

Factors and cognitive impairments of cybersickness
in virtual reality

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Justin Maximilian Mittelstädt

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Erstgutachter: Prof. Dr. Jan Wacker

Zweitgutachter: Prof. Dr. Lars Schwabe

Vorsitzender des Prüfungsausschusses: Prof. Alexander Redlich

Disputationsgutachter: PD Dr. Kirsten Hötting

Prof. Dr. Martin Spieß

Tag der mündlichen Prüfung: 15.02.2019

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Abstract

Virtual reality (VR) gains popularity in the entertainment industry and various professional contexts, such as healthcare, rehabilitation and aviation. Due to the vast technological advances in the last decades, the opportunities to develop applications allowing to experience and interact with immersive virtual environments have increased substantially. Despite its wider dissemination and improved technology, many users of VR still complain about symptoms of cybersickness during and after an exposure to virtual environments, including nausea, disorientation and headache. Cybersickness can be ameliorated to some extent by adjusting characteristics of the VR application and the hardware system but large inter-individual differences in the susceptibility to cybersickness remain. As symptoms of cybersickness can linger for a prolonged period of time after termination of the exposure, manufacturers of VR equipment recommend refraining from driving or using machines until symptoms cease. Still, the effect on cognitive performance remains undetermined.

In Study 1 of this project, I investigate the effect of different presentation devices and motion control methods on the degree of cybersickness and determine the influence of experienced symptoms on different parameters of cognitive performance as a VR aftereffect.

In studies 2 and 3, empirical analyses of two possible determinants of motion-related sickness related to emotional and cognitive processing of aversive bodily signals are conducted. The project is complemented by a comprehensive literature review exploring correlates and causes of individual differences in motion-related sickness susceptibility. Thus, this project contributes to a deeper understanding of the phenomenon of cybersickness.

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Unrelated publications

Below you will find a list of publications which were published during the time of the doctorate but are not related to the present project.

Grassmann, M., Vlemincx, E., von Leupoldt, A., **Mittelstädt, J. M.**, & Van den Bergh, O. (2016). Respiratory changes in response to cognitive load: A systematic review. *Neural Plasticity*, *8146809*, 1-16. doi: 10.1155/2016/8146809 .

Mittelstädt, J. M., Pecena, Y., Oubaid, V., & Maschke, P. (2016). Construct validity of the Temperament Structure Scales within the Big Five framework in aerospace selection. *Aviation Psychology and Applied Human Factors*, *6*(2), 68-80. doi: 10.1027/2192-0923/a000101.

Mittelstädt, J. M., Pecena, Y., Oubaid, V., & Maschke, P. (2016). Psychometric personality differences between candidates in astronaut selection. *Aerospace Medicine and Human Performance*, *87*(11), 933-939. doi: 10.3357/AMHP.4548.2016.

Pecena, Y., **Mittelstädt, J. M.**, Seemüller, A., & Maschke, P. (2018). Psychological selection of female space flight participants (SFP) candidates. In: *Flugsicherheit in Forschung und Praxis* (pp. 57-63). Fürstfeldbruck: DGLP.

Glossary

Cybersickness	The sickness that arises from the sole presentation of visual stimuli, typically visually represented movement. In contrast to <i>visually-induced motion sickness</i> , cybersickness refers to digitally created content that depicts a comprehensible virtual environment.
Head-mounted displays (HMD)	(<i>also VR glasses</i>). This term describes a technological device which can be put on like a pair of glasses or a helmet and through which a virtual environment can be perceived. HMDs usually cover all visual information of the real environment and transfer the head movements of the user to the movements of the virtual head.
Motion sickness	Sickness caused by extreme motion, such as rotational motion or in various motion vehicles (for example in a car, at sea or in an airplane).
Motion-related sickness	This term is used within this project to indicate that the statement made is not related to a particular type of sickness, but to all types of sickness caused by visual or vestibular motion (including motion sickness and cybersickness) alike.
Simulator sickness	Sickness caused by the use of simulators (usually flight or car simulators). Simulators always include a visual representation of the simulated environment. Some also offer vestibular feedback about the movements performed in the simulator.
Visually-induced motion sickness (VIMS)	Sickness induced by the continuous presentation of a moving visual pattern. In contrast to <i>cybersickness</i> , these stimuli do not necessarily have to be generated digitally and represent simple visual patterns instead of complex virtual environments.

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Introduction

Motion sickness is a well-known syndrome many people experience while traveling by car, train, airplane or being at sea. The condition is experienced as very unpleasant for affected persons who often quickly abandon the situation and seek to avoid it in the future. Among the symptoms that occur in affected persons are nausea, vomiting, dizziness, vertigo, headache, loss of concentration and increased fatigue up to, in extreme cases, complete incapacitation (Kennedy, Lane, Berbaum, & Lilienthal, 1993; Reason & Brand, 1975). This raises the questions of when and why does motion sickness occur, who is particularly susceptible and what are the short-term effects of motion sickness.

The most recognized theory for describing *when* (passive) motion leads to the development of sickness is the sensory mismatch theory (sometimes also referred to as neural mismatch theory). According to this theory, motion sickness is caused by an incongruence between the expected response of motion-relevant senses (vestibular, visual and proprioceptive) and the actual responses of these senses to a given motion stimulus. Since these senses usually coincide in their response to movement, motion sickness is often triggered when the responses of senses are incongruent (Reason & Brand, 1975). The principle can be illustrated by an example: while a boat or ship moves up and down during normal waves, the optical line of the water always remains constant. However, a vestibular movement is detected (up and down heave of the hull) which is not supported by the visual sensation (constant optical line). In this case, the incongruent information of visual and vestibular sensory organs (sensory mismatch) triggers motion sickness in many individuals. While potentially suffering extremely when a certain situation is first encountered, one can habituate to a certain pattern of movement stimulation and the situation loses its negative effect.

As to the question *why* people get motion sick, the evolutionary hypothesis of motion sickness (Treisman, 1977) provides the most popular and widely accepted approach. Treisman (1977) suggests that the ingestion of different neurotoxins causes similar symptoms of discordance between visual and vestibular senses as in motion sickness. In cases of neurotoxin poisoning, it is an evolutionary advantage if the body reacts with vomiting and the immediate ejection of the hazardous substance. Motion, as described above, can lead to similar symptoms of discordant sensory information and motion sickness is thus proposed to be a byproduct of this mechanism which in itself does not provide

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an evolutionary advantage (Treisman, 1977). Notably, motion sickness usually occurs in situations associated with more or less new technological advances (from seafaring to supersonic jets) which are likely to be unaffected by evolutionary adaption processes.

The condition of motion sickness is not new and has been known for a long time. Even the ancient Greeks and Chinese reported nausea in seafarers. These early reports of the negative effects of movement on the body are surprisingly detailed. Accordingly, the ancient Greeks described that especially those who have little experience with seafaring and pronounced anxiety are most susceptible to the emergence of motion sickness (Huppert, Oldelehr, Krammling, Benson, & Brandt, 2016) which is very similar to results in modern research (see chapter on Individual differences).

Moreover, the phenomenon was so well known in ancient China that already in 300 A.D. there were two separate Chinese letters for seasickness and for sickness triggered by the use of horse carts (Brandt, Bauer, Benson, & Huppert, 2016). There were similar reports of Napoleon's expeditions, during which his soldiers became ill not only at sea, but also because of the passive movement triggered by riding on a camel's back, a phenomenon consequently termed camel sickness (Huppert, Benson, & Brandt, 2017).

