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Psychophysiological and Performance Aspects on Motion Sickness

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*Nothing shocks me.
I'm a scientist.*

Harrison Ford (1942-), as Indiana Jones.

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Abstract

Motion sickness is not an illness, but rather a natural autonomic response to an unfamiliar or specific stimulus. The bodily responses to motion sickness are highly individual and contextually dependent, making them difficult to predict. The initial autonomic responses are similar to the ones demonstrated when under stress. When under the influence of motion sickness, motivation and ability to perform tasks or duties are limited. However, little is known about how specific cognitive functions are affected. Furthermore, standard mitigation strategies involve medications that induce fatigue or strategies that require cognitive capabilities. Both of them may result in reduced capability to perform assigned tasks or duties. Hence, there is a need for alternative mitigation strategies. The aim of the thesis was to study psychophysiological and performance aspects on motion sickness. The long-term goal is to provide strategies for mitigation and prevention of motion sickness by identifying psychophysiological responses as predictors for both wellbeing and performance. This thesis comprises four studies, in which 91 participants were exposed to two different motion sickness stimuli, either an optokinetic drum or a motion platform. Before the tests, a method for extracting fixations from eye-tracking data was developed as a prerequisite for studying fixations as a possible mitigation strategy for reducing motion sickness. During exposure to stimuli that triggers motion sickness, performance was studied by testing short-term memory and encoding and retrieval. In the final study, the effects of an artificial sound horizon were studied with respect to its potential to subconsciously function as a mitigating source. The results of the measurements of the psychophysiological responses were in accordance with previous research, confirming the ambiguity and high individuality of the responses as well as their contextual dependencies. To study fixations, a centroid mode algorithm proved to be the best way to generate fixations from eye-movement data. In the final study, the effects of the sound horizon were compared to the effects of a non-positioned sound. In the latter condition, both fixation time and the number of fixations increased over time, whereas none of them showed a significant time effect in the sound horizon condition. The fixation time slope was significantly larger in the non-positioned sound condition compared to the sound horizon condition. Number of fixations, heart rate, and skin conductance correlated positively with subjective statements that referred to motion sickness. Among participants that were susceptible to motion sickness symptoms, short-term memory performance was negatively affected. However, no effects of motion sickness on encoding and retrieval were found, regardless of susceptibility. Future studies should continue focusing on autonomic responses and psychological issues of motion sickness. Factors such as motivation, expectancies, and previous experiences play a major and yet relatively unknown role within the motion sickness phenomena.

List of publications

This thesis is based on the following four studies. The studies are referred to by their roman numerals.

- I Falkmer, T., Dahlman, J., Dukic, T., Bjällmark, A., Larsson, M. (2008). Fixation Identification in Centroid Versus Start-Point Modes Using Eye Tracking Data. *Perceptual and Motor Skills*. 106, 710-724.
- II Dahlman, J., Sjörs, A., Lindström, J., Ledin, T., Falkmer, T. (2008). Performance and Autonomic Responses During Motion Sickness. *Human Factors*. (Pending minor revision).
- III Dahlman, J., Sjörs, A., Lundgren, P., Ledin, T., Falkmer, T. (2008). Effects of Motion Sickness on encoding and retrieval. (submitted).
- IV Dahlman, J., Sjörs, A., Ledin, T., Falkmer, T. (2008). Could Sound be Used as a Strategy for Reducing Symptoms of Perceived Motion Sickness? *Journal of Neuroengineering and Rehabilitation*. (In press).

2 Preface

At first, the science of motion sickness may not seem appealing, but rather evoke bad memories and traumas associated with nausea and vomiting. However, when realizing that motion sickness is so much more than just these moments of emesis – that it is the result of a complex set of events that originates from a normal bodily reaction to something that, by our brain, is interpreted as a conflict, toxin, risk or threat – it becomes interesting. Despite its name, motion sickness is just a normal response to an unfamiliar stimulus, initiated long before we actually sense anything with our perception. Once, I overheard a statement regarding the occurrence of motion sickness: “...*the unfortunate coincidence of the few seconds in evolution that humans developed means of transportations that, by our biological sensory systems, would be interpreted as inconsistent*”. This statement was one of the reasons that the phenomenon of motion sickness caught my attention.

Although most of us only suffer from motion sickness during certain types of travelling or when exposed to certain kinds of movement or illusions of movement, we can almost always devote our attention towards reducing symptoms by lying down, taking command of the steering wheel, trying to sleep, or aborting the nauseating activity. Even for people working in moving environments or for those who frequently are being exposed to a moving environment, motion sickness is common and creates problems long before people actually become so ill that they have to abort their duties. Much of the early research on motion sickness focused on the final stages of motion sickness, starting when the participant first perceives symptoms and ends when he or she is incapacitated by the emesis or by being totally exhausted.

My first experience with symptoms associated with motion sickness goes back to my childhood when I, together with my family, spent the summers in the archipelagos of Sweden travelling by small boats. The weather can sometimes be rough there and change dramatically within only an hour. Later, I worked for the Swedish Defence Research Agency (FOA/FOI), conducting research for the Swedish Armed Forces focusing on human performance and psychophysiological responses to motion under extreme conditions and stress in which performance was crucial.

Initially, the Swedish Armed Forces raised the question of how motion sickness affected the soldiers' performance by being transported in enclosed vehicles. Performance in these situations is often associated with over learned skills such as rifle handling, shooting, reconnaissance, and command and control. When further studying these duties, one realizes that before it actually becomes apparent that the soldier is affected by motion sickness, symptoms have already become severe and will soon incapacitate the soldier.

When studying the literature before starting to conduct the studies, I discovered that from the actual initiating conflict, detected by our senses, the autonomic responses and physiological series of events were much similar to those associated with stress. Knowing that stress has a well-established relationship to impaired performance, it became apparent to me that performance among these soldiers could be affected long before they demonstrated any observable physiological state of motion sickness.

The series of events and autonomic reactions triggered by motion sickness were fascinating and became even more so when previous research indicated the need for objective

measurements. Also, research concerning the entire motion sickness phenomenon – from early sensory detection to emesis and beyond, i.e., the adaptation phases, susceptibility, etc. – is indeed needed.

After having performed studies for the Swedish Army, I moved on to the Swedish Royal Navy and the amphibious corps before I realized that I had to continue in a more controlled setting using controlled stimulation and more objective psychophysiological measuring equipment. These prerequisites were provided at the Faculty of Health Sciences at Linköping University and this was also the location for the final work of this thesis.

3 Introduction

This thesis will regard motion sickness as a overarching term that includes contextual differences that reflect in which environment motion sickness symptoms occur, such as sea sickness, train sickness, car sickness, air sickness, and simulator sickness. Furthermore, motion sickness is regarded as a state of impaired bodily functions that leads to reduced activity according to the International Classification of Functioning, Disability and Health (ICF) [1]. The definition of motion sickness, *kinetosis*, is a state of perceived illness following exposure to motion or illusory motion [2]. The definition implies that both real and illusory motion exposure is perceived by our senses and thus may trigger an autonomic response that, if not stopped, can lead to emesis.

This thesis will have its theoretical foundation in the sensory conflict hypothesis, also known as the neural mismatch hypothesis, according to Reason and Brand [3] and further developed by Benson [2]. The general assumption of this theoretical framework is that in order for motion sickness to occur, there has to be a mismatch between two of the three sensory systems perceived either by vestibular, visual or proprioceptive receptors.

Motion sickness, although it appears as an illness due to its expressions, is not an illness but rather a natural autonomic response to unfamiliar or specific motion stimuli. Ironically, motion sickness can both be evoked by the presence of an unfamiliar motion as well as in the absence of expected motion [4]. Three of the studies in this thesis examine the effects of motion or the illusion of motion on autonomic responses, subjective perception, and its effect on performance in healthy individuals. This thesis will not focus on vestibular mechanisms, underlying motion characteristics per se, other than in terms of susceptibility, adaptation, and sensitivity to developing symptoms associated with motion sickness. The vestibular system, vision and proprioception will only briefly be described as part of the theoretical basis for understanding the sensory conflict hypothesis and the prerequisites for developing motion sickness. However, methodological issues with respect to eye movements are thoroughly addressed in study I. In addition, this thesis will not discuss pharmacological effects on motion sickness. Instead, it comprises non-pharmacological countermeasures as described in paper IV.

In this thesis, motion sickness has been measured as a psychophysiological response, as self reported/perceived statements, or as a combined measurement of both psychophysiological and self-reported/subjective statements. The term psychophysiology is closely related to cognitive neuroscience and is primarily concerned with the physiological responses caused by behavioural activities [5]. Psychophysiology is not to be confused with physiological psychology that studies psychological effects of physiological events.

In this thesis, subjective reports of motion sickness are used to obtain measurements that address the effects of certain physiological or psychological phenomenon. By perceived motion sickness, I refer to the part of the motion sickness process that manifests itself on a conscious level. One may argue that if motion sickness is not perceived, no motion sickness is present. However, I strongly believe that motion sickness is initiated on a subconscious level, starting with a change in the autonomic nervous system. This change is the result of the conflict detected by our visual, proprioceptive, or vestibular organs and not, initially, by our consciousness. In fact, not everyone perceives motion sickness symptoms, but may show autonomic responses that, if confirmed by a perceived subjective report, would be classified as motion sickness.

There are numerous reports on the psychological part of motion sickness that deals with perceived status while exposed to motion sickness triggering stimuli [6-16]. Considerable research has also been devoted to study autonomic changes and correlations among these autonomic variables [8, 9, 12, 13, 17]. Few studies question the fundamental basis of the sensory conflict theory, and the theory has also been adapted to cover new phenomena such as simulator/virtual environments sickness. Despite the large number of studies performed, motion sickness researchers constitute a small community, often closely connected to operative environments in the military domain or in high performance occupations. My ambition is to bring further knowledge to the science of motion sickness when it comes to understanding its autonomic manifestations and how it affects our ability to perform. The fact that people suffering from motion sickness are found both in operative working environments and in transport situations means that such investigations are needed. Moreover, more knowledge about the role of motion sickness in different complex environments is needed. Motion sickness is indeed contextually dependent and therefore any results from a laboratory setting have to be treated as such with regards to external validity. This thesis may contribute to the knowledge of nausea in general and its autonomic components. This knowledge may be applicable in studies on chemotherapy and diseases related to vestibular disorders and nauseogenic effects of medication. Furthermore, I hope to contribute to the understanding of motion sickness as a whole, from autonomic detection to emesis. I believe many studies focus on the later stages of symptoms (e.g., vomiting) when the manifestations are large and deficits in performance are more due to the fact that people actually cannot perform anything because of severe nausea rather than the early stages, when cognitive attention may be negatively affected.

3.1 Thesis outline

Before this thesis work, two studies [18, 19] were performed at the Swedish Defence Research Agency (FOI) on commission from the Swedish Armed Forces where field studies among conscripts were regularly performed. These two studies, carried out under extremely difficult conditions, set the foundation for future research, studying the complex relation between self-reported motion sickness and an over-learned skill (in this case shooting at fixed targets). These two field trials also studied “early symptoms” of motion sickness using detailed questionnaires. One of the phenomena identified as being part of “early symptoms” was “visual problems”, as reported by the conscripts.

To study “visual problems”, eye-tracking methodology was used. Eye movements, pupil size, and fixation patterns could be key factors for identification of those that tended to be easily and severely affected by motion sickness. Furthermore, eye tracking could be one methodology to predict the course of events in case of motion sickness. Pupil size is intimately connected to the autonomous nervous system, i.e., an indicator, while fixations and, hence, eye movements, reflect the person’s mitigation strategies with respect to motion sickness. It is assumed that fewer eye movements, i.e., longer fixations and thus reduced visual input, would render a slower development of motion sickness. The possibility of detecting fixations was, however, difficult since no reliable methods for obtaining fixations were available. Different methods are used, but seldom or never described with regards to their validity [20]. Since fixation durations were hypothesized to increase as motion sickness developed, the need for reliable and valid methods became obvious. This conclusion constitutes the basis for conducting the first study in this thesis. Study I provided a result that enabled me to obtain valid fixation data.

After performing the field trials, not included in his thesis, where I encountered problems in capturing performance decrements caused by motion sickness in an over-learned task, I realized that the following studies needed controlled environments and more cognitively demanding tasks. Therefore, in study II and III, I used an optokinetic drum in a laboratory setting to induce motion sickness symptoms to study performance in short-term memory and encoding/retrieval processes. While in the optokinetic drum, I also studied both self-reported motion sickness (study II and III), and psychophysiological measurements, e.g., pupil size, in addition to the participants' survival time in the drum (study II). I identified several interesting measurements that possibly could identify "early stages" and predict the development of motion sickness.

With this knowledge, I carried out a fourth study that investigated the effect of an artificial sound horizon as a mitigation strategy towards motion sickness. This laboratory study is based on knowledge gained in all previous studies.

3.2 Motion sickness

As mentioned, motion sickness expresses itself as a sickness, both literally and physiologically, if associated only with emesis. However, motion sickness could be described as a state of sickness resulting from motion exposure or illusion of motion, e.g.,vection [21]. Hippocrates, one of the first people to discuss motion sickness, concluded that motions caused by the ocean disordered the body. In 1838, Whiting reported that vomiting resulted from the irritation of the reflex reaction of the gastric mucosa initiated by the motion of the stomach's content [22]. By the beginning of the 1880s, Irwin began understanding that the symptoms associated with seasickness were initiated with a discord between the immediate or true visual impressions and a certain visual habit or visual sense of the order of things [23]. Irwin's theory was named "*Visual Vertigo Theory*" and resembles the sensory conflict theory, later developed by Reason and Brand [3].

Much of the early research in motion sickness focused on vomiting and questions regarding the purpose of the emetic response. Although motion sickness is much more than just vomiting, discussions in the early 1960s focused on defining endpoint criteria that could identify when a person is motion sick or not, e.g., at what stage both objective and subjective measurements could confirm motion sickness. It seems obvious that vomiting was the only end point criterion studied, since much of the subjective measurements, given in self-reports, were regarded as less trustworthy. Chinn [24] also favoured vomiting as the end point criterion with the argument that it was the only observable symptom that by certainty could be associated with motion sickness. This assumption was mostly due to the lack of methodological ways to measure many of the autonomic changes and events that are studied today. At that point in time, it was far from common knowledge what changes to look for with regards to what we today label as autonomic responses and objective measurements.

The perception of motion sickness is often associated with emesis and many of the initial symptoms are subtle and not easily perceived or associated with motion sickness. In theory, 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 [13]. In the late 1940s, Tyler and Bard stated that about 5% of the susceptible population would fail to adapt to motion sickness inducing movements [25]. During the First and Second World Wars, soldiers travelling in enclosed vehicles on land or at sea suffered greatly from symptoms of motion sickness, a condition that affected their performance. The reason for this was, of course, multidimensional. Not only were the soldiers unfamiliar with many of the environments in

which they travelled, but they were also under extreme stress and thereby susceptible to this, for some, contagious state. After the Second World War, tremendous efforts were made to better understand the underlying causes of motion sickness and its effects on performance. Much of the theoretical framework that we rely on today has been developed after these two wars.

Obviously, motion sickness can affect anyone under the influence of real or apparent motion with a functional vestibular system if the circumstances are right. This explains why so many are exposed to symptoms when, for instance, travelling. Murray [13] states that one-third of the population are highly susceptible to motion sickness; that is, these people would indicate that they become motion sick fairly often when travelling in any kind of vehicle. Reason and Brand [3] stated that there are three components that determine the severity of motion sickness: the characteristics of the stimulus, the susceptibility of the participant, and the total time of exposure. Regardless of travelling in an airplane, on a bus, on a boat, or working in a moving environment, motion sickness is likely to cause discomfort, impaired performance and, depending on the prerequisites of the travelling, have a significant impact on the ability to perform any desired activity [26].

3.2.1 The magnitude of occurrence

As previously stated, it is estimated that approximately 5% of the population never adapts to motion sickness triggering stimuli, given a fully functional vestibular system [25]. Based on the fact that the perception of motion sickness is highly individual and also contextually dependent, it is impossible to obtain a general motion sickness susceptibility level for all individuals. However, a person can be labelled as more or less susceptible to symptoms if exposed to a triggering stimulus. The most common environment in which motion sickness occurs is on boats. The reason for this is, of course, that exposure during sea travel can be extensive both with respect to time and motion magnitude [3]. It has been reported that the incidence of motion sickness on navy ships can be as high as 62% [27]. With regards to the frequent use of cars and buses, the occurrence of motion sickness in ground transportation is also common, but has been devoted little attention per se. Some early studies indicated that 57% had experienced motion sickness when travelling by car and that 32% had vomited in cars as a result of experienced motion sickness before the age of 12 [28]. Air sickness is not often reported by passengers, although it occurs under severe weather conditions. Modern airplanes are bigger and can operate on a higher altitude than previously, which enable them to avoid bad weather. Modern technology also provides better weather forecasts and route guidance. Motion sickness as a result of travelling by train has recently been studied and was also reported as a major problem when introducing the new high speed trains in Sweden [29, 30]. Much effort has been devoted to studying the dynamics and tilt of the train carts and the track geometry [31].

The increasing use of simulators has also created problems with motion sickness, especially in the military domain. After training in a flight simulator, 25% of the air force pilots reported symptoms of motion sickness [32]. Since the late 1960s, motion sickness symptoms have been reported during initial stages of spaceflight and it is estimated that up to 80% of the astronauts and cosmonauts experience “space sickness” during the first days in microgravity [33, 34]. There are, of course, limited possibilities to prepare for spaceflight on earth, but training can be provided by parabolic flights, which allows a few minutes of weightlessness in an ordinary air plane [35]. This experience is also very provocative and the incidence of motion sickness as a result of parabolic flight is high.

A common misunderstanding is that motion sickness originates from very high frequency motion and shaking of the body. Although mostly being a problem of keeping posture and balance, motion sickness may occur in high frequency movement as well, but the ultimate prerequisites are found between 0.15 and 0.25 Hz [36]. Between these intervals, the highest motion sickness incidence has been found using different motion profiles with regards to heave, pitch and roll. In a laboratory setting, motion stimuli can be created by using a motion platform, oscillating seats, translational and rotational rooms, etc. When conducting field studies, the motion profile that represents the ideal nauseogenic wave form is boat/ship movements with regards to Hz.

