most disturbing part for him was during the game while being in zero gravity he has felt a strong sense of instability (Question 4). As he defined it because there was no ground underneath his character he felt like he has no control over it. That made his scared to lose it.

Additionally, he has experienced disorientation (Question 5). He felt like his posture was bent and he didn't understand how to control it. He couldn't plan his movement and felt like his short-term memory has turned off. He also had trouble having enough control over his posture when playing because he was feeling wobbly (Question 6). He knew that he was standing but it felt odd, it felt to him like he had only a very minimal amount of control over his body. Additionally, he felt like he has been almost constantly leaning to one side (Question 7). He said he wasn't even trying to stand straight since there was no such task (Question 8). In essence, he wasn't even concentrating on how he's standing, he didn't care (Question 9). He noted that he thought our electrical stimulation actually made him feel worse since it was creating a dizziness feeling, feeling of a "fullness of the head" and even to some extent slight loss of balance (Questions 10, 11). He would consider using help from such device in similar scenarios only if it would actually work, but he was against taking away the feeling that you lose your balance. The reason people play such games is exactly to get and feel those disturbances, he says (Question 12).

2.3.6. Additional information from experiments

I had in total 5 participants who were male with an average age of 26.6 years. Four out of five people have agreed on using the maximum amount of current on the GVS device. Only one person needed it to be reduced. Also, four out of five people have completed first room in the VR game. Not a single person has said during the experiment that they feel how GVS is being triggered, although it was prematurely tested before with every participant whether they feel anything or not, how much is the shock being felt etc.

For a better grasp of overall responses collected with help of SSQ, here is a graph with mean data about every symptom that people have felt, together with an indication of a standard error.

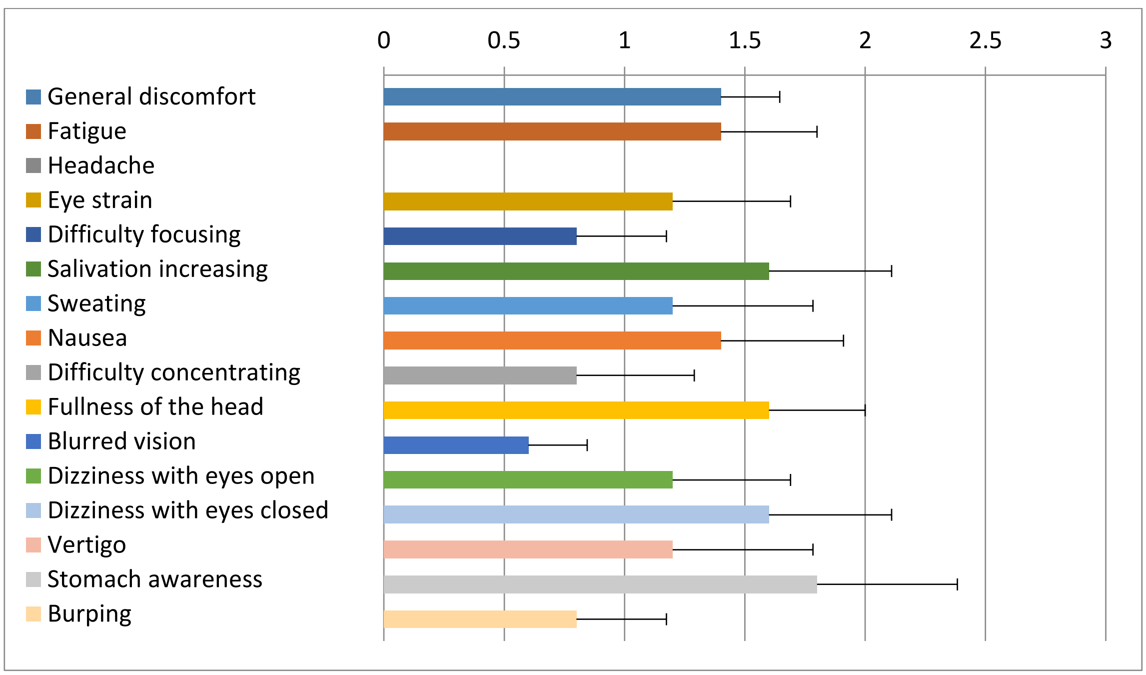

Figure 19 Mean results from a Simulator Sickness Questionnaire by every participant; Legend: 0 – None, 1 – Slight, 2 – Moderate, 3 – Severe;

Conclusion

This research has provided results, at least to some extent, for understanding how does GVS affect vestibular system during a motion sickening VR interaction. In order to achieve this, a major literature review has been conducted that provided a lot of ground facts and guidance for building the GVS device and designing the experiment. GVS device has been successfully built and used in the experiment, only with a couple of shortcomings. Experiments have been successfully conducted, enough data addressing simulation sickness has been gathered and feedback regarding the work of the device received. A thorough analysis of both recorded videos from the experiment with each participant has been finished, concluded and supported with data from questionnaires and interviews.