In more recent history, since the emergence of motorized transportation like cars and airplanes, motion sickness in those kinds of vehicles has been acknowledged to be a serious issue as well (Reason & Brand, 1975; Samuel & Tal, 2015). In an early study with data from the 1940s with a huge sample size of about one million participants, approximately 75 % of all passengers reported symptoms similar to motion sickness when flying in an airplane (Lederer & Kidera, 1954). This number seems to have decreased since then, probably due to technological development and the habituation of passengers to regular flights with airplanes. However the issue is far from solved. In a study conducted in 2000, 48 % of respondents said they experienced motion sickness symptoms during flights (Turner, Griffin, & Holland, 2000). Given the still high incidence rates in common modes of transportation, motion sickness is a threat to passenger comfort and, if pilots are affected, can pose a significant safety risks.

Pilots are not only at risk within the aircraft, but often complain about motion sickness in full-flight simulators, i.e. flight simulators which, in addition to a visual scenery, try to reproduce the

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motions of a real aircraft (D. M. Johnson, 2005; Kolasinski, 1995). Interestingly, this *simulator sickness* occurs more frequently among experienced flight personnel such as instructors who have greater experience of how the real aircraft would move, than among less experienced student pilots (D. M. Johnson, 2005).

In addition to full-flight simulators, simulator sickness also occurs in fixed-base simulators, i.e. simulators without any motion feedback. This is a first indication that motion-related sickness can also occur in the absence of any physical movement without stimulating the vestibular sense. And indeed, although the vestibular sense of motion sickness is of great importance, especially because it is the primary human sense of motion detection, motion sickness can also be triggered when there is no vestibular stimulation at all, when motion is visually presented but not actually experienced (Reason, 1969b). Numerous experiments on visually induced motion sickness (VIMS), in which participants are usually presented with an alternating pattern, for example black and white stripes in a so-called optokinetic drum, confirm the assumption that motion sickness can also be induced in the absence of any actual movement. Motion sickness therefore does not necessarily seem to be a consequence of physical movement but instead seems to be a consequence of inadequate integration of different movement stimuli in the central nervous system (Kohl, 1983).

While the experiments on VIMS are rather artificial and only slightly reflect conditions of real environments, the development of new technologies in the field of virtual realities (VR) lends new practical relevance to the topic.

VRs are digitally rendered environments which are most often presented with a head mounted display (HMD). Apart from being applicable in the entertainment industry, there are numerous applications in various professional contexts, such as the execution or training of surgeries (Seymour, 2007), physical (Plante, Aldridge, Bogden, & Hanelin, 2003) and cognitive rehabilitation (Meyerbröker & Emmelkamp, 2010), in the aviation industry, e.g. in aircraft maintenance (Ong & Nee, 2004) or during flying, or in many other areas. VR technology is particularly useful because it can provide additional information or allows an object to be viewed from different angles. In addition, immersion, a phenomenon often observed in VRs, increases the ability to experience certain situations emotionally.

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However, many users of VR complain about problems with the use of VR systems, especially symptoms that are very similar to motion sickness. *Cybersickness* was suggested as the term for this kind of motion sickness experienced in virtual realities (McCauley & Sharkey, 1992).

The phenomenon is disadvantageous for several reasons. On the one hand, sickness itself is an aversive condition and thus undesirable. On the other hand, nausea in particular has a strong influence on the negative conditioning of the nausea-inducing stimulus (the VR application) and will probably lead to the application being used less in the future (Bowins, 2010; Hu & Hui, 1997). This circumstance could therefore have a detrimental effect on the popularity and could reduce the willingness to use such technologies in professional contexts where they should actually simplify work (e.g. in aviation or in the operating room). It is also unclear to what extent cybersickness can have a negative effect on users beyond the adverse experience itself and whether it possibly poses a safety risk (e.g. through loss of cognitive performance). Therefore, research should focus on methods to reduce the number of cases of cybersickness and, when they occur, their severity.

Due to the relative novelty of the technology and the pace with which new developments are presented, there is a lack of research on the subject in many areas. However, research on cybersickness can draw on a long history of research on motion sickness, the validity of which, however, has yet to be verified in many respects within this new context.

This thesis attempts to contribute to this research by investigating aspects of application design, individual susceptibility, and consequences of cybersickness on cognitive performance.

Outline

I will first give an overview of the influence of different technical design possibilities on sickness induction. Then, I will present inter-individual predictors of susceptibility to motion sickness and visually induced types of motion sickness (including cybersickness). Since this area of research is very complex and there is a lack of a comprehensive review of the literature, I have conducted a literature review and will present the results accordingly. Finally, I will present findings on possible negative effects of cybersickness on cognitive performance.

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Following this theoretical introduction, the studies and articles that are part of this project will be outlined. Study 1 examines two separate questions and investigates the effects of different hardware components (display and control method) on cybersickness (Article 1), as well as the effect of cybersickness on cognitive performance (Article 2).

Studies 2 and 3 are represented in Article 3. This article addresses inter-individual differences in susceptibility to cybersickness and specifically examines the influence of cognitive and emotional processing of aversive body perceptions on the degree of motion sickness susceptibility (Study 2) and reported cybersickness symptoms (Study 3).

Finally, I will summarize the results and discuss their implications as well as possible future research opportunities.

Cybersickness - Technological aspects

The number of people who feel sick in a virtual reality and the severity of this sickness depends considerably on characteristics of the system used, i.e. on characteristics of the application (representation of motion, graphic complexity etc.) and on the hardware (Rebenitsch & Owen, 2016).

Even the definition of what a virtual reality is, which applications belong to it and which do not, is often very vague. Generally speaking, virtual reality is defined as a three-dimensional, digitally rendered environment that gives users a sense of presence within a different non-physical reality, a sense of "being there" (Steuer, 1992). While there are clear differences between technologies in their ability to create this sense of presence, the definition of VR also strongly depends on individual tendency (the same system could be called a VR when applied with one person and not when applied with another).

This definition is not strictly adhered to in the literature and VRs are often defined according to the technology used rather than whether it could create a sense of presence for every user. Sometimes the definition is even extended to situations that may not correspond to the given definition, like normal video games or 3D movies. In most cases, VR is equated with virtual 3D environments represented with certain presentation technologies.

Display

One of these technologies is the so-called head-mounted display (HMD), a type of spectacles worn by the user, also often referred to as VR glasses. The virtual environment is presented to the user via two small displays, one for each eye, which are worn only a few millimeters in front of the eyes. In addition to the displays, the visual surroundings are masked by the black coating of the HMD. Importantly, in a HMD the movements of the head are tracked and transferred to the movements of a virtual camera, often a virtual head. This makes it easy to control the virtual viewing direction with one's own head movements.

Likewise, a CAVE (computer-aided virtual environment), a structure with three to six walls that are illuminated by separate projectors and whose representations change according to the

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movements of the user, is a different immersive system used to present virtual environments, however considerably less often than HMDs because of their vast costs and difficult spatial requirements.

HMDs and also CAVEs are used because they offer greater immersion compared to normal screens, giving the user more opportunity to dive into the virtual world. Similarly, greater immersion may offer advantages in professional applications: a surgeon viewing a virtual model of an MRI scan with a HMD can intuitively view the tissue from all sides and may be able to make better surgical decisions (Sadda, Azimi, Jallo, Doswell, & Kazanzides, 2013) or might practice his surgical skills in a virtual application before a surgery (Seymour et al., 2002). An operator who remotely controls a vehicle or flying object may be able to make more intuitive decisions because the spatial conditions are perceived from an ego perspective, i.e. a perspective from the virtual character's viewpoint, and do not need to be transferred into a mental spatial model (McIntire, Havig, & Geiselman, 2012; Ruddle, Payne, & Jones, 1999). CAVEs are often used because they offer the possibility to imagine interiors more easily. In addition, CAVEs usually have a wider field of view than HMDs as the projected scenery usually fills the entire visual field.