Another way of experimentally provoking motion sickness is to use an optokinetic drum, which provides a type 2 conflict according to Reason and Brand [3]. The optokinetic drum has effectively been used in a number of studies [37-41]. The optokinetic drum can create a sensation of self-movement, i.e.,vection, although the participant is sitting/standing still. Further provocation can be made by having the participant rotating in the opposite direction, sitting on a chair, and/or performing head movements. The stripes painted on the inside of the drum also give rise to nystagmus [42]. Normally, the optokinetic drum has a range in width between 100 cm up to an entire rotating room, but the ones used when sitting on a chair in the middle of the drum, typically will have a diameter between 100 cm to 150 cm. The striped cloth is usually black and white and long enough to cover the entire visual field of the participant sitting in the centre of the drum. No visual references should be given to the environment outside the drum; therefore, the floor and ceiling are covered with a black cloth.

Recently, virtual environments have also become popular in training and entertainment, but they are at the same time reported to create, what is referred to as, simulator sickness [12, 43]. Symptoms of simulator sickness are similar to the ones perceived in any other moving or illusory moving environments, although there are reports of increased drowsiness, pallor, sweating and increased salivation rather than genuine illness and vomiting in simulator sickness [44].

3.3 The sensory conflict theory and related theories

As mentioned, a theory that is widely accepted in explaining the origin of motion sickness was developed by Reason and Brand [3] from the original work of Claremont [45]. It describes two types of sensory rearrangements, the (a) visual-inertia and the (b) canal-otolith. The visual-inertia is described as including both the vestibular and the non-vestibular proprioceptors, while the canal-otolith occurs when the vision is absent. According to Reason and Brand [3], the relationship between these two types of sensory rearrangements can be affected in at least three ways (Table 1).

Table 1. Three ways in which sensory rearrangement can occur between visual-inertia (*a*) and canalolith (*b*) conflict [3].

Type 1:	<i>a</i> and <i>b</i> simultaneously signal contradictory or uncorrelated information.
Type 2:	<i>a</i> responds in absence of an expected confirmatory signal from <i>b</i> .
Type 3:	<i>b</i> responds in absence of an expected confirmatory signal from <i>a</i> .

As illustrated in Table 1, the sensory systems are dependent of each other and they also rely on functional vestibular nuclei. Reason and Brand also concluded that susceptibility to motion sickness is highly individual, but susceptibility can also be affected by frequently repeated exposure to similar motions. The sensory conflict theory does not answer the question of why motion sickness occurs, but makes an effort in trying to explain the motions that produce motion sickness. However, it states nothing about the relationship between these motions and the fact that it leads to emesis [4]. The sensory conflict theory gives us nothing on the evolutionary development of motion sickness or why, for that matter, we respond to the conflict with nausea and vomiting instead of any other physiological response.

One theory that tried to explain the evolutionary perspective of motion sickness and provided us with an answer to “why?” was developed by Treisman [46]. The sensory conflict theory supports Treisman’s theory. Not only does it provide us with an explanation to why motion sickness occurs, but it also attempts to explain the connection between vomiting and the vestibular system. Treisman identified four mechanisms that would prevent poison from getting in to the stomach. The first was rejection by taste, the second was vomiting provoked by effects on the stomach lining, the third was vomiting provoked by stimulation of appropriate chemoreceptors after absorption into the blood of some of the poison, and, lastly, vomiting provoked by a mechanism that responds to minimal physiological disturbances produced by any absorbed toxins. Moreover, Treisman described the continuous need for neural input from sensors such as the eyes, the vestibular system, and from our limbs, i.e., proprioception. Any disruption in this activity would constitute a perfect cause for what would be interpreted as physiological disturbance that could be produced by ingested toxins and, hence, result in vomiting. Unexpected movement or illusion of movement could be an example of such disruption. Treisman claimed that the trigger of motion sickness does not lie within the movement itself, but rather in the repeated attempts to maintain the relationship between what we see and our head movements, or between the head and body system, or in some cases both of them [46]. The theory is closely related to the sensory conflict theory, but does not consider past experience or expectations. Instead, it focuses on the present input situation, where sensory systems must work continuously in parallel.

Although most theories of motion sickness have originated from the sensory conflict theory, there are exceptions. In 1991, Riccio and Stoffregen presented an ecological theory of motion sickness and postural instability [47]. The ecological theory claims that no sensory conflict exists. Instead, it explains motion sickness as a result of a lost postural and stability control following prolonged instability. They concluded that motion sickness is not a result of the movement itself and/or our perception of it by our senses but rather related to behaviour. The theory gained little attention. Nevertheless, it highlights one of the most debated concerns in

motion sickness research, namely why only certain types of movement can give rise to motion sickness and not others. Bos, Bles and Groen [48] developed a theory based on the opposite of the ecological theory, which describes visually induced motion sickness. The subjective vertical mismatch theory takes its starting point in the fact that people only develop motion sickness when there is an apparent change in gravity to their head. These situations are characterised by a sensed vertical that constitutes of information from the eyes, the vestibular organ and the non-vestibular proprioceptors. This information is in variance with what we expect to perceive based on our individual past experiences. The theory is similar to the one described by Reason and Brand [3], but focuses on the discrepancy between the sensed and the expected vertical with regards to the position of the head.

Another theory, also relying on vision and eye movements as the primary source for the development of motion sickness, is the theory presented by Ebenholtz [49]. Ebenholtz claimed that nystagmus always follows as an initial autonomic response to movement or illusory movement exposure. This initial nystagmus stimulates the vestibular nucleus, which initiates a vagal response that eventually leads to emesis. Flanagan, May and Dobie [21] studied vection, postural instability, and eye movements and concluded that nystagmus played an important role in the elicitation of motion sickness.

3.3.1.1 The vestibular system

The vestibular system detects and controls the position of the head and registers any changes in position caused by motion [50]. The vestibular system provides the visual system with information by stabilizing the images projected on the retina. In each inner ear, there are identical sets of semicircular canals and otolith organs that constitute the vestibular organ. The semicircular canals are arranged in three planes and detect angular motion in three dimensions (anterior-, posterior-, and horizontal plane). When exposed to angular motion, the inertia of the endolymph fluid contained in the canals starts to move the small hair cells (cilia) attached inside the cupola. The bending of the cilia is the signal sent to the brain telling us that the head is moving [51]. The mechanical structure of the semicircular canals allows it to be receptive for angular accelerations >0.1 Hz.

The part of the vestibular organ that is responsible for detecting linear acceleration is the otolith organ, which is placed near the entrance of the semicircular canals, in the saccule and utricle. It consists of calcium carbonate crystals that rest on a gelatine material that also has cilia. When the body is exposed to linear or transient movement, the otoliths, due to inertia, move in the opposite direction, bending the cilia that signal linear motion to the brain. The otoliths serve as gravitational sensors and their frequency range for detection of movement is <0.1 Hz. Information from both the semicircular canals and the otoliths partly regulates muscle tension, helping us to maintain posture [52]. In the equilibrium centre in the vestibular nuclei, located in the brain stem, the information from the semicircular canals and the otoliths can be stored to prolong the endurance of motion exposure and also to help us adapt to lower motion frequencies. This storage is called the velocity storage mechanism and has in some motion sickness research proven to depend more on information from the otolith organs than on information from the semicircular canals [53, 54].

The vestibular organ constitutes one of the three essential parts that are involved in motion sickness. It has long been known that in order for motion sickness to occur a functional vestibular system is required [55] regardless of stimuli. This was also confirmed in 1929 by Sjöberg, who conducted studies on labyrinth function. People without a functioning vestibular apparatus withstood both caloric and rotational stimulation [56]. In the late 1940s, Tyler and

Bard presented three theoretical trends with regards to which vestibular receptors were involved in the development of motion sickness [25]. The first only involved the semicircular canals, the second only the utricle otoliths, and the third consisted of a combination of the semicircular canals and otolith organ. There is no debate on the fact that the vestibular system is a critical component in the development of motion sickness and that motion acts upon the vestibular receptors either through the eyes or directly onto the vestibular apparatus. From that activation, the vestibular system initiates a response that normally follows ingestion of toxins and triggers vomiting [4].

3.3.1.2 The visual system

As mentioned above, one of the three essential components of motion sickness theory is vision and, in a sense, what we expect to see [57]. What we see is often used as reference to what the other receptor organs tell us to expect, and if the vestibular organ tells us that we are exposed to movement of some kind, the visual system is used to verify this movement. The importance of the eyes in maintaining posture and balance is manifested by the vestibulo-ocular reflex (VOR). The VOR is a reflex that moves the eyes in the opposite direction of the head movement in order to stabilise images on the retina. The VOR does not depend on input from the eyes and works in the same way during darkness or when the eyes are closed [58]. The reflex plays a crucial role in the relationship between the vestibular system and the eyes, and thereby also in the development of motion sickness. Without a functional VOR, patients have problems stabilizing images on their retina when performing head movements [59]. One of the more common strategies for reducing symptoms of motion sickness is to close the eyes to reduce visual input that further enhances the conflict.

3.3.1.3 Proprioception

Our ability to sense posture and body position with our limbs is called proprioception. It constitutes the final part of the conflict theory that together with the vestibular system and vision make up the theory described by Reason and Brand [3]. Regardless of whether the movement of the body is consciously or unconsciously performed, the information from our sensory receptors is sent to the cerebellum, which is the primary centre for motor control and sensory perception [50]. Damage to nerve fibres at the receptor or somewhere along the way towards the cerebellum can cause problems in handling everyday activities, such as walking, standing, and holding things with your hands (i.e., impaired body functions [1]) depending on where the damage is located [60]. The cerebellum regulates posture and movements by functioning as a comparator between the intended movement and actual movement performance. The information concerning the intentional movement is called internal feedback and actual sensory information associated with the actual movement is referred to as external feedback stimulated by the environment [61].

3.4 International Classification of Functioning, Disability and Health (ICF)

As previously mentioned, motion sickness can be regarded as a state of impaired bodily functions that leads to reduced activity according to the International Classification of Functioning, Disability and Health (ICF) [1]. ICF is part of the international classifications developed by the World Health Organization (WHO). The ICF provides a standard language and framework for the description of health and health-related states. It is designed to be multidisciplinary and provide a scientific basis for understanding and studying health and its related states. The common language approach strives to improve communication between different health care professions, including scientists, policy makers and people with

disabilities. The ICF also facilitates comparison of data and provides a systematic coding scheme. The ICF content is organized into two parts: **functioning and disability (part 1)** and **contextual factors (part 2)**. Each of these two parts has two underlying components (Figure 1). For part 1, the components are **body functions and structures** and **activities and participation**. For part 2, the components are **environmental factors** and **personal factors**. Body functions can be both physiological and psychological and include the functions of the body systems. Applied to motion sickness, body functions and structures would represent the signs and symptoms as well as the different components described in the sensory conflict theory – vision, vestibular, and proprioception. Activity is described as the execution of a task or an action. In studies of motion sickness, this could be the performed task. Participation is the involvement in a life situation and could include the person’s ability to interact socially as part of a team. The two remaining components are environmental factors, described as the physical and social environments, in which we live. This could be referred to as the motion sickness inducing stimulus, either experimentally created or originated in real life. The final component in the ICF model is personal factors, which represents the individual and his/her different prerequisites. This component is not further classified in the ICF because of the large differences in social and cultural factors. When applied to motion sickness, personal factors can include susceptibility, previous experiences, and motivation.

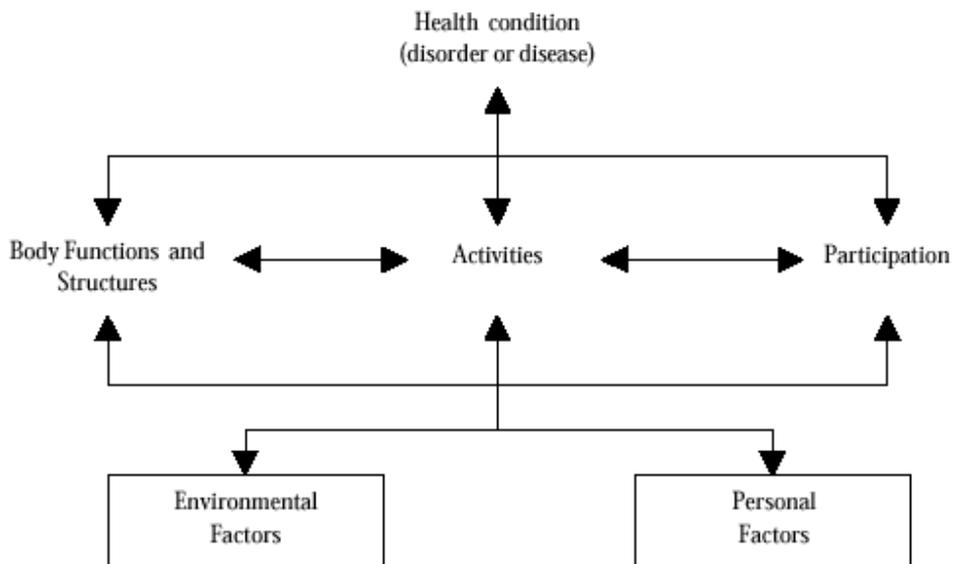


Figure 1. The different components in ICF and their interactions.

In this thesis, the ICF is presented to show that motion sickness can be translated into an existing terminology developed to provide a common language with regards to functioning, disability, and health. Furthermore, it can serve as a common ground for discussing motion sickness in relation to other physiological/health states using a common terminology. It also supports the findings in the studies included in this thesis with special focus on the final work (study IV). Being an environmental factor according to ICF, the sound based mitigation strategy used in Study IV intended to not affect the visual, vestibular, or proprioceptive systems. The idea was rather to make it function as an additional, hopefully over riding,

stimulus using a different modality not addressed in the sensory conflict theory. The intention was also to have it function subconsciously.

3.5 Cardinal signs and symptoms

As mentioned, vomiting, frequently associated with motion sickness, was often the focus of early research. However, when searching for signs and symptoms of motion sickness, many of the initial events take place where they cannot be observed by ocular inspection or even felt by the person affected. Therefore, it is important to discriminate between signs and symptoms of motion sickness, since signs do not necessarily have to be observable by the affected person, even during severe motion sickness. Signs of motion sickness should be observed by a person other than the affected person, e.g., a physician or a test leader. The most commonly described cardinal sign of motion sickness is pallor [62]. Symptoms, on the other hand, are observed and felt by the affected person and some of the more common symptoms of motion sickness are stomach awareness, sweating, nausea and vomiting [9, 62]. These signs and symptoms are commonly described as pathognomonic. Although many of the described signs and symptoms are detected during the early stages of motion sickness, the initial response to an unfamiliar motion or sensation of movement is not detectable by our perception or observable from the outside. The initial disturbance in the vestibular, visual or proprioceptive systems triggers a set of autonomic responses that, in turn, disturbs the balance in the autonomic nervous system (ANS) between the two subdivisions of the ANS, the sympathetic and parasympathetic nervous systems [63].

3.5.1 Psychophysiology of motion sickness

As a result of a sensory conflict, the ANS initiates a series of autonomic events that affect the balance between the sympathetic and parasympathetic nervous systems. The sympathetic nervous system is dominant when the body is in a state of alert. Its primary neurotransmitters are epinephrine and norepinephrine. The parasympathetic antagonist is acetylcholine. Although acetylcholine inhibits receptor organs, it has some sympathetic effect and can stimulate sweating [64]. The sympathetic nervous system antagonist is the parasympathetic nervous system, which is dominant in a state of relaxation. Under normal conditions, the balance between the two systems shifts and is dynamic [5]. The autonomic responses associated with motion sickness are not exclusive for motion sickness triggering stimuli. In fact, they are similar to general arousal and stress responses. Under the influence of real or apparent motion, the body prepares by releasing epinephrine and norepinephrine, neurotransmitters that act on the sympathetic nervous system. Persons who are susceptible to motion sickness will most likely develop signs and symptoms quickly. This initial, subliminal response puts the body in a state of sympathetic arousal and is often not observable, which makes it hard to categorize as sign or symptom. The reason for this difficulty is that the initial sympathetic arousal can best be traced by measuring the result of vasoconstriction, which initially is not detected on a cognitive level. Although most people develop motion sickness symptoms, given the right prerequisites with regards to both physical and environmental factors, the end criterion does not necessarily have to be nausea or vomiting. The sopite syndrome – generally characterized by mood changes, lethargy, drowsiness and unwillingness to perform and participate associated with exposure to movement – is a state described as distinct from motion sickness [65]. Lawson and Mead [66] refer to a number of features that highlight the importance of the sopite syndrome, which further manifests its distinction from motion sickness. For example, the sopite syndrome is often observed during prolonged motion exposure and is persistent long after nausea has subsided. In order for the sopite syndrome to occur, a strong stimulus is not needed and reports show that symptoms

associated with the sopite syndrome were apparent after just 15 minutes during exposure to relatively non-nauseogenic stimuli in a controlled laboratory setting [67].

In the following sections, I describe some of the most common psychophysiological responses that are associated with motion sickness, how they respond to motion stimuli, and how these measurements are registered. Psychophysiological responses associated with motion sickness are numerous and different studies use different measurements in their attempts to find correlations between autonomic responses [62]. The autonomic similarities with other types of stress reactions and closely related responses further complicate the issue. According to the components of the ICF, the following psychophysiological responses can be labelled as body functions and structures [1].