Every proposal from the hypothesis has been answered and it is possible to say that the hypothesis has not met expected results. As a result, removing or diminishing sensory conflict while in a VR interaction has ended up as the opposite. Analysis showed that some participants have felt the simulation sickness and some have even felt how did the stimulation manage to amplify this effect. As for the assistance in control of posture – both positive and negative answers can be assigned to the results. As extracted from video analysis it was noticeable that some participants have been correcting their posture during the stimulation from the device, although they have reported that they haven’t felt the effects (most of the times) due to immersion in the game. Another side of this result is further addressed in final paragraphs.

To conclude I can say that even if the results have turned out not as initially expected, at least some knowledge regarding this field of research has been obtained and hopefully would become a good use in future researches.

Lessons learned

One thing was understood, that the device has probably worked like an SVS rather than GVS oriented device because of the loss of voltage due to the resistance of the skin of every participant as well as electrodes themselves. A direct connection from a 9V battery gives much more current and the effect is greater but that could be the problem. If the effect is great it pushes you and it might be so hard that you won't be able to centre yourself (especially while wearing an HMD) but rather start swaying in another direction if not fall completely. Probably, the device didn’t work exactly like SVS. SVS in this scenario would only slightly tighten up the responses of the vestibular system but our GVS was actually slowly but steadily affecting participants. The posture change was different for every participant but it was slowly changing. I haven't done any long duration tests in order to decrease the risk of the vestibular system getting used to the stimulation – that would decrease the effect once VR game would start affecting the participant.

Besides obvious indications from previous works that were saying that range in which GVS provides appropriate results is from 1.0 mA till 2.5 mA, due to having no previous experience with such topic, both electrical stimulation and conduction of a physiological experimental research, it is possible that subconsciously it has been decided to use one of the minimal amounts of current for this research, in order to reduce any random risks and simply feel more confident doing it. Because technically it was possible to implement a higher voltage source in the circuit. It just hasn’t been done because during initial tests the voltage that has been used has shown at least some effects thus it was decided to stick with it.

Fair to point out that there is always a possibility, that most of our participants simply had a really low sensitivity to GVS or naturally high skin impedance.

It is also left to decide which is the best mindset – to try to be as stiff as possible and respond to simulator sickness with even more stiffness, or actually, be relaxed let your body sway but try to give a chunk of your concentration towards assessing your posture and try to control it.

Future work

As most of the sources concentrated on currents around 1 mA I decided to follow. Because of the fact that everyone's sensitivity of vestibular system towards electrical stimulation is different, together with the difference in skin resistance, the main conclusion from that is the use of a higher voltage source (e.g. 12V batteries). The only problem is that higher currents create a stronger effect, and that means it would be vital to find the balance. If the effect would be too strong then the person would be swayed by the stimulation into another threshold on the other side and that in return would do the same. A result would be unacceptable – the participant would behave like an inverted pendulum. Combine that with motion sickness from the game and general disorientation that stimulation would've provided when you don't see the environment you are in.

A possibly correct method to achieve balance, avoiding weak stimulation, would be to set different threshold angles on the device. For example, instead of 6 degrees, I would use 15. First of all, it would've required a much more motion sickening game, for example where a player would be constantly rotating in 6DOF together with a confusing and delayed control scheme. Let us ignore the fact that such kind of VR game would create severe motion sickness multiple times faster than what we've used for our experiments. SSQ questionnaire would be full of maximum answers and no doubt if someone would even start puking during an experiment. If a participant would lose the balance so much that they would enter this threshold, get stimulated but a more potent stimulation, "pushed" in another direction – he would have more time to prevent himself from going into the opposite threshold. Possibly some other type of reaction would've occurred instead since the effect of the stimulation would be so distinct. A participant might've tried to stabilize themselves and it is quite hard to say what the results would've been considering at that moment he would be getting alterations in balance through GVS, not seeing the surroundings due to wearing an HMD and playing a motion sickening game.