Despite their advantages, results from several studies suggest that HMDs induce more cybersickness compared to displaying the same virtual environment on a large or projector screen (Liu & Uang, 2011; Rebenitsch & Owen, 2017; Sharples, Cobb, Moody, & Wilson, 2008; Tan, Leong, Shen, Dubravs, & Si, 2015; Tong, Gromala, Gupta, & Squire, 2016). Similarly, CAVEs also induce more cybersickness than applications on a simple desktop screen (Kim, Kim, Kim, Ko, & Kim, 2005). These results suggest that those display technologies which provide greater immersion also induce more cybersickness.

However, there were also results to the contrary. Keshavarz, Hecht, and Zschuschke (2011) found in their study that the level of cybersickness was higher when a movie from the inside of a car driving on a race track was presented on a projector screen than when participants watched it with a HMD. The effect no longer persisted when the physical reality of the projector was masked to the same field of view as the HMD. They proposed that the size of the field of view determines to a large extent the severity of cybersickness induced, a claim confirmed in other studies (Lin, Duh, Parker, Abi-Rached, & Furness, 2002; Seay, Krum, Hodges, & Ribarsky, 2002).

However, they also assumed that the visible physical context next to the projector screen (e.g. the floor illuminated the screen) further amplified the sensory mismatch by not fitting in with the action depicted on the screen (Keshavarz et al., 2011). This stands in contrast to the theories on independent visual backgrounds which claim that visual cues remaining unchanged, independent of the actions on the visual scenery, help alleviating symptoms of cybersickness (Duh, Abi-Rached, Parker, & Furness, 2001; Prothero, Draper, Furness, Parker, & Wells, 1999).

Due to the fact that the most recently presented results stand in stark contrast to the previous studies on differential effects of different display systems, the results of the studies will be replicated or reviewed within the scope of this project. This study should determine differences in cybersickness inducement between HMDs and large screens. For this purpose, the VR was presented in both on an HMD and on a large screen including visual masking of the external environment in Study 1 of this project.

Control device

Another aspect that, however, has received less attention compared to display technology is the implementation of motion control within the VR application. Many applications use passive motion, e.g. a roller coaster ride, or avoid motion at all. This is especially true for commercially available applications in the gaming industry, where the incidence of cybersickness in users is to be drastically reduced. Since virtually presented motion is assumed to be the primary cause for cybersickness, motion in such applications is often considered to be too high a risk. This often eliminates the need for active motion control. Teleportation, i.e. the user is teleported from one spot to the next without possibility to roam the space between designated spots, is a common mechanism that is used instead.

Sometimes, however, active control is desired, as it increases the possibility of free exploration and can improve the overall user experience. In these cases a generic control method is often used, for example gamepads or joysticks, since these are already known from commercial games, readily available and easily integrated into new applications.

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Realistic control methods may have the advantage of generating more sense of presence (Slater, Usoh, & Steed, 1995) and in turn may have benefits for professionals using the technology. Moreover, using equipment for physical exercise such as a bike ergometer for controlling movements in a VR could have a positive effect for those who have to work with this equipment anyhow, e.g. in rehabilitation (e.g. Plante et al., 2003) or for astronauts on the ISS (Trappe et al., 2009).

More realistic control methods are used in simulators (car or flight simulators), in which a cockpit or the dashboard of a car including a steering wheel are re-created (e.g. Helland et al., 2016) but they are rarely used in VR applications with HMDs and have rarely been examined systematically for effects on the degree of cybersickness. Yet, realistic locomotion controls could reduce the degree of cybersickness. According to the sensory mismatch theory, motion sickness occurs when the perceived movement in individual sensory organs deviates from the expected pattern of responses (Reason & Brand, 1975). Since proprioceptive sensory sensations are also involved in the integration of movement perception, cybersickness might be reduced by performing the same motor actions one would do in physical reality to control movement.

When investigated, studies often use walking as a realistic mode of motion, either on a treadmill (Aldaba, White, Byagowi, & Moussavi, 2017; Jaeger & Mourant, 2001), walking in place, i.e. walking movements on the spot that are captured (Bhandari, Tregillus, & Folmer, 2017; Lee, Kim, & Kim, 2017), or outside with a position estimation system and the VR equipment in a backpack (Llorach, Evans, & Blat, 2014). A different approach was presented by Tregillus, Al Zayer, and Folmer (2017), who enabled users to control their movements with head tilts.

Jaeger and Mourant (2001) and Llorach et al. (2014) found that walking motions were superior in preventing cybersickness compared to a generic control method. However, Bhandari et al. (2017), Aldaba et al. (2017), Lee et al. (2017) and Tregillus et al. (2017) were not able to determine any significant differences in sickness induction between their navigation method and a generic one. Aldaba et al. (2017), for instance, compared an omni-directional treadmill, i.e. a treadmill that works in every possible direction, with other more generic modes of navigation, including a joystick and a wheelchair joystick and were not able to determine differences in their effect on cybersickness.

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Since the data is still sparse and contradictory and the type of locomotion so far only refers to walking, more research is needed to determine possibilities for the prevention of cybersickness with different control devices. Hence, Study 1 of this project will investigate the effect of generic control and a more realistic control of motion on cybersickness by using a virtual bike simulator.

Cybersickness - Individual differences

Even within the same setting, the same motion vehicle, simulator, or VR system, studies of motion-related sickness typically yield vast differences between individual sickness experiences which cannot be attributed to the utilized stimulus. The causes of these inter-individual differences in susceptibility to motion-related sickness have been subject to many investigations since the 1950s (e.g. Kottenhoff & Lindahl, 1958). Nevertheless, a definite explanation of these differences remains undetermined.

Due to a lack of a comprehensive review of factors for individual differences, I conducted a literature review applying some systematic approaches. The goal of this review is to provide a comprehensive overview about past research, to identify factors which reliably contribute to the explanation of inter-individual differences and to reveal possible factors associated with motion-related sickness that need further clarification.

As many of the included studies used widely different methods (from the type of motion exposure to the outcome measurement), the aggregated parameters reported in the following review will only provide a rough overview and no exact estimate.

Literature research

Searches of electronic databases PubMed and PsycINFO were conducted using the following search term:

[motion sickness OR cybersickness OR simulator sickness OR visually induced motion sickness OR vr sickness OR gaming sickness] and [personality OR ability OR individual differences OR age OR gender OR gene OR susceptibility OR anxiety OR neuroticism].*

Auto-exploding of both databases was enabled, using thesaurus expressions for all terms included in the query. No date restrictions were set.

The query resulted in 1282 references in the PubMed database and 496 references in PsycINFO. I pre-screened publication titles and abstracts regarding fit to the subject of this review.

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Irrelevant publications were excluded. The remaining references were subjected to a detailed full-text screening.

The goal was to identify (stable) individual characteristics that affect motion-related sickness or are empirically related to it. This does not necessarily imply trait-like characteristics (e.g. personality) but assumes reasonable stability across different situations (e.g. habituation or experience) and precludes any characteristic induced by a treatment (e.g. anti-motion sickness drug) or due to context of the situation (e.g. being the driver vs. passenger).