3.5.1.1 Psychophysiology measurements used in this thesis

Cold sweating and skin conductance

Hemingway describes cold sweating as a phenomenon that occurs in the absence of an adequate thermal stimulus [68]. There are two types of sweat glands in the skin, the apocrine and the eccrine [64]. The apocrine glands are found in the genital areas and armpits. The eccrine are the ones most studied in psychophysiology and are distributed practically all over the body. The palmar surface, fingers and forehead are mostly used for studying electrodermal activity and it is estimated that the palm contains about 3,000 sweat glands [5]. As previously mentioned, the sympathetic neurotransmitters are norepinephrine and epinephrine. However, the eccrine sweat glands have a nerve supply from cholinergic fibres that produce acetylcholine activated by sympathetic functions. In contrast to thermal sweating over the rest of the body, sweating from palmar and plantar regions are generally thought to occur due to psychological stimulation [62]. When studying motion sickness, electrodermal activity is used to register relative changes in comparison to baseline measurement of sweating. Previous research shows that sweating increases as a result of motion sickness [8, 15, 69, 70]. There are two ways of studying sweat activity that may appear confusing at first. As stated above, there is no reason to think that sweating would decrease as a result of motion sickness. However, this may be measured either by studying skin resistance or skin conductance [64]. Skin resistance decreases as the participants' sweating increases, since the resistance on the skin surface, the epidermis, provides less friction. Skin conductance provides a measurement of how much the participant is sweating by measuring skin potential between two electrodes. The more the participant sweats, the higher the value. However, galvanic response has a great interindividual difference regardless of stimulus and susceptibility, which makes group comparisons difficult. When measuring electrodermal activity, distinctions are made between tonic and phasic responses. The quick stimuli response reactions in electrodermal activity are termed phasic responses, whereas the slow and stable responses over time are labelled tonic responses. The initial reaction to a motion stimulus or unfamiliar environment will result in a phasic reaction and then level out in a more tonic development. However, if the participant is presented with tasks or different movements, phasic reactions could instead occur [5]. Cold sweating cannot be a single measurement of motion sickness, but rather be viewed as a spontaneous electrodermal activity that follows the initial sympathetic activation. Therefore, cold sweating should be considered as an initial phasic arousal.

Skin conductance can be measured from different locations on the skin using the same technique [64]. There are debates regarding the optimal locations for recording electrodermal activity on the body. Some researchers prefer using the palmar sites [9, 69], while others prefer the forehead [11, 15]. The primary question is where on the body galvanic response,

which follows as a result of motion sickness, may best be recorded and differentiated from general arousal, thermal sweating, or other conditions. Another important issue is the degree of arousal the measurement itself induces. A participant coming to a laboratory environment is likely to respond more easily to any stimuli, especially if the participant is aware of the fact that the stimulation is nauseogenic.

Heart rate

Heart rate, a measurement of cardiac activity, can be used for studying physical activity. Heart rate is also of great interest to scientists when studying psychophysiology and autonomic activity [71]. Cardiac activity can be analyzed in many different ways and calculation of heart rate is one of them. Heart rate is simply calculated by counting the average number of beats within a time frame, e.g., beats per minute (BPM) [72]. The average beat is derived from the R waves, found in the P, Q, R, S, and T complex that represent a single heart beat (Figure 2). The Q, R, and S wave symbolises the ventricular depolarization and completion of the cardiac cycle.

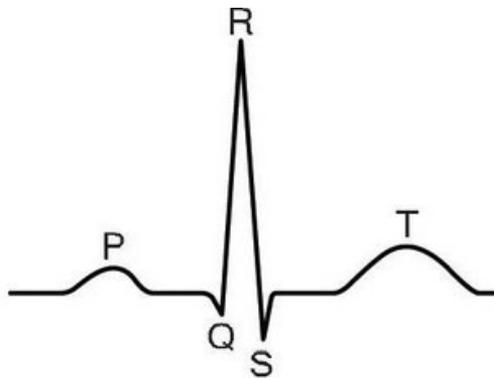


Figure 2. Heartbeat consisting of both diastolic (P-R) and systolic period (S-T). The systolic phase is referred to as the contraction phase of the heart and the diastole, the relaxation phase.

Other measurements of cardiac activity include power spectrum analysis (Fast Fourier Transform analysis) that studies the heart activity with regards to its dominant frequency range. Spectral analysis is often used to isolate heart rate variation in the respiratory frequencies. Low and medium frequencies are associated with mainly sympathetic activity and non-neural cardiac activity. The high frequencies are mostly associated with parasympathetic activity. The low frequencies are found within the range of 0.04-0.15 Hz and the high frequencies within 0.15-0.40 Hz [73]. Some studies identify a third frequency level that refers to the very low regions from 0.04 Hz and below. Very low frequencies have been associated with, for example, thermoregulation and changes in mental states [73]. Another commonly used Heart Rate Variability (HRV) measure is RR-variability, which reflects the variability in distance between the R waves: a longer distance between the R waves indicates slower heart rate and vice versa. Cardiac activity can then be analysed to see how heart rate has changed over time [72].

Respiration has an effect on heart rate through the respiratory sinus arrhythmia (RSA). The RSA is a natural fluctuation in heart rate that occurs as an effect of breathing rhythm, and heart rate increases during inspiration and decreases during expiration [71]. On the electrocardiogram, the RSA can be seen in the R-R interval. The distance between the R waves increases during expiration and shortens during inspiration. In motion sickness

research, heart rate over time [9, 74-76] and power spectrum analysis [12, 70, 77, 78] is commonly used to reflect autonomic activity.

Cardiac activity is measured using electrodes placed on the chest or on the limbs. The electrodes are arranged differently depending on the purpose of the study [71]. When measuring cardiac activity, the electrodes have to be placed so the current that registers the heart beat goes across the heart. During motion sickness, heart rate usually increases as a sympathetic response and its magnitude depends on susceptibility and duration of the stimulus [9]. The largest increase is found initially, just after start of exposure, in an experimental situation. During exposure, the development varies and susceptible participants normally have a steady increase along with increased feelings of nausea [17, 62]. Towards the end point and during severe nausea, heart rate increases.

Peripheral blood flow

Peripheral blood flow, also referred to as blood volume pulse (BVP), is a measurement of vasoconstriction and dilation as a result of autonomic nervous system activity. When the body is in a state of sympathetic arousal, the blood flow in the peripheral parts of the body resigns as a result of vasoconstriction [5]. When the parasympathetic nervous system activity increases, the blood vessels dilate again, letting more blood pass through to the peripheral parts of the body. The BVP is sensitive to general changes in cardiac activity and blood pressure levels, which also complicates the measurement with regards to activity [5]. Normally, measurement of BVP is obtained using plethysmography, a method that measures the blood concentration in the fingers or feet [5]. The most common method is to use a photoelectric transducer that measures the amount of blood in the tissue by registering changes in light intensity that passes through a segment. Studies have also been made trying to detect blood flow changes using heat cameras [79]. This approach has proven to be contextually difficult and sensitive to the surrounding environment. Regardless of measuring equipment, the problem is the amount of measurement noise and artefacts created by movement of the measured body part. The unit used for reporting changes in blood volume when using a photoelectric plethysmography is arbitrary and only relative changes over time are reported, usually compared to a baseline period [5].

When studying motion sickness, measurements of BVP are used to detect blood concentration as a result of a sympathetic arousal that normally initiates the psychophysiological response associated with motion sickness [9, 62]. Over time, the BVP response changes and there is some evidence that as motion sickness progresses, BVP drops as a result of a sympathetic domination [80]. Normally, when the participant initially is exposed to an experimental setting, there is a natural sympathetic arousal that makes it difficult to discriminate between a normal state and the state induced by the movement. Furthermore, this arousal complicates the development of the BVP response, since it requires a baseline period to reach representative levels before any change can be observed as a result of a stimulus. The BVP response has a large inter-individual variability and is also context dependent [9].

Skin temperature

Skin temperature is, in contrast to core body temperature, a measurement of temperature at the volar surface of the skin. The core temperature of the body is a more valid measurement of body temperature, but it is more complex to measure from an ethical or procedural perspective. Changes in core temperature are normally small and difficult to assign to any specific stimulus.

Skin temperature is normally measured by using a thermometer placed on the skin surface either on the hand, forehead or feet [8]. Similar to the BVP response, skin temperature is studied as change over time, but reported in degrees Celsius or Fahrenheit. The skin temperature is closely related to electrodermal activity and sensitive to environmental factors like ambient temperature [81].

Motion sickness is normally indicated by an elevation in skin temperature [82]. However, some studies have reported decreases in temperature during motion sickness [83]. Since temperature is affected by electrodermal activity, it is also affected by what is referred to as cold sweating.

Respiration

Within psychophysiological research, breathing (i.e., respiration) is studied in conditions where the participant is not under the influence of a physical activity. Normally, an adult uses breathes 12-20 times per minute [84]. Breathing is affected by cardiac activity, as previously mentioned, and when calculating heart rate variability, paced breathing is preferred, since breathing gives rise to respiratory sinus arrhythmia (RSA). Normally, measuring respiration is done through use of a strain gauge that measures chest expansion and respiration rate. The strain is located around the chest and gives a metric value for the chest expansion that can be used to study respiration over time and also to discriminate between different types of breathing, such as slow, fast, or deep breathing [84]. A spirometer measures lung volume and is attached to the mouth. This device is somewhat awkward and prevents the participant from behaving naturally. When measuring respiration responses to a stimulus, two factors are reported to contribute to the quality of the data: the apparatus and the instructions given to the participant [85]. Instructions to the participant on how to breathe often result in an abnormal type of respiration that gives rise to arrhythmic and irregular breathing patterns. Because of the sensitivity and bias in measuring breathing, its use in psychophysiological research is questioned and the many confounders further complicates the detection of autonomic or central nervous system responses [85]. Despite the complexity, respiration is often used as a measurement of autonomic activity in response to motion stimulus [9, 12, 76]. The occurrence of motion sickness symptoms initially increases respiration rate. Furthermore, between the elevated initial response and end criteria, the respiration rate is reported to decrease, but then again it usually increases during vomiting [9]. It has been reported that motion sickness can give rise to hyperventilation and since increased CO₂ in the blood affects the vomiting reflex, an increase in the respiratory circle could prevent nausea and decrease CO₂ levels [86].

Eye movements

Eye movements, or more specifically fixations, are a primary source in the development of motion sickness according to the sensory conflict theory [3, 21]. The eyes, being part of the visual system, are a central component in maintaining balance and when the head moves, the vestibulo ocular reflex (VOR) moves the eyes in the opposite direction to the head [87]. Eye movements can be divided into saccades, micro saccades, tremor and drift. Fixations include tremor and drift [88]. Saccades are what we normally would refer to as eye movements and are ballistic movements between 20 ms to 150 ms, with a velocity up to 800°/sec [89]. The saccades are accompanied by micro saccades that last about 25 ms. Through this process, pictures are projected onto the fovea. When fixating an object, the eye is keeping the picture and processing it by tremor and drift. Tremor is small eye movements from the muscles holding the eye with a magnitude of about 0.005°, and drift is small adjustments with a magnitude of 0.08°. Fixations are normally dependent on the cognitive processing time and varies from about 80 ms up to 500 ms [88, 90]. When studying eye movements, the purpose is

often to determinate how long a person is viewing a certain object [88]. This is done by studying fixations, not saccades, since virtually no information can be obtained during saccades [91].

Studies of eye movements or fixations are primarily done with the use of an eye tracker that consists of an eye camera that catches the eye movements and characteristics of the eye, and a scene camera that captures the environment in front of the person. These two images are then connected through a calibration process and results in a video either with cross hairs superimposed or coordinates of the eye superimposed as well as eye physiology data [20]. Most eye trackers also provide data on pupil size, blink frequency, velocity, drift and tremor [92]. Analysis of eye-tracking data can be very time consuming if the purpose of the study is to know where a participant is focusing his/her attention. Each time frame/fixation has to be analyzed separately and manually to obtain valid data. When analyzing eye-tracking data, it is important to know which fixation identification algorithms are used to compare results and for validity and reliability reasons [93]. The three main techniques that are used to identify fixations are velocity, area, or dispersion based [93]. Velocity based algorithms use velocity of successive data points to separate fixations from saccades. Since fixations are slow and saccades are fast, the algorithm compares distance between data points. Area based algorithms identify fixations within a specific area and cannot locate fixations within the visual field of view. Only a predefined area, i.e., an area of interest, can be analyzed and within that area everything is considered being fixations, hence, also saccades. The dispersion based algorithm is based on the simple fact that fixation points are clustered closer together than saccades [88]. Using this dispersion-based algorithm introduces another problem: how to optimize the dispersion-based algorithm so that it includes both micro-saccades and drift, i.e., correcting the initial landing position and the very last fixation position. Using one of the two dispersion-based methods can compensate for initial landing position and last fixation position errors: start-point mode or centroid mode (Figure 3) [94].

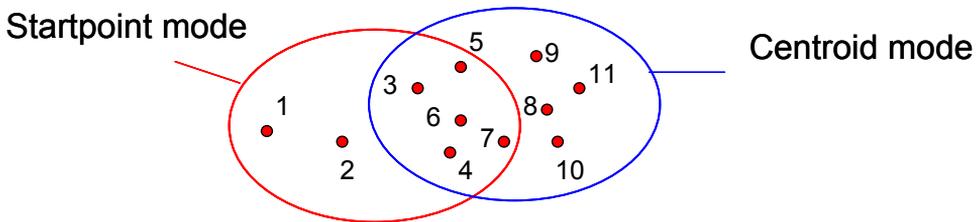


Figure 3. The two dispersion based methods: Start-point mode and centroid mode (numbers indicate fixation points from landing position 1).

The start-point mode is based on the first position of the eye and calculates the maximum dispersion from that point, i.e., the landing position. The centroid mode uses a weighted position that allows for the human eye to first land close to the object of interest and then for micro saccades to adjust the eye to the object that we want to fixate. The fixations in this case would only consist of those data points that follow the adjustments made after the eyes landing position. Unfortunately, it is rarely reported which of the two dispersion-based algorithms are used: each method produces different results.

The human eye responds to changes in autonomic activity, primarily to the parasympathetic nervous system (PNS) through the third cranial nerve. The PNS acts on the pupil by constriction, while the sympathetic nervous system's (SNS) dominance results in dilatation of

the pupil [5]. Motion sickness is influenced more by central/foveal vision rather than peripheral vision, which, in turn, has more influence on vection [42, 95]. Since vision is a primary component in the development of motion sickness, according to the sensory conflict theory [3], one of the strategies to reduce symptoms of motion sickness is to reduce visual input [96], eliminating one of the potential sources of conflict.

3.5.1.2 Psychophysiology measurements not used in this thesis

Pallor

Facial pallor, a symptom usually perceived as cold sweating, is one of the most obvious initial signs of motion sickness. Pallor is the result of a parasympathetic withdrawal and the vasoconstriction associated with it. The neurotransmitter norepinephrine is released by the sympathetic system acts on the smooth muscle tissues of the blood vessels [5]. Blood is concentrated to the central body organs and withdrawn from the limbs. Facial pallor is most common. However, pallor can also be observed on the hands and feet. Measurement of pallor can be made through the use of both subjective techniques like visual observation and by infrared reflectance plethysmographic techniques that measures blood concentration non-invasively by studying colour changes [62]. Measurement of pallor is sensitive to factors such as the environment the participant is monitored in, e.g., the environment's temperature. Facial pallor is often present during the entire state of motion sickness and subsides as a result of vasodilatation and increased parasympathetic activity.

Gastric activity

Gastric activity is a measurement of intestinal movement through electrogastrography. It can also be measured by subjective reports [62]. Under normal conditions, the gastric smooth muscle activity is controlled by the autonomic nervous system and oscillates around a frequency of 0.05 Hz (3 cycles/minute) [97]. People are sensitive to gastric change and can subjectively report stomach discomfort on a subtle level. When exposed to a motion sickness triggering stimulus, gastric activity resigns and as a result of an autonomic nervous system response, the pylorus is closed, indicating that no content can pass through to the duodenum. It has long been known that situations involving fear, swinging/rotation of the head and caloric stimulation inhibited tachygastria and, in some occasions, shut down gastric motility completely and even provoked nausea [98].

When using electrogastrography to study gastric activity, electrodes are placed on the stomach surface, i.e., non-invasively. The electrogastrogram is sensitive to motions and physical activity because of the abdominal muscles that are found between the electrodes and the intestine. Any movement of the muscles in the abdominal region will appear as an artefact on the electrogastrogram and complicate the analysis [97]. The result of the electrogastrogram is a frequency spectrum that shows tachygastria change. In motion sickness research, electrogastrogram are often used together with other autonomic measurements and self-reported symptoms [44, 63, 99, 100]. Previous research has shown relations between tachygastria and subjective reports of motion sickness [44].

3.6 Subjective measurements of motion sickness

No matter how sophisticated psychophysiological measuring equipment is, motion sickness has to be perceived and reported by the participant to verify that the outcome of the motion sickness triggering stimuli is the intended, namely motion sickness. If the participant show autonomic activity that is in accordance with what can be expected as motion sickness develops, but reports none, then it cannot be ruled out that something else is going on. In an

experimental situation where the participant is aware of the fact that he/she will be made motion sick, expectations can easily trigger feelings of stress that further complicates the interpretations of the dependent variables. Young, Adelstein and Ellis [101] asked whether the fact that the participant took a motion sickness questionnaire actually made him/her motion sick. Results from this study indicated that participants got sicker if questionnaires were administered before motion sickness inducing tests rather than after.

There are numerous subjective reporting tools that can be used to assess motion sickness symptoms. The most commonly used are The Pensacola Motion Sickness Questionnaire (MSQ) [102] and the Graybiel malaise score [103]. Different scales are used for different purposes and some are used to screen and detect previous experiences and obtain a susceptibility score, while others are used to collect dynamic changes during motion exposure. All these questionnaires and subjective reporting scales presuppose that the participant associate the perceived state with what he/she would normally describe as motion sickness. If, however, the experimental situation is obvious and the participant is aware that he/she can get motion sick, they will be prone to look for that and disregard other states that normally could be due to stress or some other factor. There is always a trade-off between how many questions are needed and how specific they should be in order to obtain a valid measure of the participants' perceived state. When studying motion sickness, the experimental context usually involves stimulus directed either towards the vestibular organ, vision, proprioception or any combination of them. Keeping in mind that symptoms of motion sickness can further be triggered by confounding variables in the environment, it is of great importance to consider how the subjective states are reported and how much effort is required from the participant. One less commonly used rating scale in motion sickness research is the Borg scale [104]. The Borg scale is a verbally levelled-anchored ratio scale, also known as a category rating scale, that consists of verbal anchors that help the participant to determine the level not only by using numbers, but numbers connected to words as shown in Figure 4.

●	Absolute maximum
10	Extremely strong
9	
8	
7	Very strong
6	
5	Strong
4	
3	Moderate
2	Weak
1	Very weak
0.5	Extremely weak
0	Nothing at all

Figure 4. The Borg CR 10 rating scale.