Those are all speculations based on the results obtained from this research but this is definitely a good topic to address in the future researches.

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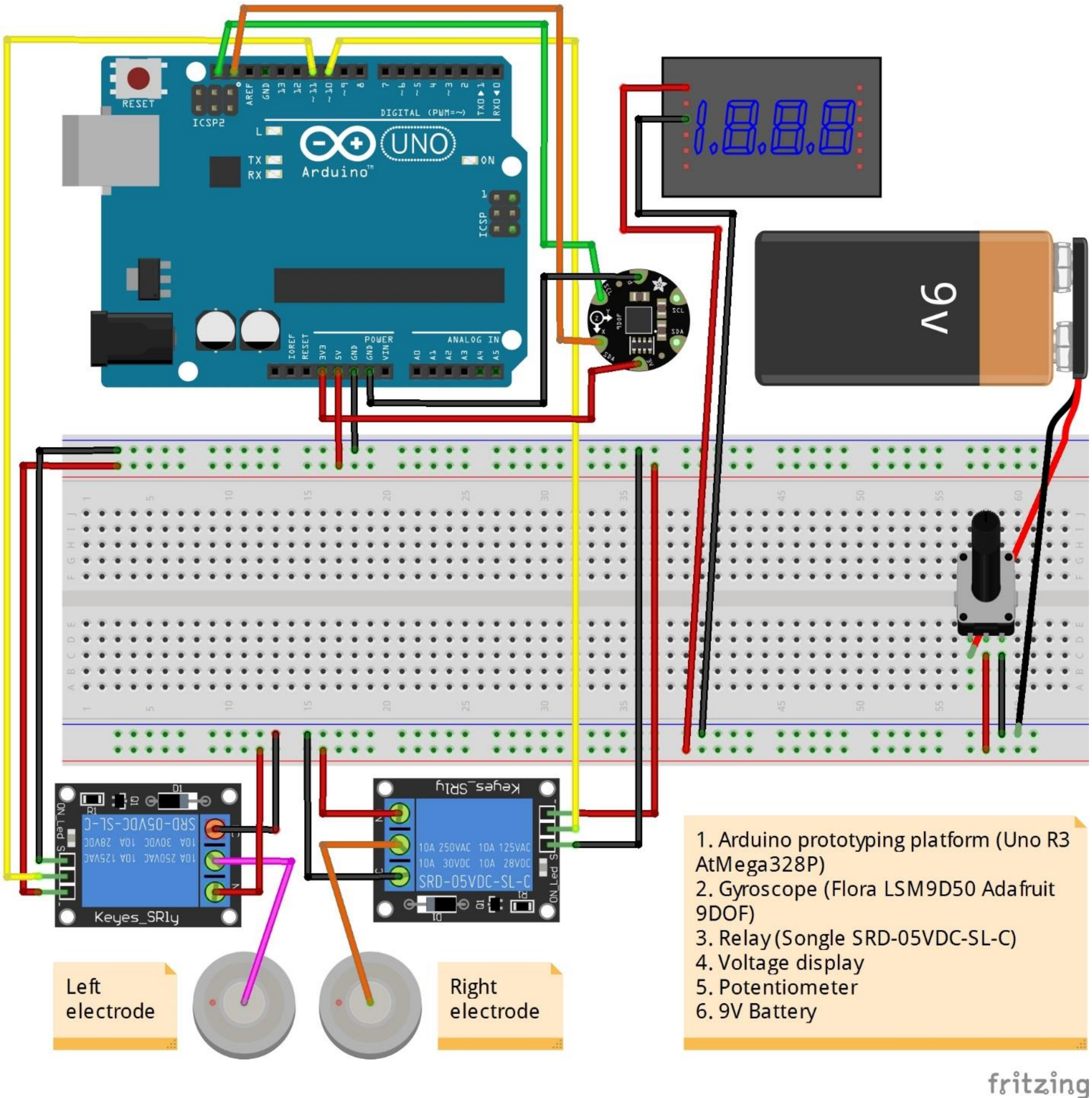
Kokkuvõte

Selle uurimusliku pilootuuringu eesmärgiks on saada ülevaade tulemustest, mis tagavad galvaanilise vestibulaarse stimulatsiooni (GVS) mere haiguse ajal (MS) (simulatsioonihaiguse esilekutsumine) virtuaalreaalsuse (VR) interaktsiooni mängus. GVS-i pakutakse meetodina, mis võimaldab võidelda sensoorse konfliktiga, aidates säilitada kontrolli oma tasakaalu üle, saates väga nõrga voolu läbi pea, et selektiivselt aktiveerida vestibulaarset süsteemi. Kvalitatiivsed eksperimendid viiakse läbi selleks, et hinnata loodud simulatsiooniriski tõhusust, hinnata enda valmistatud, kaaskantava ja automaatse GVS-seadme rakendust ja saada tagasisidet kogemuste kohta. Tulemuste põhjalik analüüs näitab, et sellistes stsenaariumides ebastabiilsuse vastu võitlemise meetod nagu GVS pole ainult ebapiisav, vaid see suurendab sensoorseid konflikte sellise interaktsiooni ajal.