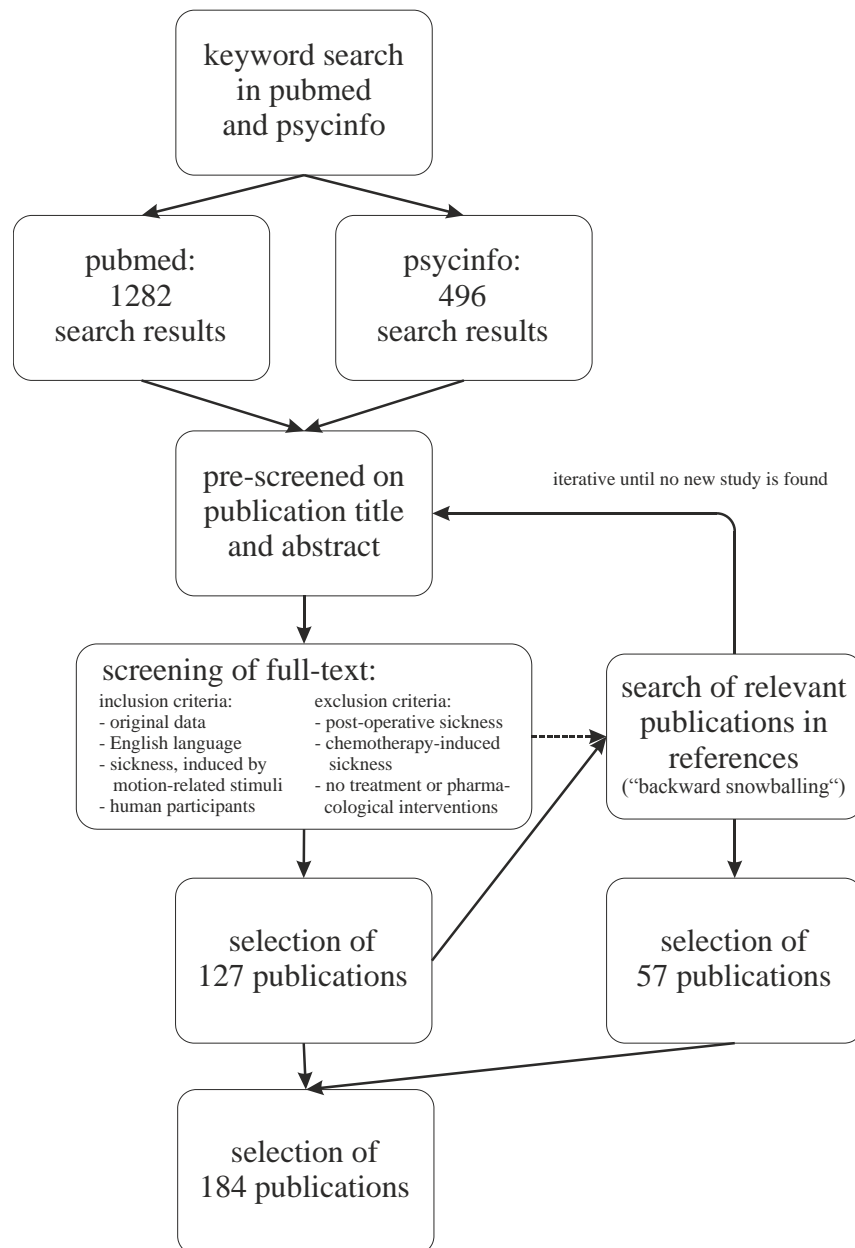


Figure 1. The procedure for the selection of publications

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Studies were selected for inclusion in the present review based on multiple criteria. I selected studies with original data in English language covering sickness induced by motion-related stimuli, i.e. extreme motion, motion vehicles and visually presented motion. This excluded all studies investigating post-operative sickness, chemotherapy-induced sickness and all kinds of sickness without reference to motion-related stimuli. I furthermore excluded all studies using a treatment to alter motion sickness susceptibility, unless reporting separate results for a control group. This included pharmacological interventions using anti-motion sickness drugs.

Finally, only studies involving human participants were included in the review. This narrows down the available evidence, especially with regard to physiological factors influencing motion-related sickness. However, it prevents a discussion on the generalizability of findings in animal studies to human organisms.

The screening of title, abstract and full-text, applying the inclusion criteria, yielded 127 publications fitting the purpose of this review. All of the selected publications were peer-reviewed journal articles.

Subsequently, I searched the reference lists of all selected publications for relevant papers following the same procedure and inclusion criteria from the original search (“backward snowballing”). After the first iteration of searching the reference lists, I repeated the procedure for the newly selected publications until no novel relevant publication could be identified. This method yielded 57 additional publications. These publications included peer-reviewed journal articles, conference proceedings papers and technical reports, for example from the National Aeronautics and Space Administration (NASA).

The procedure for the selection of publications is outlined in Figure 1.

Study characteristics

A total of 184 publications were included in this review. Study characteristics and key findings that appeared relevant were extracted from the full-text and entered into a list. The list of relevant study information eventually included meta-information like title, authors, journal and year of publication as well as the following study characteristics: sample size, sample composition (male only/

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female only/ both genders), type of sickness induced, sickness induction method, outcome/sickness measurement, and information on significant and non-significant predictors of sickness analyzed in the study. Table 1 summarizes the study characteristics of the 184 publications.

Sample sizes covered a large range from 8 to 80,494 participants. The largest sample size by far was used by Hromatka et al. (2015) in the investigation of genetic predictors. However, the median sample size was 50 participants. Most studies investigated mixed samples with male and female participants but 25 studies (14 %) only considered one gender. Studies investigating only male participants were mainly conducted with military personnel or seafarers while the female only studies often investigated the effect of the menstrual cycle.

The most frequently assessed type of sickness was the motion sickness history (not counting studies in which motion sickness history was used as an independent variable) which is not actually experimentally induced but reported in a survey from past motion sickness occurrences. The different sickness inducing techniques illustrate the abundance of different methodology used in this field of research. Especially for motion sickness, motion stimuli differed quite substantially ranging from a space flight to a boxing fight. These methodological differences largely do not allow meta-analytical methods to be applied.

The variety of methods is also reflected in the list of different sickness measurement tools. Most studies use report questionnaires filled in by the participants or a trained observer. Many studies use self-made symptom checklists, self-made sickness history questionnaires, or provide insufficient reference to where they obtained their assessment method. These self-made tools are, however, often similar to the published questionnaires and usually involve an inquiry of nausea, dizziness and headache which are rated on a specified scale. Only few studies used self-determined termination or a clearly defined physiological response such as vomiting as measurement of motion-related sickness.

In the following, the results of the literature review will be presented in more detail.

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Table 1. Characteristics of selected studies ($N = 184$).

	<i>Number of studies</i>	<i>% of studies</i>
Sample		
Median size (range)	50 (8 – 80,494)	
Male only	17	9.24
Female only	8	4.35
Both gender	159	86.41
Type of sickness induced		
Motion sickness	55	29.89
rotation device	26	14.13
parabolic flight	9	4.89
on the sea	6	3.26
boxing bout	2	1.09
space flight	2	1.09
training train ride	2	1.09
military flight	1	0.54
rocking chair w/ prism glasses	1	0.54
Simulator sickness	11	5.98
driving simulator	10	5.43
helicopter simulator	1	0.54
ship motion simulator	1	0.54
Visually-induced motion sickness (VIMS)	39	21.20
optokinetic drum	29	15.76
moving room	8	4.35
rotary prismatic visual stimulation	2	1.09
Cybersickness	21	11.41
virtual reality	19	10.33
3D movies	2	1.09
Motion sickness history	64	34.78
Sickness measurement		
Simulator Sickness Questionnaire (SSQ)	34	18.48
Graybiels diagnostic criteria (CSSI)	26	14.13
Motion Sickness Susceptibility Questionnaire (MSSQ)	20	10.87
Motion Sickness Questionnaire (MSQ)	16	8.70
Seasickness Susceptibility Questionnaire	10	5.43
Pensacola Diagnostic Index	5	2.72
Self-made symptom checklist (SR)	5	2.72
(Time to) abort	4	2.17
Self-made motion susceptibility (Mirabile)	3	1.63
Motion Sickness History Questionnaire (MSHQ)	3	1.63
Nausea Profile (NP)	3	1.09
Brief Vestibular Disorientation Test (BVDT)	2	1.09
Self-made symptom checklist (Kerguelen)	2	1.09
MSAQ	2	1.09
Airsickness and Health Assessment Inventory	1	0.54
Body sway	1	0.54
Diagnosis of chronic intractable motion sickness	1	0.54
Fast Motion Sickness Scale (FMS)	1	0.54
Illness Rating (IR)	1	0.54
Time to occurrence of symptoms	1	0.54
Vision and Motion Sensitivity Questionnaire (VMSQ)	1	0.54
Vomiting	1	0.54
Self-made symptom checklist	35	19.02
Self-made sickness history questionnaire	15	8.15

Demographic aspects

Gender.