Different ratings scales target different parts of the perceived motion sickness phenomenon and are thus different with regards to extensiveness. Furthermore, ratings of single

physiological responses during exposure require more from the participant than ratings of general psychological states; i.e., the participant has to make distinctions between different physiological responses.

Screening questionnaires are often used to obtain a measurement of a participant's individual susceptibility to motion sickness triggering environments. One of the first and still commonly used is the Reason and Brand MSSQ (Motion sickness susceptibility questionnaires) [3] that covers both history of exposure, specific environments and the extent of the symptoms. More recently, the MSSQ has repeatedly been modified by Golding [105, 106] into both a longer, more specific version and a shorter version. The Graybiel [107] malaise score is used to measure motion sickness during exposure to motion or shortly after. The malaise score consists of ratings on numerous psychophysiological variables, e.g., stomach awareness, dizziness and cold sweating. From the ratings on each variable as slight, moderate or severe, a malaise score is calculated. The Graybiel questionnaire is also available in a more extensive version in which a modified version of the MSQ is included together with pre-experimentation questions regarding physical fitness, etc.

It has been argued that two ways of predicting motion sickness susceptibility are either to use a screening questionnaire or to pre-test susceptibility to a standardized stimulus [108].

3.7 Motion sickness and performance

It is not difficult to realise that the ability to perform anything will be affected by motion sickness when it involves vomiting and stages of severe nausea. Working in a moving environment is usually associated with performing a task – physical, intellectual, or both. Performance in previous literature is measured in cognitive, perceptual, or motor activities [109]. For those that are transported without having to perform anything, the motion may result more in physical performance defects than mental defects, since they, at least, can devote their attention to mitigating the effects of motion sickness. At the same time, it is hard to maintain posture and balance when exposed to a moving environment [110, 111]. Whether decrements in performance is due to motion sickness, the movement itself or just lack of motivation is still a matter of debate [109].

Previously, performance was assigned to the activity component of the ICF [1]. Being under the influence of motion sickness can eventually impair activity as a result of either impaired body functions or due to personal factors. If effects on performance are due to motivational factors or previous experiences, they can be referred to as personal factors. However, if the development of the psychophysiological responses are large enough and affects the ability to perform, the relationship between body functions and activities will be in focus.

Examples of environments in which performance is crucial are military command and control environments, land-based or sea-based onboard moving platforms, e.g., boats, trains, airplanes and land vehicles. Much of the previous research on performance as a result of motion sickness has been performed in controlled laboratory settings and only relatively few studies are performed in real life settings, e.g. [109]. Susceptibility and adaptation to motion sickness symptoms are crucial for how much performance will be affected. When studying performance under the influence of motion sickness, it is important to discriminate between whether the performed task is over learned or novel to the participant [112]. In the case of a novel task being performed, more cognitive, perceptual, or motor activity is required, which leaves less resource to handling the motion sickness symptoms. The novel case situation is also expected to include learning effects, but has the advantage that participants share, more

or less, the same performance level, at least initially. Studying motion sickness using over learned performance tasks requires less activity from the participant and allows more attention to be devoted to handling the motion sickness symptoms. Two of my first studies, not included in this thesis, used shooting accuracy as a performance measurement [18, 19] after transportation in enclosed land-based vehicles and sea vessels. Shooting was a task performed by the participants on daily basis and although experiencing symptoms of motion sickness in both studies, little or no effects on performance were observed.

Previous research also shows that evaluating performance peak is difficult when tasks are complex and when sustained performance is required over a longer time [110]. The same results also indicate that performance decreased when participants were given the possibility to control their own working phase. These findings could, as stated by the authors, be interpreted as lack of motivation due to the perceived motion sickness rather than reduction in performance capacity [113, 114]. Furthermore, Gal [115] observed that the participants who were affected by motion sickness during sea trials were not necessarily the ones that performed worse. He further concluded that the participants' ability to cope with the symptoms was a far better predictor than motion sickness per se. Gal's studies focused on coping and control strategies, which he tried to establish using motion sickness history questionnaires and subjective reports.

Few studies have studied the differences in performance between men and women. However, Levine and Stern found that women performed worse than men when exposed to motion sickness triggering stimulus during a spatial performance task [116].

Since humans have started exploring space, reports of motion sickness have reached between 60-80% of the first time flyers [33]. Normally, the symptoms reside within 2-3 days, but during that time, no extra vehicular activities are performed. Since performance is crucial in space, symptoms are normally reduced by administration of drugs [117]. Cowings et al. showed that small doses of Promethazine reduced cognitive performance capability. Studies in space have also showed that perception of time and reaction time were impaired during space travel [118]. The same results also showed a correlation between longer reaction time and motion sickness severity.

Effects of drugs on performance and perceived motion sickness also include increased fatigue and tiredness following drug administration [117]. This further highlights the need for motion sickness mitigation strategies that do not affect the physiological ability to perform irrespective of motion sickness. Enduring motion sickness on a normal basis does not include strategies like biofeedback and autonomic control. Attempts have been made trying to support postural control by means of sound impulses [119], which reduced postural sway in a standing condition. Furthermore, there have been attempts to reduce motion sickness by visually aided cues [120-122] that reduced both postural sway and perceived motion sickness compared to no visual cues. The operational use of such aids requires dedicated attention from the participant that in many cases would reduce other necessary operational performance. The use of alternative methods for reducing symptoms of motion sickness and performance decrements should therefore be focused on acquiring as little attention as possible of the participant.

Despite the number of studies devoted to finding both effects on performance due to motion sickness and methods to obtain a reliable performance measurements, concerns are raised that the different attempts using different instruments will further complicate comparability [109].

Baker [123] concluded that if motion sickness and exposure to motion stimuli give rise to decline in performance, the participant will successively gain ability to perform during exposure, depending on adaptability and learning effects. Furthermore, Baker points at the fact that few studies have explored after effects of motion sickness on performance following motion exposure. He claims that motion sickness resides at an individual phase and that the potential effects on performance disappear quickly after removal of the triggering stimuli.

Since most studies of motion sickness are conducted in laboratory settings, the performance tasks are usually constructed to represent ecologically valid tasks performed in a working context. Furthermore, since vision is a major part of the motion sickness aetiology, it is difficult to use that sense when studying performance deficits due to motion sickness. Many of the triggering stimuli used depend on vision and therefore cognitive tasks such as decision making and memory performance are more easily administered and provide better measurements of motion sickness effects on performance. Field studies, or experimental situations where no movement restrictions exist, are suitable to study motor activity under the influence of motion sickness. Using cognitive performance tasks also makes it easy to introduce novel tasks to participants and thus to obtain results that are normally difficult to obtain unaffected by previous experiences and skills.

3.8 Motion sickness and personal factors

As mentioned above, personal factors are a major contributor to how the participant will react to the motion sickness triggering stimulus, i.e., the environmental factors according to ICF. Personal factors include abilities such as adaptation and susceptibility, but also sex, age, health condition, fitness, coping styles, etc. [1]. However, if the participant has a physical condition, e.g., vestibular defect, it is ascribed to body functions and structures rather than as a personal factor. In the following two sections, adaptation and susceptibility will be described as part of personal factors.

3.8.1 Adaptation

Adaptation to motion sickness usually occurs within 48 hours, if the person is continuously exposed [124] and medicated [125]. People who are continuously exposed for such a long time include people on boats, long distance trains, or travelling in space. When undergoing a de-sensibilization or an adaptation program to eliminate signs and symptoms of motion sickness, adaptation is usually achieved by repeated exposures separated by a day or two [126]. Although the sensation of motion sickness is reduced as the person adapts, the initial autonomic psychophysiological response is activated but not as much as during previous exposures [87]. However, the adapted state is not persistent. If the participant is absent from the motion that he/she has adapted to for some time, re-adaptation is required [126]. This re-adaptation process usually requires less time than first-time adaptation. Furthermore, a study using controlled breathing during repeated exposure proved to reduce symptoms of perceived motion sickness and the adaptation time [127]. More recently, the ability to habituate the velocity storage has also provided further understanding of the phenomena of susceptibility and adaptation, especially regarding time of the adaptation process [53, 128].

Another, more exclusive way to adapt to motion sickness provoking environments is biofeedback training [129]. This method has been used primarily by NASA to train astronauts to control their autonomic responses in preparation for zero gravity. Successful biofeedback training teaches the participant to identify his/her primary autonomic response and how to increase or decrease single autonomic responses [129, 130].

3.8.1.1 Susceptibility

Individual differences to motion sickness are mostly due to susceptibility, the ability to adapt, and expectations. Furthermore, differences in age, sex and use of medication affect the individual susceptibility. Women are more sensitive to developing motion sickness than men, especially during pregnancy or menstruation [131]. However, there is no consensus regarding the effect of sex on motion sickness symptoms [132]. Children are believed to be resistant to symptoms before the age of two because the vestibular organ is not fully developed [133]. However, susceptibility is considered to be worst from around five years up to puberty [126]. Motion sickness among older people is said to be less frequent due to different factors. Older people are less active and thereby are not exposed to conflicting situations during travelling as frequently as younger people. Furthermore, there are possible changes in sensitivity of the vestibular organ that could contribute [131]. With regards to susceptibility, there are studies that have looked at genetic components of motion sickness based on the fact that certain monkeys have shown resistant behaviour to stimulus that triggers motion sickness [134].

3.9 Thesis rationale

Although a considerable amount of research has focused on motion sickness, a more ‘combined’ perspective is needed. That is, motion sickness studies should include early stages as well as the entire development towards emesis. Furthermore, little research has been devoted to studying effects of motion sickness on cognitive performance that is relevant when working in moving environments. Motion sickness affects activity and/or performance either through motivational, postural, physiological or cognitive processes. The importance of studying these processes from early detection to emesis is indeed obvious and, hence, a focus on cognitive abilities – e.g., short-term memory and encoding and retrieval processes – with regards to performance may be of interest since they are both challenged as part of task solving in high performance profession duties in moving environments. Previous research has shown that motion sickness can be studied using both psychophysiological recordings and subjective reports, either separately or in combination. The context and research questions determine which measurements are chosen but, based on many of the studies performed in military domains and other high performance complex environments, one should strive to obtain both objective and subjective data.

Psychophysiological research on motion sickness has not identified the autonomic responses/psychophysiological parameters that constitute a single or combined predictor for motion sickness susceptibility or course of development. Individual variations and different response magnitudes have proven too large, and, combined with methodological difficulties, obtaining valid and reliable measurements in both applied and experimental conditions is hard. To further develop the methodology of measuring psychophysiological responses, possible changes in fixations as a result of motion sickness is of importance. Since one of the key strategies to mitigate symptoms of motion sickness is to reduce visual input, it can be assumed that this can occur both on a conscious and subconscious level. When studying the literature on fixation generation, methodological issues arise that complicate the decision of which method to use for identification of fixations from eye-tracking data. The major concern in using a dispersion-based algorithm to generate fixations is choosing between a centroid or a start point mode approach (further described in section 3.5.1.1). Before any collection of eye-tracking data recorded during motion sickness, it has to be determined which of the two approaches that would best generate fixations. The question may appear trivial, but when studying fixations and eye characteristics during motion sickness, accurate methods are called for since small differences can make a great change to the course of development of motion

sickness. Considering these small changes, it is of great importance that only valid fixations are included in the analysis and not saccades, blinks, etc. This issue remains to be solved.

The relatively limited research within the area of motion sickness and its effects on cognitive performance, i.e., short-term memory and encoding and retrieval, encourage looking for effects on performance with regards to both exposure time and susceptibility to symptoms. The reason for studying both short-term memory and encoding and retrieval is that both are representative for tasks that are performed in operative environments. Information and tasks performed there usually include using both short-term and long-term memory. The latter may be tested as encoding and retrieval performance. Screening for susceptibility is mostly done using pre-screening questionnaires and/or in a stimulus response trial. However, the questionnaires are still based on subjective ratings of previously perceived experiences and can be misleading. Having a participant perform a pre-test run in, for example, an optokinetic drum or something similar also produces possible adaptation effects, further confounding the results.

It can be assumed that many of the precautionary actions taken to reduce the impact of motion sickness are pharmacological, an assumption confirmed by previous research. The most common side effects of medication against motion sickness are drowsiness, tiredness, and fatigue. It is also possible, partly based on my own experiences, that many of the tasks being performed in moving environments depend on time critical information and decision-making. This would mean that short-term memory performance constitutes a major part of how well a participant would perform in general. If under the influence of drugs, given the normal side effects, this participant's ability would not only suffer from lack of motivation and possible motion sickness, but perhaps from pharmacologically induced fatigue, factors that could all lead to cognitive latency.

Previous attempts to affect the occurrence of motion sickness using non-pharmacological methods have mainly consisted of visual aids and biofeedback. The common factor among those is that they require attention from the participant. When that attention is devoted to handling motion sickness symptoms, performance is likely to be negatively affected. However, by providing an artificial sound horizon, the intent is to create an audio reference that, in theory, could affect the participant at a subconscious level. Maintained ability, activity and performance are essential when exposed to motion sickness triggering environments. Although the use of a sound horizon is more of a conceptual idea at this stage, it opens up new possibilities to consider different modalities and alternative approaches to traditional pharmacological interventions.

4 Thesis purpose

The overall aim of this thesis is to study psychophysiological and performance aspects on motion sickness. The long term goal is to provide strategies for mitigation and prevention of motion sickness by identifying possible psychophysiological responses as predictors for both wellbeing and performance.

4.1 Study I

The aim of the first study was to compare and evaluate the two dispersion-based algorithms, the centroid mode and the start-point mode when analyzing eye-tracking data.

4.2 Study II

The second study aimed to investigate how motion sickness, triggered by an optokinetic drum, affects short-term memory performance and autonomic responses.

4.3 Study III

The aim of the third study was to investigate the impact of motion sickness on encoding and retrieval.

4.4 Study IV

The aim of the fourth and concluding study was to investigate the impact of a mitigation strategy for perceived motion sickness, based on an artificial sound horizon compared to a non-positioned sound source.

5 Material and methods

5.1 Study I

5.1.1 Design

Study I, a comparative study, examines two fixation identification algorithms used to generate fixations from eye-tracking data.

5.1.2 Participants

The raw data for the comparison of the two algorithms came from a random selection of eye-tracking data from 48 participants, comprising of 1,400 fixations.

5.1.3 Measurements and procedures

Eye-tracking data were collected using a head mounted eye tracker, iView X HED (SMI®), which included software. Eye movements were registered from the right eye, and the sampling frequency was 50 Hz. The in-house software [94] was a dispersion-based algorithm that used the text file generated by the eye tracker. The software generated fixations that had a minimum duration of 100 msec. and a maximal allowed separation within the group of fixation points that could be defined for the specific requirements. There are two ways of calculating dispersion in the pixels that depends on which viewing distance was used and if the participant was fixed to that viewing distance or not. In this case, the distance was fixed during the entire data collection. When this was done, fixations were identified by using both the start-point mode and centroid mode algorithms. The validation started by calculating the percentage of fixations with identical start and stop frames and different start and stop frames in both modes. By doing this, fixations could be categorized into four categories, a part from the three mentioned, also fixations with both different start and stop frames that could not be compared.

A **three step** procedure was used to compare the two dispersion based modes and subjective ratings were done manually frame by frame for both modes. In **step I**, two raters independently classified 50 randomly selected identical fixations to establish interrater reliability (IRR) and Kappa with $\alpha=0.05$. Each fixation, in each mode, was then either classified as “valid” or “not valid”, except for the unclassifiable ones. The raters made each classification without knowing which mode was used for each fixation. The following are criteria for “valid” and “not valid”:

“Valid”: From the result of the frame by frame video analysis, the raters subjectively assessed whether the suggested fixations in each mode were in accordance with the gaze symbol. This implied that the crosshair remained within the suggested fixation area. That, in turn, was based on the objects on which the viewer fixated.

“Not valid”: The crosshair moved from the object area during the suggested fixation duration. This implied that the position of the crosshair, relative to the object, showed no consistency with respect to what would make sense to fixate on that particular object.

In **step II**, the comparison of the two modes based on the scene camera video, with the superimposed crosshair, was carried out by four independent raters using the same assessment technique on the 1,400 fixations. Each suggested fixation was compared in both start-point and centroid mode. Additionally, the odds ratios were calculated.

5.1.4 Statistical analyses

Statistical tests were conducted using SPSS version 14.0 for Windows with the two-sided statistical significance level set at $\alpha = .05$.

Interrater reliability and Kappa statistics were used in step I to determine the relationship between the two independent raters. In **step III**, χ^2 statistics were used to analyze whether there were significant differences in distributions for the two modes.

5.1.5 Ethical considerations

Not applicable in this study.

5.2 Study II

5.2.1 Design

This study, an experimental laboratory study with a between group design, used an optokinetic drum.

5.2.2 Participants

The 38 healthy participants (17 male, mean age 26.8, range 20-43, and 21 female, mean age 23.6, range 20-31) were recruited through e-mail advertisement sent to students at the local university.

5.2.3 Measurements

Motion sickness was induced by a rotating optokinetic drum. The participant sat on a fixed chair placed so that their heads were in the centre of the drum. A verbally level-anchored ratio scale, the Borg CR 10 scale shown in Figure 4 [104], was used to obtain subjective ratings of perceived motion sickness once every minute during baseline and exposure period of the experiment. The Borg scale has previously been found to correlate well, i.e., $\rho > 0.8$ [135] with the Malaise score [107] on the symptom diagnostic scale. The question connected to the Borg CR 10 scale was “*[right now] what degree of motion sickness are you experiencing?*” The verbal short-term memory test used in this study was a modified/extended version of the Listening Span Test [136].

Heart rate (HR), skin conductance level (SCL), and blood volume pulse (BVP) were collected using the digital real-time monitoring system MobileMe (Biosentient Inc.). Pupil size was recorded by a ViewPoint EyeTracker[®] (Arrington Research Inc.) [92].

5.2.4 Procedures

The participants were instructed not to eat for 2-3 hours before start of the experiment. Intake of anti-motion sickness medications, anti-emetic medication, antihistamines or alcoholic beverages was not allowed within 24 hours before the experiment. This was checked for on a self-report basis.