Appendix 1 – GVS device scheme



Appendix 2 – Arduino code

```
#include <SPI.h>
#include <Wire.h>
#include <Adafruit_Sensor.h>
#include <Adafruit_LSM9DS0.h>
#include <Adafruit_Simple_AHRS.h>

int right = 9; int left  = 8; float norm_pos = 0.0;

Adafruit_LSM9DS0 lsm = Adafruit_LSM9DS0(1000);  // assaigns a unique ID for a sensor
- #1000
Adafruit_Simple_AHRS ahrs(&lsm.getAccel(), &lsm.getMag()); // creates a simple AHRS
algorithm using the LSM9DS0 instance's accelerometer and magnetometer

//configures range and sensitivity of sensors & setups the gyroscope
void configureSensor(void)
{
  lsm.setupGyro(lsm.LSM9DS0_GYROSCALE_245DPS);
}
void setup() {
 Serial.begin(9600); // initializes serial connection for console
 lsm.begin(); // initializes sensor
 configureSensor();
 pinMode(right, OUTPUT);
 pinMode(left, OUTPUT);
 digitalWrite(left, LOW);
 digitalWrite(right, LOW);
 delay(500);
 }
void loop() {
  sensors_event_t gyro; //variables for gyro data
  sensors_vec_t orientation; // variables for orientation object
  ahrs.getOrientation(&orientation); //get orientation object
  Serial.print("Orientation: \n");
  Serial.print("Pitch (Y axis): ");Serial.print(orientation.pitch);
Serial.print("?°\n");
    if (orientation.pitch > 6.0 && orientation.pitch < 70.0){rightToLeft();}
    if (orientation.pitch > -70.0 && orientation.pitch < -6.0 ){leftToRight();}
    if (!(orientation.pitch > 6.0 && orientation.pitch < 70.0) && !(orientation.pitch
    > -70.0 && orientation.pitch < -6.0 )){zeroItOut();}
  Serial.println("\n");
  delay(500);
}
void leftToRight(){
 digitalWrite(right, LOW);
 delay(200);
 digitalWrite(left, HIGH);
 delay(200);
 Serial.print("Leaning left. Right stimulus");
}
void rightToLeft(){
 digitalWrite(left, LOW);
 delay(200);
 digitalWrite(right, HIGH);
 delay(200);
 Serial.print("Leaning right. Left stimulus");
}
void zeroItOut(){
 digitalWrite(left, LOW);
 delay(200);
 digitalWrite(right, LOW);
 delay(200);
}
```

Appendix 3 – Consent form

CONSENT FORM

The purpose of this study is to investigate the work of a method called Galvanic Vestibular Stimulation (GVS) in Virtual Reality (VR) interaction. We are working on a novel system that uses electric pulses of GVS to help your orientation in VR by stimulating your vestibular system. Your participation involves playing one short stage of a VR game, answering a simulation sickness questionnaire, completing a short interview about the experience with the GVS device and doing a test to determine your general physical abilities. You will be asked to wear a VR headset, through which you will play the game and a GVS device that will be attached to you and carefully calibrated for your personal body preferences. This experiment will take approx. 30 minutes (or fewer, to be specified for each experiment).

Expectancies from a Participant

You are expected to have a moderate/high tolerance for motion sickness (e.g. you do well in VR games, roller coaster rides, boat/ship rides, etc.) and as a common precaution - have no background of epilepsy. You are expected not to have taken any anti-motion sickness medications, antihistamines, or alcohol prior to the experiment, and to refrain from eating for at least an hour prior to the experiment.

Benefits and Risks

There is no immediate benefit to you other than learning about the human-computer interaction research, contributing to it and experiencing a virtual reality system combined with a vestibular stimulation. You may experience motion sickness while wearing the virtual reality headset and playing the game. The experimenter will explain how you can take breaks during the experiment to relieve this or to withdraw completely if a strong symptom of motion sickness is going to occur and you would wish to stop. The only negative effect from the GVS that you might feel is tingling in the area of the electrodes when the device triggers.