Gender has been the most investigated predictor with regard to motion-related sickness. Furthermore, differential sickness scores for gender or gender comparisons are given in many publications despite not being the main research question. Thus, gender is probably the predictor least affected by publication bias.

In my set of selected publications, 37 provided gender comparisons. These studies differ considerably in their applied methods of motion-related treatment and outcome measurement. As can be seen in Table 2, about half of the given scores compared gender differences in motion sickness history, asking for past motion sickness incidences in various motion vehicles. The remaining studies reported sickness incidences or symptom scores following an experimental treatment. These treatments themselves differed tremendously in duration and stimulus quality, from motion sickness incidence during approximately 60 hours of initial flight training (Lucertini, Lugli, Casagrande, & Trivelloni, 2008) to cybersickness in an immersion to a virtual reality for up to 15 minutes (Munafo, Diedrick, & Stoffregen, 2017). Most of these studies used symptom or general sickness severity ratings. Three studies simply used self-determined quitting of the exposure as outcome measurement.

Seven of the included publications provided comparisons for both motion sickness history and sickness ratings following an experimental exposure.

Table 2 shows that 17 of 19 comparisons found significantly higher motion sickness history scores for women when asked in a survey for motion sickness history. The only studies not indicating higher motion sickness history for women are Study 2 of this project and Yanus and Malmstrom (1994) who did not provide descriptive or test statistics on the comparison but solely reported a non-significant difference.

Besides motion sickness history, only six of 23 studies found significant differences in symptom severity scores following the exposure to an experimental sickness-inducing stimulus. Three of four studies reported significant gender differences in the rate of quitting a motion exposure due to sickness symptoms.

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Table 2. Number of studies reporting significant and non-significant differences between genders for motion sickness history, actual symptom ratings and quitting.

	<i>Significant difference</i>	<i>No significant difference</i>
Motion sickness history	17	2
Actual symptom ratings	6	17
Quitting	3	1
Total	26	20

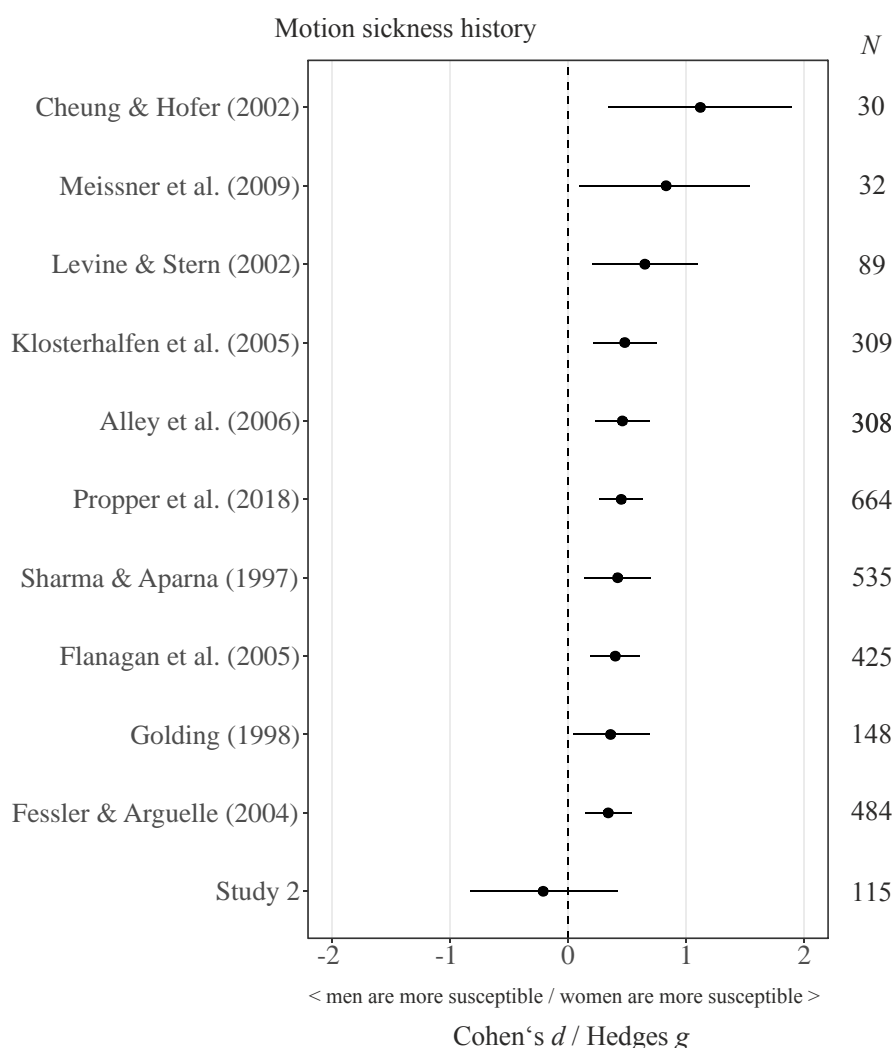


Figure 2. Gender effect on motion sickness history. Effect sizes with 95% confidence interval.

In order to more closely investigate the evidence, I performed analyses of the effect sizes for the differences of male and female participants. Twenty seven effect sizes could be extracted from the publication sample. Sixteen studies did not provide enough information to compute effect sizes. Figure

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2 to Figure 4 present an overview about the effect sizes separated for motion sickness history (Figure 2), (actual) sickness severity (Figure 3) and quitting (Figure 4). For studies reporting mean and standard deviations of scores, *t*-tests or *F*-tests, Cohen's *d* was computed. However, for studies using a χ^2 -test, Hedges *g* was used.

Analyses of the mean of effect sizes, weighted by sample size, yielded an average effect size of .34 (CI: .26 - .43).

Due to the differences in the number of significant results indicated for motion sickness history and symptom severity, I performed separate analyses for the different types of outcome measurements. The results can be seen in Table 3. While the average weighted effect size for motion sickness history was at .45 (CI: .35 - .54), the average effect size for actual severity ratings was considerably lower (weighted mean: .22; CI: .08 - .36) and highest for quitting (weighted mean: .60; CI: .55 - .66). The analysis of quitting, however, was only based on three studies, including my own. It must be noted that the weighted effect size does neither include the quality of the study nor publication bias.

The analyses indicate a stronger gender difference in motion sickness history than in sickness severity ratings when exposed to an actual motion-related stimulus. These findings have already been reported in the literature, especially those publications reporting both differences for susceptibility and severity ratings (e.g. Klosterhalfen, Pan, Kellermann, & Enck, 2006).

Table 3. Sample size-weighted mean and SD of effect size for gender. CI = confidence interval.

	<i>weighted mean d</i>	<i>weighted SD d</i>	<i>%95 CI</i>
Motion sickness history	.45	.16	(.35 - .54)
Actual symptom ratings	.22	.29	(.08 - .36)
Quitting	.60	.05	(.55 - .66)
Total	.34	.23	(.26 - .43)

A greater susceptibility of women to motion-related sickness has often been explained with hormonal changes during the menstrual cycle. Six studies have investigated the role of the menstrual cycle in the genesis of sickness to motion-related stimuli. While two did not find a cyclical alteration

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of sickness susceptibility (Cheung, Heskin, Hofer, & Gagnon, 2001; Gianaros, Reh, Burke, & Stern, 2000) four of them found a significant effect.