After introducing the participant to the experimental procedure, background data were collected for each participant before mounting the measurement equipment. A set of practise sentences was given to each participant when they were seated in the drum before the start of the test. The test was initiated by a three-minute baseline period during which psychophysiological data were collected. The participant was also given two sets of sentences during the baseline period and motion sickness ratings were obtained once every minute. The Listening Span Test comprised of three-word sentences in Swedish that were read to the participant. After a set of three sentences, the participant was asked to repeat either the first or last word of each sentence in the order they were read. Percentage of correct recalled words per minute was used as the performance measure. The optokinetic drum rotated for a maximum of 25 minutes as sentences were read either for the entire 25 minutes or for as long as the participant endured. After termination, the drum was brought to a complete stop and the trial was over as soon as the participant exited the drum and the measuring equipment was removed.

5.2.5 Statistical analyses

Statistical tests were conducted using SPSS version 15.0 for Windows with the two-sided statistical significance level set at $\alpha = .05$.

The autonomic variables were one minute mean values of HR derived from Electrocardiogram (ECG), in addition to SCL, BVP, and pupil size. Short-term memory (STM) performance data, a percentage of correct responses, were collected every minute. Analyses were performed on data collected during the last minute of the Baseline, first minute of drum rotation (Start), last minute before termination (Stop), which was either after 25 min or when the participant requested termination, and one minute midway through each participant's test (Mid test). These sampling points are hereafter called time points. Differences from baseline were used for the statistical tests and these were calculated at the three time points during drum rotation (Start, Mid test, and Stop). Spearman's correlation test was used to test for possible correlations between perceived motion sickness, STM performance and autonomic responses at Baseline (except for pupil size), Start, Mid test and Stop.

Each variable was analyzed using a linear mixed regression model with the fixed factors time and group, i.e., non-termination (NT) versus termination (T) group, and participant was analyzed as a random factor. The division into each group was based on if the participant terminated the trial (T) before full time or not (NT). Baseline values were used as covariates in all analyses to control for differences between participants in baseline characteristics. For variables with one or both main effects (group and time) that were significant, the interaction effect group*time was added to the model.

5.2.6 Ethical considerations

Informed consent was obtained after the experimental procedures had been fully explained. The study design and procedures conformed to the declaration of Helsinki regarding ethical principles for medical research involving human participants.

5.3 Study III

5.3.1 Design

The third study, an experimental study that used a within subject design, induced motion sickness using an optokinetic drum.

5.3.2 Participants

The 40 participants were recruited among employees at Linköping University Hospital and through e-mail advertisement sent to all the medical students at Linköping University. Twenty were male (mean age 24.7, range: 19-49 years). The females' mean age was 25.6 (range: 20-51 years). According to self-reports before the experiment, all participants were healthy. No one had previously been exposed to an optokinetic drum.

5.3.3 Measurements

For perceived motion sickness ratings, the Borg scale was used once every minute. The performance task was a continuous recognition task (CRT) that studies encoding and retrieval capabilities, in this case, before, during, and after motion sickness. The CRT consists of three consecutive phases. It starts with encoding of familiar words, followed by encoding and retrieval of words during drum rotation, and, finally, a retrieval phase after drum exposure. The purpose of using the CRT was to investigate the ability to encode and recognize words presented during motion sickness. An initial questionnaire was completed before the experiment with questions regarding susceptibility to and previous experiences with motion sickness.

5.3.4 Procedures

The participants were instructed not to eat for 2-3 hours before start of the experiment. Intake of anti-motion sickness medications, anti-emetic medication, antihistamines or alcoholic beverages was not allowed within 24 hours before the experiment. This was checked for on a self-report basis.

Before starting the experiment, the test leader provided each participant with information about the experimental procedure. The participant was given verbal instructions to the CRT and was given the Borg rating scale explained as their tool for rating motion sickness. The CRT consists of three consecutive phases. It starts with encoding of familiar words, followed by encoding and retrieval of words during drum rotation, and a retrieval phase after drum exposure (Figure 5).

The test procedure started with the first encoding phase, where the participant was instructed to memorize 48 words (lists A1 and A2) presented on a computer screen outside the drum. Thereafter, the participant entered the optokinetic drum and sat down on a chair, finding a relaxed position. While sitting on the chair, the participant was given the instruction to keep the eye gaze straightforward and asked not to move during the experiment. The participant sat in the drum with eyes open for approximately five minutes before the motion sickness triggering exposure began as the drum started to rotate. Each word was shown for three seconds. When the participant first scored 2 or more on the Borg scale (corresponding to weak sensations of motion sickness), phase two of the CRT began and lasted for eight minutes. In the second phase, 96 words were presented to the participant and he/she responded "new" or "old" to each of these words. The wordlist comprised 48 new words (lists B1 and B2), 24 old words that were in the encoding wordlist (list A1), and 24 repetitions of

words from the 48 new words in this phase (list B1) that were now considered as “old”. Hence, the words in the B1 list were both encoded and retrieved during motion sickness. The recognition success for the A1 list was expected to reveal the ability to retrieve words during motion sickness.

After phase two of the CRT, the drum exposure continued for collection of physiology data, which will not be presented in this thesis. The optokinetic stimuli lasted for a maximum of 25 minutes and the participant could abort whenever he/she wanted to, but was asked to continue for as long as possible. When the exposure period ended, the drum was put to an immediate halt and the participant could exit the drum.

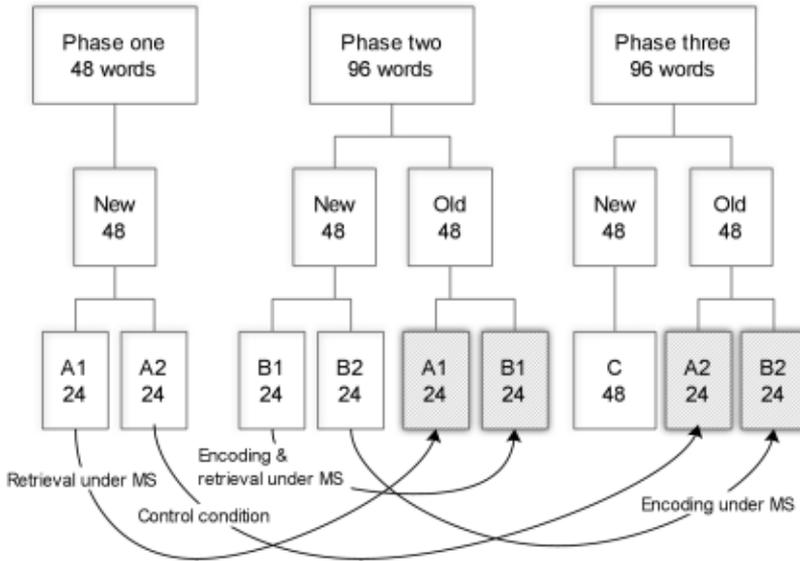


Figure 5. The CRT protocol with the number of words in each phase and for each word list (list A1 to C). Phase two is conducted during exposure to the optokinetic drum and, hence, under the influence of motion sickness (MS). The gray boxes indicate where successful retrievals are measured.

Lastly, a second list of 96 words was presented, in which 48 were previously presented in the first or second phase (lists A2 and B2) and 48 were new (list C). The participant gave the same new/old responses to these words as they did in the second phase. The third phase was expected to reveal the participant’s ability to encode words during motion sickness. List A2 was used as a control condition, since neither the encoding nor the retrieval of these words was done under the influence of motion sickness.

After drum exposure, the last phase of the CRT was completed. Each participant also completed a questionnaire regarding their experience of the optokinetic drum exposure and the CRT.

Since the participants were required to look at the stripes while inside the optokinetic drum to produce the desired effect, the second phase of the test had to be conducted with pre-recorded words instead of words shown on a computer screen. Most of these words were gathered from

a website connected to the Language Council of Sweden, Lexin, the words not found here were recorded by the test leader using a Sony ECM-T7 tie microphone.

5.3.5 Statistical analyses

Statistical tests were conducted using SPSS version 15.0 for Windows with the two-sided statistical significance level set at $\alpha = .05$.

Retrieval was defined as a correct response to an “old” item and retrieval rate was the conditional probability of a correct response. False alarm was defined as an incorrect answer to a “new” word. Accordingly, false alarm rate was the conditional probability of responding “old” to a novel item. Successful retrievals were analyzed using Friedman’s test to assess differences between retrieval of the A1, A2, B1, and B2 lists. The false alarms and total number of correct answers were compared between phase two and phase three with Wilcoxon’s signed ranks test. Spearman rank correlations were calculated to further investigate the possible influence of motion sickness on performance. Correlations were calculated between mean Borg scores from phase two and retrieval and between false alarm and mean Borg scores from phase two.

5.3.6 Ethical considerations

Before the experiment, a general information sheet was sent to the participants through e-mail. Participation was on a voluntary basis and the participants gave their written informed consent. The study design and procedures conformed to the declaration of Helsinki regarding ethical principles for medical research involving human participants.

5.4 Study IV

5.4.1 Design

The study had a within-group design and was performed in a controlled laboratory setting. A motion platform (Moog 6dof2000E), with six degrees of freedom producing low frequency movements similar to those of a sea vessel was used to provoke symptoms of motion sickness.

5.4.2 Participants

A total of 6 men and 17 women (mean age 29.0 years, range 20-51 years) volunteered to take part in the study. The participants were recruited through public advertisements. Applicants with perceived high susceptibility to motion sickness were of special interest and therefore selected for participation. Individuals with vestibular and/or hearing dysfunctions or who were on medication that could confound the psychophysiological measurements and/or contribute to nausea were excluded.

5.4.3 Measurements

An electronic questionnaire was constructed to measure subjective reactions, i.e. perceived motion sickness, to the experimental conditions and comprised question 1-10 of the Graybiel scale [107]. The electronic questionnaire was answered with a two minute interval on a touch screen. Measurements of heart rate (HR), skin conductance level (SCL), blood volume pulse (BVP), skin temperature (TEMP), and respiration rate (RR) were made. All psychophysiological measurements were recorded throughout the entire exposure and baseline period.

Eye movements were recorded using a head mounted ViewPoint EyeTracker[®] (Arrington Research Inc) [92], which recorded pupil size and the x and y coordinates of the eye. The coordinates were initially run through a centroid mode fixation generation analysis [20] to filter out fixations from other eye movement data. Next, the average number of fixations (NoFix) and fixation duration (Fixdur) over the time periods were calculated for each participant. To compare actual fixation time (Fixtime) across the conditions, NoFix was multiplied by Fixdur. The maximum duration, i.e., Stop Time (ST), was measured as the number of minutes the participants remained in each trial.

5.4.4 Procedures

The participants were instructed not to eat for 2-3 hours before start of the experiment. Intake of anti-motion sickness medications, anti-emetic medication, antihistamines or alcoholic beverages was not allowed within 24 hours before the experiment. This was checked for on a self-report basis.

The participants were seated in a chair located in a closed cabin on the platform to ensure that no outer points of reference were visible. A visual distraction task kept the participants occupied so they could not take deliberate countermeasures against the development of motion sickness.

The sound used in this study was “pink noise”; i.e., low pass filtered white noise, with equal energy per octave [137]. The sound originated from four loudspeakers positioned in a square, either on or outside the platform. The sound was equally loud in both conditions. For each speaker, the sound level was kept within 56-57 dB as measured at the participant’s seat. Sound level measurements were performed using Lvie IE-33J decibel meter and a HP IPAQ 5450. The microphone was placed at the participant’s ears so the actual sound level experienced during the trials could be determined. The background sound level with the speakers turned off was 53 dB, which resulted in total sound level of 59.6-60.0 dB. The participants were tested in two conditions. In the first, speakers were placed on the platform. In the second, the “sound horizon” condition, the speakers were placed at the participant’s horizontal ear level outside the platform to create a fixed auditory reference. All participants were given two separate trials, one in the non-positioned sound and one in the sound horizon, with a minimum of one week apart. They were not informed about which experimental condition they were exposed to until after they had performed both trials, and the debriefing session took place, which is further described below. On arrival, the participants were given a chance to examine the equipment and to ask questions. Each participant was instructed in advance to ride as long as he or she could, short of vomiting. Maximum duration of exposure for each trial was 40 minutes.

The participant’s were exposed to the following experimental conditions during both trials:

(1) *Five-minute rest period.* Participants were asked to rest comfortably on the platform in front of a blank screen. The first half of these five minutes served as a familiarization phase, and the last 2.5 minutes served as baseline. The participant then completed the first subjective rating of perceived motion sickness using the electronic questionnaire.

(2) *Motion sickness stimulation.* The motion platform and video were initialized and continued running throughout the trial. Ratings of perceived motion sickness were obtained at 2-minute intervals using the electronic questionnaire, which took approximately 30 seconds to complete (i.e., an approximate cycle time of 2.5 minutes). During the trial, participants were

subjected to either the non-positioned sound or the sound horizon. Each participant performed one trial in each auditory setting in a randomly selected order, which meant that half of the group started with the non-positioned sound and the rest of the participants with the sound horizon. The participants were not informed about the order of the trials or about the different sounds. The trial was terminated when either a) the participant requested termination or b) the maximum duration of the trial had been achieved.

(3) *Debriefing*. After completing the first of the two trials, all participants were given the chance to terminate the study before scheduling the second appointment. When both trials were completed, the participants were fully informed about the purpose of the study in accordance with the approved ethical application.

5.4.5 Statistical analyses

Analyses were conducted using SPSS (version 15.0 for Windows). Motion sickness ratings, i.e., Mal, psychophysiological measurements (HR, SCL, BVP, RR and Temp) and eye movements (NoFix, Fixdur, Fixtime) were compared across conditions using paired samples t-tests. For Mal, HR, SCL, BVP, RR, and Temp, the slope from baseline to termination was calculated for each participant: (Last measurement – baseline) / ST. For eye movement data, the slope was calculated from the first 2.5 min interval to termination since there were no baseline measurements. A positive slope indicates an increase over time and the larger the slope, the faster the increase. Paired samples t-tests were also used to investigate any differences in duration of exposure, i.e., ST between the two sound conditions and between the first and second trial. Pearson correlations were calculated to investigate relations between variables with Bonferroni correction applied for multiple testing [138]. Variables were tested for normal distribution with the Kolmogorov-Smirnov test for normality and variables not normally distributed were analyzed with Wilcoxon signed ranks test and Spearman correlations. The level of statistical significance was defined as $\alpha = 0.05$.

5.4.6 Ethical considerations

The study was approved by the local Ethics Committee (Dnr M114-05). Written consent was obtained from the participants after informing them of the possibility of acquired discomfort from exposure to motion stimulation. They were also informed of the right to withdraw from the experiment at any time without stating a reason. The participants were not informed about the purpose of the study until after the second trial due to the experimental design. The study design and procedures conformed to the declaration of Helsinki regarding ethical principles for medical research involving human participants.

6 Results

6.1 Study I

The odds ratio for centroid mode over start-point mode was 2.86. Thus, the centroid mode algorithm was 2.86 times more likely to find a valid fixation than the start-point mode algorithm. Moreover, the odds ratio increased to 4.16 when the start and/or stop frames in the two modes were different. To establish the IRR, the 50 fixations produced a value of 88% (80% in start-point mode, Kappa = .67, $p < .001$, 96 % in centroid mode, Kappa = .56, $p < .001$) between the two independent raters. Among the 50 fixations, 20% were identical with respect to start and stop frame. In the data set of 1,400 fixations, 48% (666) were identical.

The χ^2 test showed a significantly higher share of valid fixations in the centroid mode (74%) than in the start-point mode (52%), $p < .001$.

6.2 Study II

Across all 38 participants, one moderate correlation was found between perceived motion sickness and short-term memory (STM) performance at Stop ($\rho = -0.44$, $p = .006$).

In total, 22 of the 38 participants endured the entire 25-minute exposure time; the remaining 16 terminated due to motion sickness. Based on this result, the participants were divided into two groups. In the non-termination (NT) group, Borg scores levelled out over time and they were not expected to develop severe perceived motion sickness even if the exposure time had been extended (Figure 6). Mean exposure time for the T-group was 14.6 (SD 5.2) min.

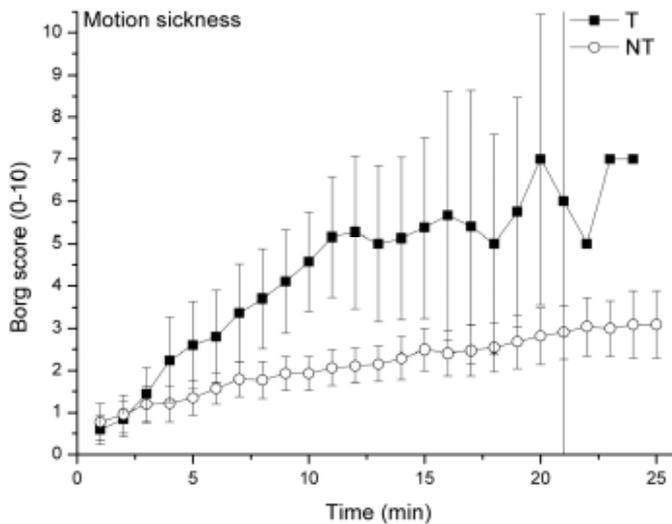


Figure 6. Mean and 95% CI for motion sickness ratings (Borg scores) each minute during baseline and drum rotation. The variance increases with time in the T group as the number of participants drops. T= termination group, NT=non-termination group.

Motion sickness ratings changed during exposure ($p < .001$) with a steady increase from the Start. All time points had significantly increased ratings compared with Baseline and compared with the previous one. The effect of group was significant ($p < .001$), which indicates significantly higher motion sickness ratings in the T-group. The interaction effect was also significant ($p < .001$), i.e., changes in motion sickness during exposure were significantly different in the two groups (Figure 7). The estimated mean difference between groups over time was 2.0 points (95% CI 1.4 to 2.5).

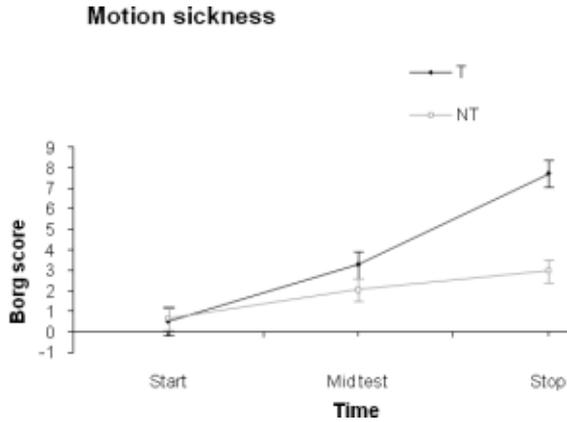


Figure 7. Estimated marginal means and 95% CI for motion sickness ratings during drum rotation. Data presented here are differences from baseline and the horizontal line hence indicates baseline level. T= termination group, NT=non-termination group.