Principal Investigator and Supervisor

The principal investigator is Erik Krivorukov. If you have any questions or concerns for him, please email erik.krivorukov@tlu.ee or call (+372) 5131128. Principal investigator's supervisor is Assoc. Prof. Aleksander Valjamae. If you have any questions or concerns for him, please email aleksander.valjamae@tlu.ee or call (+372) 5183957.

Voluntary Participation

Your participation in this project is voluntary and you are free to withdraw your consent and discontinue participation at any time without penalty. You are free to stop the experiment at any time if you are going to feel any discomfort or strong sickening effects.

Use of Data Collected and Confidentiality of Records

Results may be present only in this research's thesis. No personally identifying information will be stored or disseminated with the results. Your confidentiality will be maintained by placing only a participant's order number in the experiment, and no personally identifying information, in the resulting data files.

Participant's Consent

The study has been described to me and I understand that my participation is voluntary and that I am free to withdraw my consent and discontinue my participation in the project at any time without penalty. I attest that I am at least 18 years of age. I also understand that the results of the study will be treated in strict confidence and reported as group data sets without personally identifying information, possibly in this experiment's thesis, and no video materials will be shown in public. I understand that if I have any questions or concerns about this experiment, I may pose them to Erik Krivorukov (erik.krivorukov@tlu.ee) or Assoc. Prof. Aleksander Valjamae (aleksander.valjamae@tlu.ee).

I have read and understand the above information and I consent to participate in this study by signing below.

_________________________ _____________________

Signature Date

____

Signature of Investigator

Appendix 4 – FICSIT-4 balance test

FICSIT-4 (Frailty and Injuries: Cooperative Studies of Intervention Techniques)
Tests of Static Balance: parallel, semi-tandem, tandem, and one-legged stance tests

Timing is stopped if:
- the person displaces their stance foot
- the suspended foot touches the ground
- the suspended foot touches the other calf for support (cue the person to avoid this)

INSTRUCTIONS: Demonstrate each position to the subject, then ask them to perform and time.

F-1. FEET CLOSELY TOGETHER, UNSUPPORTED, eyes open (ROMBERG POSITION)
INSTRUCTIONS: Stand still with your feet together as demonstrated for 10 seconds.
[ ] 04 able to stand 10 seconds safely
[ ] 03 able to stand 10 seconds with supervision
[ ] 02 able to stand 3 seconds
[ ] 01 unable to stand 3 seconds but stays steady
[ ] 00 needs help to keep from falling
If subject is able to do this, proceed to the next position, if not, stop.

F-2. FEET CLOSELY TOGETHER, UNSUPPORTED, eyes closed (ROMBERG POSITION)
INSTRUCTIONS: Please close your eyes and stand still with your feet together as demonstrated for 10 seconds.
[ ] 04 able to stand 10 seconds safely
[ ] 03 able to stand 10 seconds with supervision
[ ] 02 able to stand 3 seconds
[ ] 01 unable to keep eyes closed 3 seconds but stays steady
[ ] 00 needs help to keep from falling
If subject is able to do this, proceed to the next position, if not, stop.

F-3. SEMI-TANDEM: eyes open HEEL OF 1 FOOT PLACED TO THE SIDE OF THE 1ST TOE OF THE OPPOSITE FOOT (SUBJECT CHOOSES WHICH FOOT GOES FORWARD)
INSTRUCTIONS: Please stand still with your feet together as demonstrated for 10 seconds.
[ ] 04 able to stand 10 seconds safely
[ ] 03 able to stand 10 seconds with supervision
[ ] 02 able to stand 3 seconds
[ ] 01 unable to stand 3 seconds but stays steady
[ ] 00 needs help to keep from falling
If subject is able to do this, proceed to the next position, if not, stop.

F-4. SEMI-TANDEM: eyes closed HEEL OF 1 FOOT PLACED TO THE SIDE OF THE 1ST TOE OF THE OPPOSITE FOOT (SUBJECT CHOOSES WHICH FOOT GOES FORWARD)
INSTRUCTIONS: Please close your eyes and stand still with your feet together as demonstrated for 10 seconds.
[ ] 04 able to stand 10 seconds safely
[ ] 03 able to stand 10 seconds with supervision
[ ] 02 able to stand 3 seconds
[ ] 01 unable to keep eyes closed 3 seconds but stays steady
[ ] 00 needs help to keep from falling
If subject is able to do this, proceed to the next position, if not, stop.