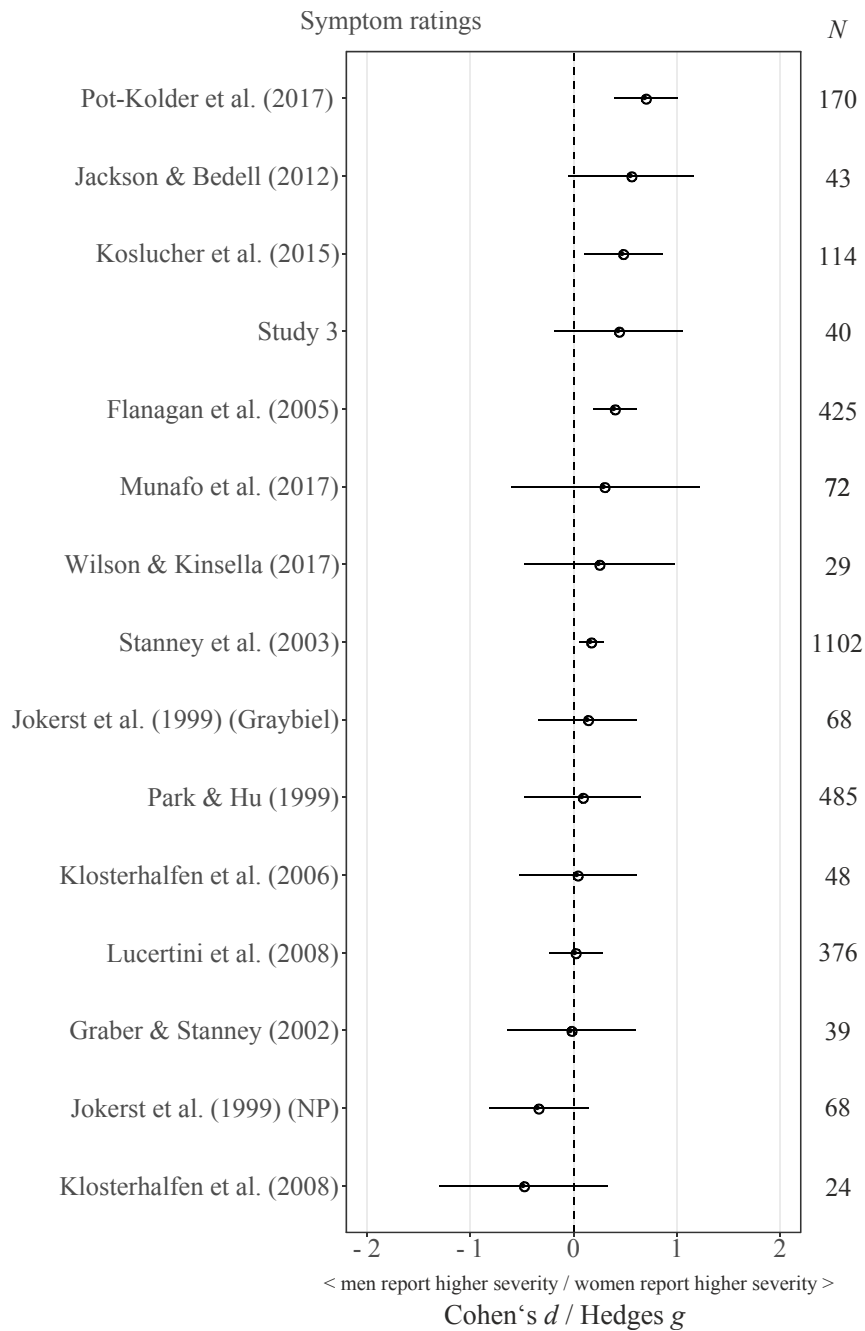


Figure 3. Gender effect on symptom severity ratings. Effect sizes with 95% confidence intervals.

Of these, three studies reported increased sickness symptoms during menstrual and peri-menstrual phases (Golding, Kadzere, & Gresty, 2005; Grunfeld & Gresty, 1998; Matchock, Levine, Gianaros, & Stern, 2008) while one study found the opposite and observed stronger symptom severity

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during the ovulation (Clemes & Howarth, 2005). In addition, Matchock et al. (2008) failed to determine a fluctuation of sickness susceptibility during the menstrual cycle for women who took oral contraceptives at the time of the experiment and were thus regulating their hormone balance. The influence of the menstrual cycle on sickness susceptibility was suggested to be caused by fluctuating estrogen levels (Clemes & Howarth, 2005; Matchock et al., 2008). Women near their ovulation tend to be more sensitive to auditory, olfactory and visual stimuli and may therefore be more sensitive to sensory mismatch. Moreover, high estrogen levels can increase the number of dopamine receptors which are usually inhibited by some effective anti-emetic drugs (Beattie, Lindblad, Buckley, & Forrest, 1991). However, instead of the absolute estrogen level which is highest during ovulation, Beattie et al. (1991) suggested that changes in estrogen concentration before and at the end of the menstruation sensitize chemoreceptive trigger zones.

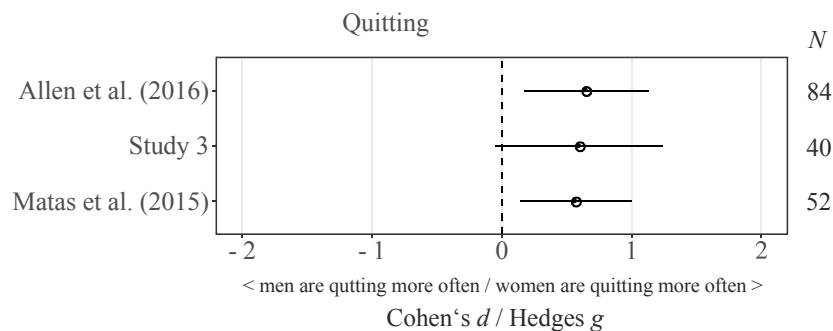


Figure 4. Gender effect on quitting a motion exposure.

Besides fluctuations during the menstrual cycle, another explanation has been presented in anthropometric differences between males and females, e.g. differences in height or center of body mass. Differences in certain anthropometric properties can yield differences in the ability to maintain postural stability when being exposed to motion-related stimuli which in turn might lead to increased sensations of motion sickness (Smart, Stoffregen, & Bardy, 2002). Few studies have been carried out investigating anthropometric differences with sickness symptoms. Koslucher, Haaland, Malsch, Webeler, and Stoffregen (2015) found that increased VIMS was associated with shorter foot length and smaller height (when controlling for gender, weight, and/or body mass index), both characteristics more prevalent in women. Stanney, Hale, Nahmes, and Kennedy (2003) found a weak but significant

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correlation ($r = .07$) of the body mass index, but only with oculomotor symptoms of sickness and not with nausea or disorientation.

Golding (2006) suggested a hypothetical evolutionary adaptation as a reason why women should be more susceptible to motion-related sickness. According to that hypothesis, higher sensitivity to nausea-inducing stimuli gives an advantage in protecting a fetus from dangerous toxins. However, this has not yet been empirically investigated.

Despite all these explanations, the results indicate a stronger gender difference when asking for past occurrences of motion sickness than when assessing symptom severity after actual exposure to an adverse stimulus, suggesting at least a partial contribution of response bias when asking with a survey.