Baseline STM performance did not differ significantly between the two groups. A significant effect of group was seen in STM performance ($p=.01$), and there was a significant group-time interaction effect ($p=.025$). The changes over time points also reached statistical significance ($p=.049$), mainly due to a decrease in STM performance at Start. The largest difference between the groups in number of correctly recalled words was seen at the last minute of the test, in which the T-group had decreased STM performance and the NT-group had increased STM performance (Figure 8). The estimated mean difference between groups was -11% (95% CI, -19 to -3).

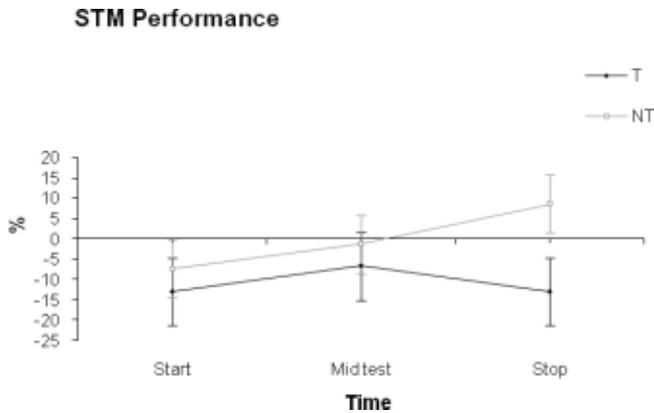


Figure 8. STM Performance measured as percentage of correctly recalled words. Estimated means and 95% CI for differences from baseline. Baseline level is indicated by the horizontal line. T= termination group, NT=non-termination group.

No significant differences in baseline values were found between the two groups in any of the variables.

There was a significant main effect of time ($p < .001$) on HR, mainly due to an increase in HR at Start. For HR, the main effect of group was not significant ($p = .1$). The interaction between time and group showed that changes in HR during exposure differed between groups ($p = .001$). At Stop, HR increased for the T-group, whereas it decreased for the NT-group (Figure 9). The main effect of time was significant for SCL ($p = .016$) with increased SCL at Start and Stop (Figure 9). There was no significant main difference in SCL-levels between the two groups ($p > .3$). SCL also developed similarly in the two groups: there was no interaction effect between time and group.

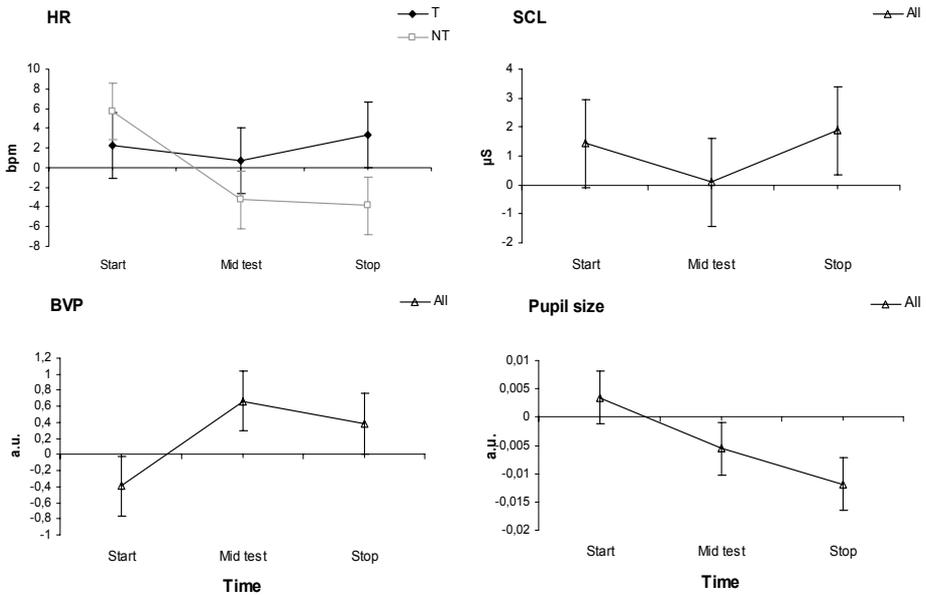


Figure 9. Changes in autonomic responses measured as heart rate (HR), skin conductance level (SCL), blood volume pulse (BVP), and pupil size. Estimated marginal means and 95% CI for differences from baseline. Baseline level is indicated by the horizontal line. T= termination group (n=16), NT=non-termination group (n=22), all (n=38), bpm=beats/minute, a.u.=arbitrary units.

Table 2. Differences from baseline in Skin Conductance Level (SCL), Blood Volume Pulse (BVP), and pupil size for the NT-group (n=22) and T-group (n=16). No significant differences were found between the NT- and the T-group with respect to these variables.

Variable	Time	NT-group Mean (SD)	T-group Mean (SD)	Change over time (unadjusted) Mean (95% CI)	Change over time in the mixed model Mean (95% CI)*
SCL (μ S)	Start	1.3 (3.1)	1.4 (3.1)	1.3 (.4 to 2.3)	1.4 (-.1 to 2.9)
	Mid test	-.8 (6.0)	.9 (2.5)	-.03 (-1.7 to 1.6)	.1 (-1.4 to 1.6)
	Stop	.9 (7.0)	3.0 (3.2)	1.8 (-.1 to 3.7)	1.9 (.3 to 3.4)
BVP (a.u.)**	Start	-.5 (.6)	-.3 (.9)	-.4 (-.7 to -.2)	-.4 (-.8 to -.03)
	Mid test	.4 (1.5)	1.0 (1.7)	.6 (.1 to 1.2)	.7 (.3 to 1.0)
	Stop	.3 (1.4)	.4 (1.1)	.4 (-.1 to .8)	.4 (.01 to .8)
Pupil size (a.u.)**	Start	.003 (.008)	.004 (.011)	.004 (-.000 to .007)	.003 (-.001 to .008)
	Mid test	-.005 (.012)	-.005 (.016)	-.005 (-.010 to -.001)	-.006 (-.010 to -.001)
	Stop	-.010 (.014)	-.014 (.020)	-.012 (-.018 to -.006)	-.012 (-.016 to -.007)

*Estimated marginal means

**Arbitrary units

Furthermore, the effect of time was significant with respect to BVP ($p < .001$), indicating that changes in BVP occurred throughout the trial. BVP dropped below baseline at Start, increased at Mid test, and decreased slightly towards Stop (Table 2). However, there was no difference between the two groups, neither in BVP level ($p = .152$) nor in the development over time. There was a significant effect of time on pupil size ($p < .001$). However, there was no main effect of group ($p > .3$) and no interaction effects. Pupil size was slightly higher at Start compared to Baseline, but it lowered at the following time points (Table 2).

6.3 Study III

Because five participants never reached 2 on the Borg scale, they were excluded from all analyses. Fourteen participants prematurely terminated the drum exposure and 21 sat through the entire 25-minute exposure period. The median exposure time for those who terminated was 16 minutes (range 8 to 22 minutes). All participants completed the CRT phase two before termination. The motion sickness ratings from phase two of the CRT increased from 2.5 points in the beginning to 4.0 points at the end of the phase (Figure 10). The mean Borg rating for phase two was 3.3 points (SD 1.1).

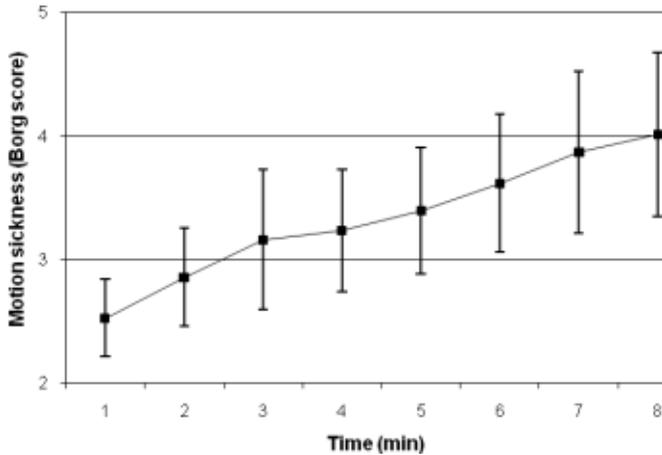


Figure 10. Motion sickness ratings during CRT phase two (mean and 95% CI).

In the initial questionnaire, the participants were asked whether they thought they would become motion sick in a situation where 50% of all people normally develop motion sickness. Thirteen participants answered “no” and 22 “yes”. In the group of participants terminating prematurely, three answered “no” and 11 “yes”. The corresponding figures for those who endured the 25 minutes were 10 “no” and 11 “yes”. Regarding previous experiences of motion sickness, 14% reported that they often experience motion sickness, 40% sometimes, and 31% seldom become motion sick. Only 5% reported that they very seldom or practically never experience motion sickness.

After completion of the experiment, the participants reported which strategy they adopted with regards to performing at their best or trying to reduce motion sickness (Figure 11). The participants were also asked to rate (from 1 to 7) the stressfulness of the experiment and the mental strain during the experiment. Median ratings were 3 points for stress and 4 points for mental strain. After phase two of the CRT and just before leaving, the mean Borg score was 0.8 points (SD 0.8). For 85% of the participants, the symptoms triggered by the optokinetic drum were considered to be representative of symptoms usually perceived during motion sickness.

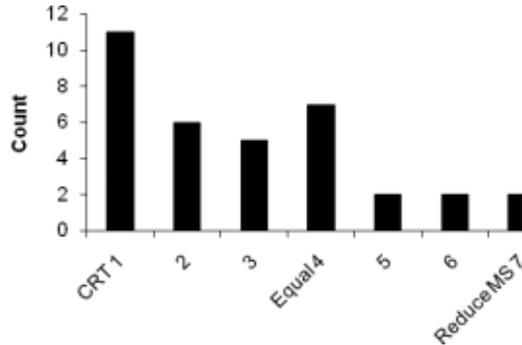


Figure 11. The distribution of participants with respect to whether they reported focusing their energy on performing the CRT or on trying to reduce motion sickness (MS).

There was no significant difference ($\chi^2 = 0.98$, $p > 0.8$) in success of retrieval between the four word lists (Table 3). Hence, the ability to encode and retrieve words was the same regardless of whether the encoding, the retrieval, or both were carried out under the influence of motion sickness

Table 3. Retrieval from the four word lists measured as number of words correctly recalled as being “old”. The results for lists A1 and B1 are from phase two and results for A2 and B2 from phase three.

	Control condition	Retrieval under motion sickness	Encoding and retrieval under motion sickness	Encoding under motion sickness
Word list	A2	A1	B1	B2
Correct retrievals Mean (SD)	20.1 (3.0)	20.4 (3.2)	20.1 (5.0)	20.4 (3.0)
Retrieval rate (%)	83.7	84.9	83.8	85.1

There was a significant difference in number of false alarms between phase two and phase three ($Z = -3.9$, $p < 0.001$). The false alarm rate was higher in phase three than in phase two (Table 4). A difference between the number of false alarms indicates a change in the participants’ attention to “new” words between phase two and three.

Table 4. Number of false alarms, i.e., wrong answers to “new” words.

	Phase two	Phase three
Number of false alarms Mean (SD)	5.1 (5)	7.6 (6)
False alarm rate (%)	10.6	15.9

There were no significant correlations between level of motion sickness during phase two and encoding and retrieval performances.

6.4 Study IV

Table 5 presents descriptive statistics across the conditions.

Table 5. Descriptive statistics for the slope across sound conditions for all variables.

Variable	Sound	Mean	95% CI	Paired mean difference	95% CI
Mal (Mal score / min)	Non-pos	1.80	1.14 to 2.46	0.27	-0.11 to 0.65
	Horizon	1.77	1.07 to 2.47		
HR (bpm / min)	Non-pos	0.79	0.41 to 1.17	0.00	-0.44 to 0.45
	Horizon	0.74	0.33 to 1.15		
SCL (μ S / min)	Non-pos	0.76	0.46 to 1.07	0.17	-0.09 to 0.43
	Horizon	0.57	0.33 to 0.81		
BVP (a.u. [†] / min)	Non-pos	-0.10	-0.21 to 0.00	-0.09	-0.19 to 0.02
	Horizon	-0.02	-0.07 to 0.03		
RR (bpm / min)	Non-pos	-0.14	-0.29 to 0.00	-0.11	-0.26 to 0.03
	Horizon	-0.03	-0.15 to 0.10		
Fixdur (msec / min)	Non-pos	0.10	-0.64 to 0.84	0.47	-0.58 to 1.52
	Horizon	-0.26	-0.78 to 0.26		
NoFix (count / min)	Non-pos	2.45	0.79 to 4.11	2.16	-0.48 to 4.80
	Horizon	-0.02	-1.50 to 1.45		
Fixtime (msec / min)	Non-pos	482.12	151.36 to 812.88	554.09	95.59 to 1012.58
	Horizon	-76.56	-327.59 to 174.47		

The average reported Mal score when the participants terminated the trials was similar for both the sound horizon (22.9 points, SD 7.2) and the non-positioned sound condition (23.8 points, SD 6.2). Paired mean difference between the sounds was 1.1 points (95% CI -0.8 to 3.9, $p = 0.186$) and the correlation was $r = 0.67$ ($p = 0.001$). Mal scores increased over time, i.e., Mal slope was significantly larger than zero (Table 5). The difference in Mal scores between the two sound conditions was not significant (Table 5).

Mean ST in the two sound conditions was 18.1 min (SD 12.3) for non-positioned sound and 20.2 min (SD 13.6) for the sound horizon (Figure 12). Paired samples t-test showed no significant difference in ST between the non-positioned sound and the sound horizon ($p = 0.123$).

However, a comparison of the first test trial versus the second test trial revealed a significant difference in ST ($p < 0.001$). Participants endured the motion sickness stimulation longer when they came back for the second trial. Mean ST was 16.9 min (SD 11.7) for the first trial and 21.4 min (SD 13.8) for the second trial (Figure 12).

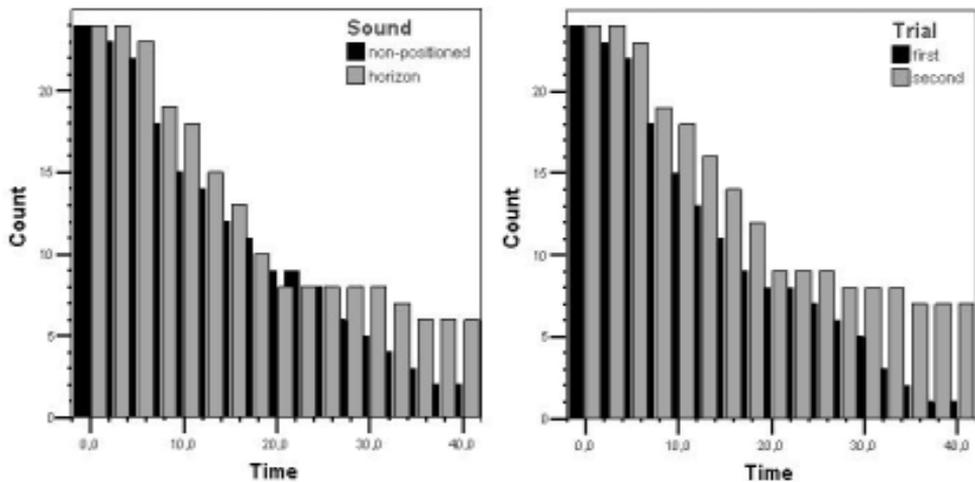


Figure 12. Left table shows the number of participants over time in the two sound conditions. Right table shows number of participants over time as a result of first and second trial.

Because temperature data were not normally distributed, they were not analyzed with non-parametric tests. Possible time effects, indicated by a non-zero mean slope, were investigated for non-positioned sound and sound horizon separately since measurements from the two sounds are not independent. HR and SCL slopes were significantly larger than zero (Table 6), indicating increase over time in both sound conditions, whereas BVP and RR slopes were negative, however, not significant. Median temperature slopes were 0.004 °C/min for non-positioned sound and 0.017 °C/min for sound horizon. None of the psychophysiological variables had significantly different slopes in the non-positioned sound compared to sound horizon.

Pearson correlations were calculated between the slopes for all psychophysiological variables and the Mal slope. There was a significant positive correlation between Mal slope and HR slope as well as between Mal slope and SCL slope (Table 6).

Table 6. Correlations between Mal slope and slopes for the psycho-physiological and eye movement measurements.

	HR	SCL	BVP	RR	Temp	Fixdur	NoFix	Fixtime
r	0.59	0.61	0.29	0.16	0.14 [†]	-0.11	0.45	0.38
p	<0.001	<0.001	0.058	>0.3	>0.3	>0.3	0.003	0.013 ^{††}

[†] Spearman's rho

^{††} Not significant after Bonferroni correction

In the non-positioned sound, both Fixtime and NoFix increased over time, whereas none of them showed a significant time effect in the sound horizon (Table 6). Fixdur did not show a significant time effect for any of the sounds. Fixtime was the only variable showing significant differences between non-positioned sound and sound horizon. Fixtime slope was significantly larger in the non-positioned sound compared to the sound horizon ($p = 0.02$).

Possible correlations between Fixtime, NoFix, and Fixdur and Mal slope were checked for and a weak but significant positive correlation was found for NoFix, indicating that participants reporting a large increase in Mal scores over time also increased their actual number of fixations, indicating that if participants become motion sick, it can be a result of increased NoFix (Table 6).

7 Discussion

The overall aim of this thesis was to study psychophysiological and performance aspects on motion sickness. A longitudinal perspective on this work is that it contributes to further search for mitigation and prevention of motion sickness. In the following sections, the findings from each of the studies will be discussed with regards to psychophysiology, motion sickness, and performance related to previous findings and theories.