F-5. FULL TANDEM: eyes open HEEL OF 1 FOOT DIRECTLY IN FRONT OF THE OTHER FOOT (SUBJECT CHOOSES WHICH FOOT GOES FORWARD)
INSTRUCTIONS: Please stand still with your feet together as demonstrated for 10 seconds.
[ ] 04 able to stand 10 seconds safely
[ ] 03 able to stand 10 seconds with supervision
[ ] 02 able to stand 3 seconds
[ ] 01 unable to stand 3 seconds but stays steady
[ ] 00 needs help to keep from falling
If subject is able to do this, proceed to the next position, if not, stop.

F-6. FULL TANDEM: eyes closed HEEL OF 1 FOOT DIRECTLY IN FRONT OF THE OTHER FOOT (SUBJECT CHOOSES WHICH FOOT GOES FORWARD)
INSTRUCTIONS: Please stand still with your feet together as demonstrated for 10 seconds.
[ ] 04 able to stand 10 seconds safely
[ ] 03 able to stand 10 seconds with supervision
[ ] 02 able to stand 3 seconds
[ ] 01 unable to stand 3 seconds but stays steady
[ ] 00 needs help to keep from falling
If subject is able to do this, proceed to the next position, if not, stop

F-7. STANDING ON ONE LEG: eyes open
INSTRUCTIONS: Stand on one leg as long as you can without holding.
[ ] 04 able to lift leg independently and hold >10 seconds
[ ] 03 able to lift leg independently and hold 5-10 seconds
[ ] 02 able to lift leg independently and hold = or >3 seconds
[ ] 01 tries to lift leg unable to hold 3 seconds but remains standing independently
[ ] 00 unable to try or needs assist to prevent fall

Total FICSIT-4 Static Balance score = ____ / 28

Appendix 5 – Simulator sickness questionnaire

Simulator Sickness Questionnaire
Instructions: Circle how much each symptom below is affecting you right now.

General discomfort	None	Slight	Moderate	Severe
Fatigue	None	Slight	Moderate	Severe
Headache	None	Slight	Moderate	Severe
Eye strain	None	Slight	Moderate	Severe
Difficulty focusing	None	Slight	Moderate	Severe
Salivation increasing	None	Slight	Moderate	Severe
Sweating	None	Slight	Moderate	Severe
Nausea	None	Slight	Moderate	Severe
Difficulty concentrating	None	Slight	Moderate	Severe
“Fullness of the head”	None	Slight	Moderate	Severe
Blurred vision	None	Slight	Moderate	Severe
Dizziness with eyes open	None	Slight	Moderate	Severe
Dizziness with eyes closed	None	Slight	Moderate	Severe
* Vertigo	None	Slight	Moderate	Severe
** Stomach awareness	None	Slight	Moderate	Severe
Burping	None	Slight	Moderate	Severe

* Vertigo is experienced as a loss of orientation with respect to vertical upright.
** Stomach awareness is usually used to indicate a feeling of discomfort, which is nausea.

Original version : Kennedy, R.S., Lane, N.E., Berbaum, K.S., & Lilienthal, M.G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. International Journal of Aviation Psychology, 3(3), 203-220.

Appendix 6 – Post-experimental interview

Interview

This questionnaire is made to get your sincere feedback on the experience you've just been having. Almost every question is meant as an open-ended question - if you feel like you've got something to add or care to explain something in a greater detail - feel free to do so. Try to be as transparent as possible, say what you think, what you feel and what you want to say. No one here is going to take it personally - this is purely for research purposes. Are you OK with that? Great. Let's begin.

1. How old are you?
2. Have you ever had a similar VR experience before?
3. Have you done any electrical stimulation before?
4. Which part of the experience you felt was the most disturbing or discomforting?
5. Have you experienced any disorientation or loss of balance?
6. Have you felt like you've had enough control over your posture when playing?
7. How well you think you've done at standing as straight as possible during the whole experiment?
8. How much effort have you dedicated to standing straight?
9. How hard were you concentrating on how straight you are standing?
10. Have you felt like something was directly assisting you?
11. Have you been feeling when the device was providing the stimulation? How?
12. Would you consider using this kind of device in the future in similar scenarios like VR games or any other balance disturbing activities to help or prevent you from falling?
13. Try to describe the whole experience in three words.