Some authors similarly expressed the hypothesis of a gender-dependent response bias. Perhaps females have the tendency to more readily admit the incidence of motion sickness or are generally more inclined to report physical discomfort (Cheung & Hofer, 2002; Flanagan, May, & Dobie, 2005). Admitting sickness might be part of a diverging socialization and ultimately more socially accepted for women than for men (Flanagan et al., 2005; Klosterhalfen et al., 2006).

However, a similar effect should be observable in reports of symptoms. It is questionable why men withhold reports of past motion sickness incidences but readily admit symptoms in an experimental setup. Furthermore, Jokerst et al. (1999) did not find the experimenter's gender influence the symptom ratings of the participants which would be expected if responses are biased by the social acceptance. Dobie, McBride, Dobie Jr., and May (2001) also found gender differences in some but not in all kinds of vehicles in reports of motion sickness history. If there is a general tendency towards less admitting sickness occurrences, males should have indicated less sickness across all vehicles.

Another explanation could be the different assessment approaches in motion sickness history and actual sickness severity. Surveys for sickness history usually ask for the incidence of motion sickness in a dichotomous "yes" or "no" format and the frequency of these occurrences. Assessments of sickness after actual exposure to motion-related stimuli typically ask for sickness severity on a continuous scale. Women might indicate more severe sickness with lower ratings on the sickness scale

than men do. Moreover, women might have a lower threshold of symptom severity above which they indicate a motion sickness incident (Flanagan et al., 2005).

Finally, Koslucher et al. (2015) suggested that gender differences may be related to the nature of the given stimulus. They proposed that women are more susceptible to sickness when exposed to linear oscillation in contrast with facing rotational motion. This is in line with the observation that gender differences in response to actual motion exposure are predominantly found in commercial transportation (Cheung & Hofer, 2002) which often involve more linear (e.g. heave of a ship) than angular movement.

In summary, the majority of studies found an effect, suggesting an influence of gender on motion-related sickness. However, future studies should determine the exact extent of response bias in gender-related differences and why this effect may be different between the report of past occurrences of motion sickness and the report of actual motion sickness severity.

Age.

Unlike gender, relationships between age and motion-related sickness were less often reported. Only sixteen studies in my sample of publications provided correlations with age or comparisons of different age groups. Since many studies were carried out using student, flight school or military participants, studies often used samples homogenous in terms of age. In those cases, a comparison of different age groups is neither possible nor useful. In order to determine age-related effects, large ranges of age, preferably from childhood to seniors, would need to be used.

Table 4 shows a summary of the studies investigating age effects on motion-related sickness in terms of sickness increasing or decreasing with age or having no effect. A fourth option is a relationship of age and sickness, however, in a complex, non-linear manner. As previous studies suggested differences in the effect of age depending on the type of sickness, i.e. the type of motion stimulus (Arns & Cerney, 2005), I further divided the descriptive statistics into physical motion induced sickness (motion sickness/ motion sickness history) and visually induced sickness (simulator sickness/ VIMS/ cybersickness).

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Table 4. Number of studies reporting an increase or decrease of sickness, a complex (e.g. non-linear) relationship or no relationship with age, separately for motion induced and visually induced sickness.

<i>Type of sickness</i>	<i>Increase</i>	<i>Decrease</i>	<i>Complex</i>	<i>No relationship</i>
Motion sickness (history)	1	4	2	1
Simulator sickness / VIMS / Cybersickness	4	0	0	4
Total	5	4	2	5

Unfortunately, many studies did not provide sufficient information to perform a detailed analysis of effect sizes. For visually induced types of sickness, susceptibility tends to increase with age and in contrast to motion sickness, no study found a decrease of sickness severity with age. However, there were also three studies which did not find a relationship between age and sickness severity in visually induced sickness.

For motion sickness, older participants tended to experience less sickness than younger participants in four of eight studies. It must be noted that all studies (with one exception) observing linear relationships between age and sickness were using adult samples. The two studies observing a complex pattern (Bos, Damala, Lewis, Ganguly, & Turan, 2007; Sharma & Aparna, 1997) also included younger children. Sharma and Aparna (1997) reported that children below the age of two are practically immune against any kind of motion sickness. Bos et al. (2007) did not observe any motion sickness below the age of five with the youngest participants being four years old. In both studies, young children have been assisted by those responsible for them in filling in the survey. It remains questionable, whether surveys of children of that age are yielding reliable data.

After the age of five, Bos et al. (2007) found a sharp increase of motion sickness severity with somewhat different progression for males and females. While females were reported having higher amplitude of susceptibility and peaking earlier at the age of 11, men were not having their highest motion sickness susceptibility until the age of 21. After their peak, susceptibility gradually decreased for both men and women (Bos et al., 2007).

This is in line with all the studies finding a trend of decreasing motion sickness scores for older participants, given that these studies only had adult participants.

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The studies on age were fairly consistent and some had large samples like the study by Bos et al. (2007) who investigated 2840 individual surveys. However, the question remains why age should have an impact on sickness susceptibility and why motion induced sickness and visually induced sickness putatively differ in their relationship to age.

Aging is accompanied by loss in visual and vestibular functioning which could desensitize older individuals to sensory conflict responsible for inducing sickness. This hypothesis might explain the decrease of motion sickness with increasing age but does not explain and even stands in contrast to the elevated susceptibility of older participants to sickness induced by visually presented motion.

Golding, Paillard, Normand, Besnard, and Denise (2017) found older participants in parabolic flight being less susceptible to in-flight motion sickness than younger participants but also noted a significant correlation of age and experience with parabolic flights. They concluded that relationships of age and motion sickness were most likely caused by the habituation of repeated exposures (Golding et al., 2017).

Similarly, many studies used commercial transportation like coach busses (Turner & Griffin, 1999) or cruise ships (Bos et al., 2007) as motion-inducing stimuli or were assessing motion sickness history with the frequency of motion sickness incidences in different common motion vehicles such as cars, ships and airplanes (Dobie et al., 2001; Paillard et al., 2013; Propper, Bonato, Ward, & Sumner, 2018; Sharma & Aparna, 1997). This might suggest that the observed effect of age might be a mere effect of habituation due to more frequent exposure to these common motion vehicles.

Habituation is also a possible explanation for the inverted relationship of age and sickness with visually presented motion, at least for cybersickness. Computers, video games and virtual environments still enjoy greater popularity among younger people. Many young people are playing video games regularly or are using digital devices in their leisure time. Since many simulators or VR applications share many characteristics, playing video games or using a computer in general could provide a similar habituation for visually induced sickness as motion vehicles for motion sickness. This hypothesis can also be used to explain the gender differences discussed above as males usually play more video games than females.

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Visually-induced motion sickness using an optokinetic drum is a stimulus, relatively uncommon in everyday life. In accordance with the previously presented rationale, the only study using VIMS to investigate a relationship with age yielded no significant association (Jackson & Bedell, 2012).

Although age seems to provide a good prediction of the susceptibility to both motion sickness and cybersickness, it remains questionable whether there is a causal connection or whether the connection is mediated by different degrees of habituation.

Habituation.

As has been mentioned in the previous section, habituation was proposed to occur after repeated exposures to an adverse motion stimulus and ameliorate motion-related sickness symptoms. Habituation is not a trait as it can be achieved by practically anyone. Only 1 % to 3 % of the population are assumed to never habituate to motion sickness (Howarth & Hodder, 2008). However, habituation can be a relatively stable individual characteristic in the form of experience. Individuals who engage repeatedly with a certain motion-related stimulus, motion vehicle or virtual environment know the effects of these stimuli on the vestibular and visual systems and might habituate or adapt in order to reduce sickness symptoms.