7.1 Result discussion

7.1.1 Psychophysiology

Psychophysiological measurements were collected in study II and IV. The data that constituted the basis for comparing the two velocity based algorithms in study I (centroid mode and start-point mode) were randomly selected eye-tracking data from 48 participants and comprising about 1,400 fixations. The odds ratio in study I clearly pointed towards recommending the centroid mode algorithm when identifying fixations in eye-tracking data. Accuracy is the main reason for choosing the centroid mode algorithm over the start-point mode algorithm. The principle of that argument is described in Figure 3 and fine-tuning of the eye after its landing position has to be seen as a crude approximation. Hence, the centroid mode algorithm takes this into consideration, while the start-point mode always includes the initial landing position and the corrections, a condition that makes this mode less accurate [93]. This finding is supported in previous research; Yarbus [88] described the ecological view of how the human eye works. The start-point mode suggests that the landing point should stipulate the fixation identification, which does not cohere with how the eye functions. In contrast, the centroid mode suggests that the weighted procedure should be applied to identify fixations [89]. Before study I was conducted, the prerequisites for identifying fixations as a possible indicator for symptoms of motion sickness, as well as a possible mitigation strategy, was not optimal. Not knowing which fixation identification method being used actually means that a reported effect could in real life have been lost due to the algorithm used. Based on the results, it is 2.86 times more likely to find a valid fixation in centroid mode compared to start-point mode.

In study II, data from the eye-tracking analysis showed that there was a significant decrease in pupil size in both groups over time. This result is somewhat confusing, since it could be expected that pupil size would increase as a result of dominant sympathetic condition [5], especially since motion sickness was perceived by so many. Pupil dilatation is an instant response that cannot last for long periods since other sight related mechanisms will overrule this response [88]. This is especially true for optokinetic stimulation, which can be considered exhausting for the eyes. Therefore, the result indicating a decrease in pupil size should be carefully interpreted and viewed as a result of the optokinetic stimulation rather than as a result of motion sickness.

In study IV, eye tracking was used to further study fixations during exposure to movements of a motion platform. The non-positioned sound condition made the participants increase their fixation time faster compared to the sound horizon condition, indicating that the participants

used more time to fixate. Number of fixations also increased in the non-positioned sound condition in comparison to the sound horizon condition. The increase in fixations over time in the non-positioned sound condition indicates that this actually could be both a deliberate strategy and/or a subconscious action taken to reduce visual input. Since none of the participants in study IV noticed any differences in the two conditions when asked afterwards, the increased number of fixations could not have been deliberately performed dependent on the two sound conditions.

The slope for number of fixations increased as malaise slope increased in the non-positioned sound condition, which was an expected finding [21, 42]: as the number of fixations increased motion sickness progressed. About a fifth of the fixation time in both conditions was dedicated to filling in the electronic questionnaire. This time is included in the analysis because the secondary task given to the participants most likely generated similar eye movements as filling in the questionnaire. One alternative way of reducing the first versus second time effect found in study IV could have been to pre-test the participants before the actual test trial. However, this could have made the participants more observant towards any differences between the test trial and the actual test, an observation that could result in a different behaviour.

In both study II and III, about 40% of the participants terminated the trials before full time due to severe perceived motion sickness caused by the optokinetic drum stimulation. In cases where we asked the participants whether the exposed stimuli created the feelings that they normally would have experienced during motion sickness, the artificial stimulus was reported to be representative. As stated previously, the autonomic activity associated with motion sickness is similar to any stress reaction and dependent on subjective statements confirming that motion sickness is perceived. Because the autonomic responses associated with motion sickness are so individual, this thesis studies their relationship, their development over time, and whether fixations had any potential influence. Psychophysiological responses have been extensively studied in motion sickness research [6, 8, 9, 11, 17, 77, 139]. Despite the amount of research, there is no identified sustainable evidence that any of the most commonly measured responses could serve as predictor for motion sickness. In study II and IV, SCL and HR proved to be the only two responses that showed significant changes over time. Only those participants who terminated showed a significant increase in HR. Initially, both groups in study II responded with increased HR from baseline as a result of a startle response and then declined towards mid test. After mid test, the two groups diverged and the T-group followed the expected development towards termination [17, 62] with increased HR. The NT-group showed decline in HR after mid test, which indicated a reduced sympathetic arousal, most likely due to adaptation and reduced expectations. Although both groups showed increased feelings of motion sickness, the progression and magnitude was larger for the T-group, indicating that the NT-group, despite moderate nausea, could endure the trial and even improve their performance.

None of the psychophysiological variables were affected by the artificial sound horizon in study IV. However, as Mal scores arose, so did the HR and SCL, which at least suggested that motion sickness was induced by the motion platform. As mentioned, SCL was elevated in both study II and IV indicating that it is a sensitive measurement for motion sickness induced by an artificial stimulus. This finding agrees with previous research [8, 11, 15, 69, 70]. The SCL result only applies to the experimental settings in this thesis and it is likely that if studied in the field, environmental factors will either add to or cancel out any effects. That is, artefacts caused by movement will affect the results. Since SCL is a stimuli-response sensitive

measurement, results must be carefully interpreted with regards to confounding variables in the experimental design and/or the surrounding environment [64]. In study II, SCL was elevated as a startle response and dropped towards Mid test. After that, it increased to levels just above its initial startle response at Stop. The decline from Start to Mid test can be explained, much like the HR response, by reduced expectations and adaptation. However, as motion sickness progresses and becomes too intense and severe to fight back, SCL elevated from Mid test to Stop. This is most likely neither a conscious act nor a part of any resource allocation function, as could be the case with regards to the performance measurement. In study IV, SCL was elevated in both trials over time and since there was a significant correlation between the Mal slope and the SCL slope, it can be concluded that motion sickness was induced. As nausea progressed, so did SCL.

The results from the other autonomic responses were ambiguous. Apart from HR and SCL, study II also measured BVP, while study IV also included BVP, skin temperature, and respiration. BVP was supposed to reflect autonomic changes and thus expected to decline as an initial sign response to the onset of the optokinetic drum rotation or start of the motion platform. Previous research has confirmed that BVP measurements are considered less stable [76] and sensitive to both environmental settings and personal factors such as susceptibility. The BVP measurement showed no significant change from baseline values in any of the two groups in study II. However, the development over time – a decrease at Start, increase towards Mid test, and decline towards Stop – is partly confirmed by previous research [8]. The BVP had a negative slope development, however, not significant. Study IV also measured skin temperature and respiration during the two sound conditions tested. None of the two measurements showed any significant differences between the two sound conditions or in relation to each other.

By studying the entire development of psychophysiological responses over time, the aim was to optimize the chances of finding early signs and symptoms and possible correlations between the different variables. Previous research has shown that individual differences are large and susceptibility to symptoms is both difficult to screen for and subject to large variability [63]. The studies included in this thesis confirm these statements. Although both study II and IV provided some evidence that SCL and HR may be potential indicators of motion sickness, they showed no correlation other than to subjective ratings of motion sickness. Clearly, motion sickness should be studied using both subjective and objective measurements.

7.1.2 Perceived motion sickness

In study II, III, and IV, motion sickness was induced artificially through a controlled stimulus. All three studies were successful in inducing motion sickness in the sense that ratings of perceived motion sickness were obtained. In study II and III, participants were recruited regardless of their susceptibility to motion sickness. In study IV, however, participants with high self-rated susceptibility were recruited.

Study IV used an electronic questionnaire that comprised question 1-10 of the Graybiel malaise score [107]. The scale ranges from 0-62 points. The malaise score is specific in its ratings: the participant rates specific signs and symptoms based solely on their own perception. The questionnaire also depends on the participant discriminating between the different physiological events that are asked about and associating these physiological events with motion sickness and not with the non-related discomforts. In study II and III, the Borg rating scale [104] was used as the only measurement of perceived motion sickness. The

reason for this was that the Borg scale had proven to be highly correlated with the Graybiel malaise score [135] and given the experimental design, using the optokinetic drum, it was more easily administered. Since study II and III also focused on cognitive performance as a result of motion sickness, we only needed to know if the participants were experiencing motion sickness not if they experienced any of the specific signs or symptoms of it. The cognitive tasks used in those two studies were also complex and followed a procedure that was not compatible with a more extensive questionnaire. It is safe to say that almost every participant arriving at a clinical experimental setting to participate in a test is under the influence of a sympathetic arousal that affects his/her autonomic responses even before the beginning of the test. In this case, the choice of instrument for subjective ratings is of great importance since participants will be more prone to look for specific symptoms if asked about them. A more non-specific instrument, like the Borg scale, asks only for the general feeling of discomfort, e.g., the degree of nausea.

Study II identified a stage where perceived motion sickness overtook the ability to perform among those participants who eventually would terminate the trial. This function allocation is based on perceived symptoms resulting from the optokinetic stimulation and up to Mid test performance improved in both groups compared to baseline. At Mid test, Borg ratings were above “moderate” for the T-group and then increased further to, on average, 7.9 (very strong) at termination. During this time (from Mid test to Stop), it is likely that the combination of illness and lack of motivation affected both the ability to focus and reduced the potential learning effect for the T-group.

Throughout this thesis, I have argued that motion sickness should be studied using both objective measurements – such as psychophysiological recordings – together with subjective ratings of motion sickness. The result of the psychophysiological measurements confirm the diversity and large inter variability previously reported. Subjective ratings of motion sickness, on the other hand, provided us with a valid measurement of the perceived status using both the Graybiel malaise score [107] and the Borg scale [104].

7.1.3 Performance

Study II and III studied performance in terms of short-term memory (STM, study II) and encoding and retrieval (study III). Both of these deal with memory performance and should be considered not to differ from an ordinary task being performed in, for example, a command and control environment. The results showed that short-term memory was affected by motion sickness in an optokinetic drum among participants that eventually would terminate their trial. This result is in accordance with Paule et al. [140] who found that performance of a working memory task was negatively affected by motion sickness induced by a rotating chair. The development of STM performance during drum exposure differed between the T-group and the NT-group. Initially, STM performance was negatively affected for both groups and then recovered towards Mid test. The most interesting finding with respect to STM performance was the development from Mid test to Stop in the T-group, which illustrates the cognitive function allocation that was expected to occur when perceived motion sickness reached a level where cognitive resources were devoted to either mitigating symptoms or performing the task. In study II, the T-group’s STM performance decreased at Stop compared with Baseline. During the same time, STM performance actually increased in the NT-group, further illustrating this phenomenon. In a working environment where performance is crucial, participants would most likely be forced to endure the motion stimuli longer than they did in this experimental condition. This implies that performance would be even more affected in real life given the same development of motion sickness as found in the T-group.

Furthermore, since both the T and the NT-group reported motion sickness to some extent, it appears that moderate levels of motion sickness do not necessarily affect performance.

Decline in performance over time and increased levels of perceived motion sickness could be devastating with regards to working in a moving environment or in professions where high performance is crucial [131, 141]. Rolnick and Gordon [110] touched upon this issue by saying that a decline in performance could be due to lack of motivation rather than motion sickness per se. Activity and activity limitations are described in ICF [1] and can be affected by both personal factors, environmental factors and, when experiencing motion sickness, impaired body functions. In this sense, the ICF model is applicable to the motion sickness effect on performance.

In study III, no effects on encoding and retrieval were found despite moderate levels of motion sickness contrary to the observations made in the Levin et al. study [142]. Whereas G-exposure affected encoding negatively, motion sickness in the present study did not. The finding that motion sickness on moderate levels did not affect encoding and retrieval is in contrast to study II, where short-term memory performance declined significantly among participants suffering from motion sickness to the extent that they eventually terminated the trial. Admittedly, short-term memory and encoding may be closely linked [143]. Although study III found no effects on encoding and retrieval performance, there were significantly more false alarms reported in phase three (Table 4) than in phase two. This observation is probably due to the amount of words processed rather than due to effects of motion sickness per se. This explanation is based on the fact that motion sickness ratings during phase three were at the same level as in phase one.

As previously mentioned, decrements in performance are reported to peak when tasks are complex and when sustained performance is required over longer periods [110]. This fact supports that it is important to discriminate between whether the task is novel or not [112]. In both study II and III, we included tasks that were assumed to be new to all participants. The benefit of using a novel task is that everyone starts at the same level of experience and that it is easier to measure any changes in performance due to environmental factors. It is also harder for a participant to compensate and manage any possible symptoms of motion sickness if his/her attention has to be devoted towards performing. In two previous studies [18, 19], shooting performance was used for studying the occurrence of motion sickness following transportation in military vehicles. Shooting was normally performed by the conscripts in their everyday activities and could thus be considered a skilled task. Neither of these two studies found any effects on performance due to perceived motion sickness despite relatively high levels of subjective reports, which could be assigned to the environmental factors. If a novel task was performed, the outcome would most likely be different.

In study II, we found that performance was negatively affected only after reaching relatively high levels of motion sickness (mean Borg score 7.9, corresponding to “very strong”). Taken together, results from both study II and III indicate that participants experiencing weak or moderate levels of motion sickness still perform at their best. How encoding and retrieval is affected by high levels of motion sickness remains to be examined. It seems that those symptoms of motion sickness caused by the optokinetic drum in study III declined so fast that participants were down to baseline values as they performed phase 3. This finding indicates that despite moderate levels of motion sickness performance may still be kept at high levels. In addition, once the stimulus is reduced, baseline capability can be obtained soon thereafter. This could also mean that efforts to reduce or eliminate motion sickness should focus on

keeping symptoms from getting too bad, i.e., reaching levels equivalent to 5 (strong) on the Borg scale.

7.1.4 Mitigation strategies

The artificial sound horizon, applied as a mitigation strategy for perceived motion sickness, showed no significant effect on Mal scores or ST in study IV. Based on these results, no effects of an artificial sound horizon as a mitigation strategy on perceived motion sickness could be identified. NoFix increased with time in the non-positioned sound condition. Moreover, fixation time increased faster in the non-positioned sound condition, on average with about half a second per minute, indicating that the participants used more time to fixate and, hence, assumingly made fewer saccades [88]. This finding could be interpreted as a mitigation strategy applied by the participants to cope with perceived motion sickness [21, 42]. In the sound horizon condition, no such changes were found. Whether this action was a deliberate strategy or occurred subconsciously remains unclear. The results clearly advocate rejecting the tentative hypothesis that the artificial sound horizon could postpone the onset of perceived motion sickness or at least keep the symptoms at a constant lower level for some time compared to the control condition. It can be concluded that the impact of the sound horizon was not large enough to be statistically significant with respect to how long the participants endured the trials, i.e., ST, in the two different sound conditions. In the sound horizon condition, the participants lasted on average 11% longer. The variation in Mal scores at the point of termination was large, but on average they were lower in the sound horizon condition, yet this finding was also not statistically significant. However, as mentioned earlier, Fixtime and NoFix increased over time in the non-positioned sound condition, indicating that eye movements seem to be sensitive to the artificial horizon.

7.2 Methodological discussion

7.2.1 Psychophysiology

The two different stimuli used to induce motion sickness in this thesis target different parts of the components in the sensory conflict theory [3]. Whereas the optokinetic stimulation provides a visually induced motion sickness, the motion platform creates a visual vestibular conflict. The first would be classified as a type 2 conflict and the latter can be assigned to a type 1 conflict according to Reason and Brand [3]. The psychophysiological responses from study II were obtained during exposure to an optokinetic stimulus, while the psychophysiological responses in study IV were collected during exposure to a motion platform. No previous research shows that any significant differences in psychophysiological responses could be expected with regards to the two stimuli used. The order and magnitude of responses were so individual that differences were more likely to be caused by factors such as susceptibility, expectations, and previous experiences rather than by which specific stimulus motion sickness was induced, given that the stimuli actually induced motion sickness. Previous research has also confirmed this high level of individuality [8, 86].

It is, however, unknown if the results from study IV could have been obtained even without the algorithm developed in study I. It is likely that the centroid mode algorithm used to identify fixations provided us with the best possibility of finding valid fixations. Study I is, however, performed using data not collected from participants under the influence of motion sickness. This fact probably has little or no effect with regards to applicability of identifying fixations during a different physiological state.

As mentioned, the results from the autonomic variables were ambiguous and only HR and SCL provided expected results as shown in study II and IV. Previous research has used similar techniques as in these two studies to identify and monitor autonomic activity, both in experimental and field conditions [9, 144]. BVP, recorded to detect early autonomic change and sympathetic arousal, showed no effect with regards to perceived motion sickness or in relation to any of the other variables. Recording BVP raises several issues that need consideration. The detection of sympathetic activity is difficult when participants know that they potentially are going to experience motion sickness. Baseline values are probably far from what could be recorded during “normal” conditions, conditions that are outside the experimental situation. On arrival to the laboratory, sympathetic arousal is already dominant and only minor fluctuations can be expected during perceived motion sickness. Furthermore, the plethysmography technique for measuring BVP is also sensitive to environmental factors and artefacts. Surrounding temperature and light conditions, electrode placement, and software can be potential sources of error.

The other measurements, respiration and skin temperature, also proved to be less favourable in both detecting and explaining motion sickness. Temperature is measured on the fingers, indicating surface temperature and is also exposed to environmental factors like ambient temperature, sitting position, size of the electrodes, etc. Alternatively, a temperature sensor that can be swallowed could have been used or a rectal thermometer. However, both for ethical and experimental reasons as little intervention as possible were desired.

Although no psychophysiological measurements were collected in study III, the results indicated that more false alarms were made during the final phase of the test. No data were available on the specific motions sickness symptoms other than a crude measurement from the Borg scale, rating degree of nausea. However, Lawson and Mead [66] have shown that it could be a result of the sopite syndrome, which is described as distinctively different from motion sickness. The sopite syndrome includes factors like mood changes and fatigue, and could maybe also comprise motivational factors. Such an assumption would support the findings of Hettinger et al. [109], who discusses motivation, or rather lack of motivation, as a primary cause for loss of performance ability during motion sickness.

7.2.2 Perceived motion sickness

The intention of using the pre-screening questionnaire was to determine the susceptibility to motion sickness symptoms before stimulation, but also to obtain data on sex, age, medications, general health condition, etc.

As mentioned, motion sickness was induced in study II, III, and IV by different stimuli. Study II and III used an optokinetic drum, which frequently has been used in previous research [37-40] and is considered a valid instrument for inducing motion sickness. The optokinetic stimulation provokes visually induced motion sickness and is considered highly effective. The fourth study used a motion-based platform for inducing motion sickness. The platform had an enclosed cabin mounted on it in which the participant sat during exposure. The movements of the platform resemble the ones of a boat that is exposed to two-three swells per ten seconds. This motion profile is said to lie within the optimal spectrum of motion sickness incidence [36]. Hence, small frequencies and periodic waveforms are more provocative than large or fast, jerky movements when inducing motion sickness. The motion sickness incidence at frequencies above 0.5 Hz is rare [36].

Other factors may have affected the outcome of study IV: speaker positioning and the sound level of the two sounds could have been further improved to optimize the prerequisites for the sound horizon to have its desired effect. This could also have affected the subjective ratings even though the sound horizon was supposed to work subconsciously. For example, the exact position of the speakers in terms of the sound spreading could have been optimized and measured. Carlander, Kindström, and Eriksson [137] have shown that the human ear can position sound sources with an exactness of 5° horizontally, but the accuracy vertically remains unknown. The sound horizon uses that vertical auditory positioning skill and a drawback of this study is that we do not know to which extent it was possible to detect the positioned sound vertically. Furthermore, the platform generated noise, and this noise may have interfered with the sound from the loudspeakers. Future experiments should thus try to minimize the influence of confounding sounds from the laboratory equipment. Since different sounds are perceived differently, future research should also investigate the effect on perceived motion sickness, using different kinds of sounds that are more naturalistic and thereby more subliminally effective. On the one hand, because the sound horizon affects the participants subliminally, it could have affected the results. On the other hand, if we had told the participants about the sound horizon, it is possible that they in one instance could have perceived it as more helpful, but in another instance would have been forced to devote cognitive attention towards it.

Another aspect not covered in this thesis is the fact that motion sickness in working environments seldom affects just one single person but several, perhaps located closely together. Factors like smells, expectations contamination effects play a major role in the development of motion sickness among a crew [145]. Probably, that is why as many as 62% have been reported to suffer from motion sickness onboard ships [27]. All the studies included in this thesis have been performed with only one participant at the time, therefore the external validity may be questioned.

7.2.3 Performance

Performance was measured using standardized tests [136, 142] that were modified for our purposes and the experimental design. Study II measured STM using a modified version of the Listening Span test [136] and study III used a modified version of a word recognition test used by Levin, Andersson, and Karlsson [142]. Both tests were selected because they resembled a normal task performed by people in a moving environment. Using a modified version of a test is never an optimal solution with respect to validity and reliability. The experimental design in study III forced us to modify the test with regards to the optokinetic stimulus, since a visual task could not be assigned to the participant, the words in phase two had to be read out loud. If the participant would have been allowed to read the words during phase two, this might have had a mitigating effect, since the attention would have been taken away from the stimulus. That would probably have affected the development of motion sickness negatively, since previous research has shown that motion sickness is more dependent on foveally presented information rather than peripherally [42, 95]. Alternatively, for future studies, the test could have been read during all three phases and would thus have been more consistent. The STM test used in study II was successful in providing a measurement of motion sickness effects on STM in an experimental setting. It remains unknown whether the test will serve the same purpose in a more realistic setting outside the laboratory. The CRT is constructed to measure accuracy, in terms of correctly recalled words. In studying motion sickness, there are other variables that could be of interest besides accuracy, e.g. response time. Since previous research showed that performance decrements, due to motion sickness, are worst when tasks are complex and when sustained performance is

required over longer periods of time [110], the results in study III may be assigned to that fact. If the CRT requires much from the participant, especially towards the end of the test, the results of study III confirms the findings of Rolnick and Gordon [110]. The results of Rolnick and Gordon [110] further show that performance was negatively affected if the pace of the task could be controlled by the participant, something that further helps explaining the findings in study III. A finding that also indicates that future measurements of encoding and retrieval should comprise not only accuracy but also response time.

The test was new to all participants, indicating that they shared the same prerequisites facing the test. Of course, variations in intellectual capacity and memory performance could have affected the results and were not tested. The novel test condition was also used in study III in which the modified word recognition test was used. None of the participants in study III had previously seen or taken the test. Although unable to show any effects of motion sickness on encoding and retrieval, the test was successfully administered. The result showing increased “false alarm” rates in phase three could, however, be interpreted as a result of fatigue or simply by the total amount of words processed at that time. It could also, as mentioned, be a result of task difficulty and forced sustained testing [110].

7.2.4 Mitigation strategies

Using an artificial sound horizon in study IV means that the risk of adding conflicting cues – further triggering motion sickness development – will be considerably lowered since visual and vestibular perception are the two dominating input channels triggering motion sickness [3]. The idea behind the sound horizon was that it would work subconsciously on the participant, which will lower the possible performance decline when experiencing motion sickness. Sound could have a similar mitigating ability as the IVB used by the Duh et al. [120] study with the exception that it would not require any devoted cognitive attention. However, as shown by Kennedy et al. [146], different visual patterns have different effects on perceived motion sickness. The same phenomenon is most likely to occur when using different sounds and auditory cues.

Deliberate or not, fixations were found to be part of a mitigating strategy in study IV. The use of the eye tracker for studying mitigation behavior seems to be a valid measurement that may also be used to make sure that the participant is keeping his/her eyes open during stimuli exposure.

As mentioned, the rationale behind study IV was to affect the participant subconsciously. By doing that, the participant only felt the obvious motions affecting his/her sensation. This sensation fits the sensory conflict theory perfect and can be described as a type 1 conflict [3]. The artificial sound horizon does not apply to any of the components that constitute the sensory conflict theory since it affects a totally different modality, i.e., a different sense. Although vision is likely the strongest sense among the three [95], there is limited research available on the influence of sound on perceived motion sickness. Applying the rationale of study IV using the ICF framework of *components* (Figure 1) [1], we can ascribe the sensory conflict theory to originate from *environmental factors* and affect *body functions and structures*. Assuming that vision is a dominant sense in the development of motion sickness, it would be part of the *personal factors*. The *environmental factors* are detected by vision, vestibular, or proprioceptive receptors. Depending on stimulus, they will target one or several of these receptors. If susceptible to motion sickness, the participant will then develop signs and symptoms and respond to the *environmental stimuli*. Previous research has supported the sensory conflict theory by providing visual cues that target one of the three components, i.e.,

vision [121, 122]. Only few studies have supported the auditory channel and then through sound pulses aiming at maintaining postural stability [119, 147]. Despite our negative findings, the artificial sound horizon, as intended, would suppress or postpone the development of motion sickness through supporting a different modality not included in the sensory conflict per se. The artificial sound horizon is part of the *environmental factors* together with conflicting stimuli and other independent variables. However, when the conflicting stimuli reaches the *body functions*, leading to *impairment*, the sound horizon could affect the development by functioning subconsciously on the *body functions* and may even affect *activity*.

7.3 Statistical considerations

To obtain a measure of Inter Rater Reliability (IRR), Kappa statistics were used. The Kappa method requires independent raters. It can always be argued that raters that share the same prerequisites can easily be biased by each other. Despite this, as long as the outcome only deals with questions of *right* or *wrong*, the method is still preferred before using, for example, Cronbach's Alpha [138]. The Kappa method compares pair by pair a part from Cronbach's Alpha and predicts the likelihood of correlations in a dataset and is used when analyzing for example questionnaires.

At a glance, the design of study II would allow comparisons using repeated measures ANOVA. However, using repeated measures ANOVA would not have been possible because of the quality of the data and the fact that there were incomplete datasets. At first, it may also appear tempting to use different types of survival analysis, e.g., Kaplan-Meier or Cox regression, to obtain a prediction on both performance and survival time in the drum. Traditional survival analysis requires a well-defined "end point" usually death or termination of a clinical trial. In this study, the end point would have been termination. The problem with methods such as the Kaplan-Meier test is that it can only handle dichotomous variables and says nothing about the underlying variables or covariates [148] that would help to explain the result. Cox regression is a complex analysis that should be used with great caution [138, 148], and requires normally distributed data. In study II, this was not the case. Since everyone also has to have a common starting point or an identifiable start point in order to apply Cox regression, the use of it is problematic. Furthermore, no control for the participants' susceptibility in an objective way was performed to ensure that they shared the same prerequisites with regards to other states than perceived motion sickness symptoms. Therefore, it cannot be said that the participants had a common identifiable starting point other than the start of drum rotation.

Traditional linear regression would not have been appropriate because it requires that the residuals – the difference between the observed value and the value given by the regression line – has equal variance and is independent. This is not the case when using repeated measures of the same variables. The solution to this problem is to use a mixed model, consisting both of fixed and random variables that are group consistent [138]. Furthermore, the mixed model allows studying random effects within the participant, which is a variable that differs between individuals such as a psychophysiological measurement. Traditional regression can only handle fixed factors. Mixed models also provide a better prediction in contrast to Cox regression [149].

For ethical reasons, the participants in study II could terminate the trials whenever they wanted. This was also the rationale behind the division into two groups: termination before

full time or not terminating. The statistical analyses were made on the assumptions that motion sickness along with the autonomic responses would develop in a similar fashion for all participants, but differently over time. The descriptive data confirmed this, so the two groups were treated the same way despite the fact that the T-group had, on average, 42% shorter exposure time than the NT-group. Further analyzing the data through division into the segments Start, Mid, and Stop could have introduced a potential confound between exposure time effects and motion sickness effects. For example, participants in the NT-group may have experienced learning effects or boredom/fatigue, which the participants in the T-group would not experience given their shorter exposure time. The choice of three time points were motivated by the fact that each of these time points comprises mean values of one minute at that time point. For the T-group, this meant that the selected minutes actually covered about 1/5 of their average time. For the NT-group, the corresponding figures were about 12%. The residuals from the mixed model analyses were approximately symmetrically distributed with homogenous variance, a finding that supported the validity of this approach.

Study IV indicated a clear problem with regards to power. The within-group design with 23 participants did not yield a minimum required power of 80% given the survival time (ST) and Mal scores that were found. Estimating the clinically relevant difference is a central component when calculating power [138]. Since the participants endured, on average 11% shorter time in the non-positioned sound condition, a clinically relevant difference of 10% using the same SD and α -value as in study IV can be used in the calculation (a statistical power of 80%). Such a calculation would then give us a required total of 65 participants.

Furthermore, study IV used a calculation of slope for Mal scores, HR, SCL, BVP, RR, and Temp. The slope from baseline to termination was calculated for each participant: (Last measurement – baseline) / ST. For eye movement data, the slope was instead calculated from the first 2.5 min interval to termination since there were no baseline measurements. A positive slope indicates an increase over time and the larger the slope, the faster the increase. This approach assumes that participants develop motion sickness in a similar fashion but with different pace of development [128]. This approach also allowed paired comparisons between the conditions regardless of individual ST across both conditions.

8 Clinical implications

Motion sickness is a state that normally does not require medical attention unless it inhibits task performance or continues for a prolonged time, which dehydrates the body. However, the physiological and psychological aspects on motion sickness can be applicable to many states of stress, impaired body functions, and effects of medication. By knowing more about the autonomic reactions during stress-related conditions, and more specifically which psychophysiological variables that are significant during motion sickness, results can be applied to illnesses, treatment, or pharmacologically induced nausea. Furthermore, methods on how to reduce motion sickness or vestibular related disorders can benefit from knowledge regarding non-pharmacological methods of treatment with regards to its side effects. The use of the sound horizon in study IV could provide such a non-pharmacological mitigation support that at the same time could allow maintained cognitive capabilities despite the fact that study IV did not find any proof. Specific knowledge about memory performance during perceived nausea is also of clinical importance when evaluating cognitive capabilities. Different medications and treatments are assumed to affect cognitive ability and by knowing more in detail how specific memory functions are affected by different stages of nausea is important.

In an operation environment like the Armed Forces, the results in this thesis can be applied to identify and evaluate the behaviour of soldiers and officers performing tasks in moving environments. Knowing that certain cognitive abilities are affected during specific conditions is essential in planning a mission and in evaluating the outcome of an operation. The situations onboard a ship or on land bound vehicles are demanding. The combinations of extreme stress, motivation, team interaction, etc. are far from everyday life situations. Hence, if affected by motion sickness in such situations where performance and physical ability are important, the effects of motion sickness may be devastating to performance.

Moreover, by applying the ICF components [1] motion sickness and its effects on both psychophysiology and performance can be ascribed to a standard language and framework. When it comes to reducing symptoms of motion sickness or related nauseogenic states, the sensory conflict theory only helps us in explaining *how* the conflict occurs. The sensory conflict theory is difficult to use in explaining the outcome of different mitigating agents, not directly affecting visual, proprioceptive, or vestibular receptors.

9 Future research

Considering that motion sickness research is a relatively new research area that gained attention after the Second World War, much research has been devoted to its physiological statements and pharmacological treatment to obtain military operational performance. Recently, focus has turned towards genetic components and issues such as susceptibility, adaptation, and screening of personnel. Today, there are many available drugs that are either intended for the stomach or the central nervous system, but most of them have side effects that are not compatible with maintained operational capability. Still, the medications induce fatigue and tiredness and in some countries the negative effect is compensated by the use of amphetamine-based drugs. The risks of using these medications in an operational environment are not fully known, but it motivates continued research on non-pharmacological countermeasures.

Furthermore, more research is needed to study the psychological parts of the motion sickness phenomenon. The role of expectations, anticipation, and previous experiences still need to be examined in greater specificity as they relate to the pure medical aspects. In addition, the importance of the velocity storage and its capabilities should render more work on not only the development of motion sickness, but also on the recovery phase and the long-term issues that follow extended space travel or exposure to motion for long periods.

10 Sammanfattning på Svenska

Rörelsesjuka är ett samlingsbegrepp som innefattar t.ex. sjösjuka, flygsjuka, simulatorsjuka, åksjuka i bil, tåg m.m. Att vara under påverkan av rörelsesjuka innebär ofta att man uppvisar ett antal symptom, som antingen är synbara för andra eller inte. Det vanligaste är att man förknippar rörelsesjuka med illamående och kräkningar men i kroppen inträffar ett antal andra processer bl.a. höjd puls, ökad svettaktivitet, minskad blodmängd i armar och ben och förändrade andningsmönster. Alla personer reagerar olika när dom utsätts för rörelse och variationen i såväl mottaglighet för symptom och i hur mycket man reagerar är stor. Att rörelsesjuka är ett problem visar sig ofta i arbetsmiljöer där man utsätts för passiv rörelse och har begränsad möjlighet att se ut. Exempel på sådana arbeten är inom militär verksamhet och i fordon (bilar, bussar, flygplan, båtar m.m.). Likaså uppstår liknande symptom som de vid rörelsesjuka under olika stress- och sjukdomstillstånd, vilket innebär att forskningen inom detta område har stor betydelse inom såväl arbetslivet som i sjukvården och även för friska som transporterar sig utanför arbetet. Att det är svårt att utföra något, oavsett vad, när man är påverkad av rörelsesjuka är inte svårt att föreställa sig, men det är viktigt att veta vilka av våra förmågor som påverkas och hur, samt om utförandet t.o.m. blir påverkad tidigt i insjuknandet. Denna avhandling har studerat hur rörelsesjuka yttrar sig psykofysiologiskt och hur detta påverkar prestationsförmåga i form av olika minnestest. Psykofysiologi i detta fall innebär att vi har studerat puls, andning, svettningar, blodflöden, ögonrörelser och ytemperatur under påverkan av rörelsesjuka som vi på konstgjord väg har inducerat hos friska försökspersoner. Under påverkan av rörelsesjuka har man sedan fått utföra uppgifter.

Den första studien gick ut på att ta fram förutsättningar för att kunna studera ögonrörelser i förhoppning om att dessa skulle kunna vara relaterade till utvecklingen av rörelsesjuka. Dessa beteenden utmärker sig genom ökat antal fixationer när man blir rörelsesjuk. De två efterföljande studierna studerade hur prestationsförmågan påverkades av upplevd rörelsesjuka och i en sista studie genomfördes försök med en ljudhorisont, som hade till uppgift att påverka försökspersonerna utan att de visste om det, för att - om möjligt - förskjuta uppkomsten av symptom eller lindra eventuellt uppkomna åksjukesymptom.

Resultaten från studierna visar att främst puls och svettningar verkar vara två psykofysiologiska variabler som ökar med stigande upplevd rörelsesjuka. Likaså verkar försökspersonerna fixera blicken mer när de inte hade tillgång till ljudhorisonten i den sista studien. Detta skulle kunna betyda att färre fixationer ingår som antingen en medveten eller omedveten strategi för att lindra symptom. Vad beträffar prestationsförmåga verkar det i dessa studier främst vara korttidsminnet som påverkas av upplevd rörelsesjuka. Däremot påverkades inte alls inkodning av information eller förmågan att plocka fram information ur långtidsminnet av rörelsesjuka. De personer, vars prestationsförmåga påverkas av rörelsesjuka är framför allt de som avbryter försöken i förtid. Den ljudhorisont som användes i sista studien visade sig inte ha den avsedda effekten. En trolig anledning till att vi inte fick någon effekt av ljudhorisonten kan vara att studien innehöll för få försökspersoner samt att försökspersonerna vände sig vid den rörelse vi utsatte dem för. Det sistnämnda visade sig i att man klarade av rörelseexponeringen mycket längre den andra gången av två som man kom för att delta i testet.

Samtliga studier i denna avhandling har bidragit till att öka kunskapen kring hur vi påverkas, såväl fysiologiskt som prestationsmässigt av rörelsesjuka. Inom sjukvården är kunskapen kring de psykofysiologiska reaktionerna viktiga i diagnostisering och behandling av patienter med liknande symptom och för diagnostisering. Att veta vilka förmågor som påverkas vid

rörelsesjukeliknande tillstånd, förknippade med illamående m.m. är av stor vikt vid behandling och rehabilitering av patienter. Fortsättningsvis rekommenderas att studera rörelsesjuka i dess vida bemärkelse och framför allt den stora psykologiska komponent som finns genom t.ex. förväntan och tidigare erfarenheter. Likaså rekommenderas att fortsätta studera hjärnans "velocity storage" för att titta vidare på hur lång tid det tar för hjärnan att anpassa sig till rörelser, avsaknad av gravitation och likaså återanpassningen efter tillvänjning, mer känt som ilandstigningssyndrom.

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