For motion sickness, experience with coach travel (Turner & Griffin, 1999), parabolic flight (Golding et al., 2017) or seafaring (Chan, Moochhala, Zhao, Yeo, & Wong, 2006; Gordon, Spitzer, Doweck, Shupak, & Gadoth, 1996; Grunfeld & Gresty, 1998; Tal et al., 2013) was associated with decreased susceptibility to motion sickness in the respective motion vehicle. Not only has repeated experience in the past reduced the risk of future motion sickness at sea (Chan et al., 2006), prolonged duration at sea also reduced the symptom severity (Gordon et al., 1996; Grunfeld & Gresty, 1998; Tal et al., 2013).

In a laboratory setting, Dobie and May (1990) observed an increased tolerance to a rotating chair and an optokinetic drum when previously adapted with the same device in comparison with a control group. Hill and Howarth (2000) and Howarth and Hodder (2008) were similarly able to show a decrease in symptom severity after repeated exposure to a virtual environment across multiple days.

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The majority of studies indicated an ameliorating effect of habituation or adaption on symptom severity in motion sickness and cybersickness. Two further questions in relation to habituation gained increased attention: the first one concerns the interval between repeated exposures and the second the generalizability of habituation to other devices or even different types of motion-related sickness.

Stern, Hu, Vasey, and Koch (1989) suggested that adaption occurs with an inter-exposure interval of two days but does not occur when the time period between exposures is 4 days or longer. In contrast, Howarth and Hodder (2008) investigated the rate of adaption for different inter-exposure intervals ranging from one day to seven days and found no difference between intervals. They concluded that the total number of exposures is more important than the inter-exposure interval. However, there is yet not sufficient research on inter-exposure intervals, especially to determine long-term adaption effects over the time course of months or years. For very short-term intervals, habituation does not seem to apply. Two studies did not find a reduction of sickness severity with an inter-exposure interval of 15 to 30 minutes, suggesting that it needs at least a couple of hours for the habituation to take an effect (Domeyer, Cassavaugh, & Backs, 2013; Zhao & Stern, 1999).

Most studies investigated the effect of habituation with the same stimulus with which the habituation was performed. Dobie and May (1990) found that repeated exposure to a rotating chair decreased symptoms in the rotating chair and in an optokinetic drum as well. However, participants who were adapted with the optokinetic drum only habituated to the drum and not to the rotating chair. The authors explained these differences with the higher relative motion sickness induction of the rotating chair. Rosa, Morais, Gamito, Oliveira, and Saraiva (2016) and my studies 1 ($r = -.50$) and 3 ($r = -.42$; unpublished result) showed evidence that video gamers (operationalized with the amount of common video game play without HMD) might be less prone to experience cybersickness in virtual environments presented with an HMD. Video games possibly provide habituation to digitally presented virtual stimuli reducing cybersickness susceptibility in the more provocative environment of an HMD exposure.

An interesting finding indicated that experienced pilots reported more sickness in a flight simulator that fits the type of aircraft they are licensed on than more inexperienced pilots (Braithwaite

& Braithwaite, 1990). Experienced pilots may be more sensitive to subtle differences between the motion behaviors of the simulator to the real-world aircraft and thus experience more sensory conflict.

Although there is insufficient evidence of generalizability of adaption to motion-related stimuli across device and type of sickness, the rate of adaption, i.e. the time someone needs to be adapted to an adverse stimulus, seems to be fairly stable across multiple motion-related devices (Graybiel & Lackner, 1983).

Handedness.

Handedness has been investigated in relation to motion sickness in two studies in my publication set. Both studies used motion sickness history surveys as outcome measurement. Handedness was investigated because it was suggested to reflect possible individual differences in brain lateralization (Mirabile & Teicher, 2002). For example, non-right handers are thought to have an altered cortical lateralization of vestibular function (Arshad, Nigmatullina, & Bronstein, 2013) and decreased motion detection functioning (Richardson, 1995).

Mirabile and Teicher (2002) found a slightly higher relative proportion of non-right handers in the motion sickness resistant group. However, they also found a similar increase of relative proportion in the extremely susceptible group. Propper et al. (2018) compared right-handers who are consistently using their right hand for various tasks and inconsistent-handers who preferred to use different hands for different kinds of tasks. Neither group showed a significant difference in motion sickness susceptibility, neither in childhood nor in adulthood.

Based on the two studies, it seems unlikely that handedness is a reliable predictor of motion sickness susceptibility.

Other demographic factors.

Other demographic variables investigated in relation to motion-related sickness include the body mass index (BMI) and alcohol abuse.

Koslucher et al. (2015) investigated the BMI in context of gender differences and did not observe a relationship of BMI but found a significant correlation of height with motion sickness

history when controlling for BMI. In a different study, Stanney et al. (2003) reported a significant correlation of BMI and oculomotor disturbances with less symptoms for more overweight participants. However, the effect size was small ($r = -.07$) and no associations with other symptoms of cybersickness were discovered. Thus, the effect of BMI and overall anthropometric constitution on sickness susceptibility seems limited.

The study by Lentz and Collins (1977) was the only study in the publication set investigating the relationship of alcohol consumption and motion sickness history. They did not find a relationship between frequency of alcohol consumption and motion sickness but reported significant correlations of motion sickness history with relative frequency and overall severity of hangover after alcohol consumption.

Physiological aspects

Vestibular functioning.

General functioning of the vestibular system and asymmetries in effectiveness of labyrinthine functioning in left and right ears are often considered to contribute to individual differences in motion sickness susceptibility. I will give a brief overview over the involved organs, their functioning and concepts to test for vestibular functioning and will then describe the findings concerning the relationship of the vestibular system and individual motion-related sickness susceptibility.

The vestibular system of humans is situated in the labyrinth of the inner ear and consists of the otolithic organs and the semicircular canals (see Glover, 2004). The otolithic organs are further divided into the utricle and the saccule. Both organs are pouches filled with a fluid (endolymph) and lined with hair cells and small crystals (the otoliths) attached to them. Whenever a person experiences linear acceleration, the fluid within the otolithic organs will be set into motion which in turn accelerates the otoliths and exerts a force on the hair cells. The resulting input is sent via the vestibular nerve to the corresponding cerebral structures indicating a linear movement of the head. The utricle is predominantly sensitive in the horizontal plane of the head while the saccule detects accelerations in the vertical plane.

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In contrast to the otolithic organs which detect linear accelerations, the semicircular canals detect angular movements. Three interconnected tubes which are attached to the utricle form the semicircular canals: the lateral, superior and posterior canal. Similar to the otolithic organs, the semicircular canals are filled with endolymph. The ampulla, a chamber containing the cupula, a gelatinous structure with embedded hair cells, is at the junction of the three canals. Whenever a person experiences angular movement, the cupula is deflected and the hair cells are stimulated in the opposite direction of the head movement. Due to inertia, the movement of the endolymph initially lags behind the movement of the head. After a short period of approximately six seconds with continuous rotation, the flow of the endolymph normalizes with the head movement and the cupula and hair cells cease to be stimulated. When the head stops rotating or the speed of rotation decreases, the endolymph will, again due to inertia, lag behind the reduced head rotation and deflect the cupula in the direction of the head movement often resulting in compensatory body movements.

Different tests are used in the motion sickness literature to determine the general functioning of the vestibular system and asymmetries of functioning between the left and right ear. These tests make use of different characteristics of the vestibular system: the vestibulo-ocular reflex, the caloric nystagmus and the vestibular evoked myogenic potentials.

The *vestibulo-ocular reflex* (VOR) is an involuntary movement of the eye in response to head movements (see Ito, 2001). When focusing a certain object and moving the head (e.g. to the right), the eye moves accordingly (e.g. to the left) in order to keep the object in the center of the visual field. The VOR is part of a functioning vestibular system and is usually tested by using a rotating chair which rotates in different patterns. One common pattern is a sinusoidal alteration of the velocity with a pre-specified peak velocity (e.g. 60°/sec) and a set of frequencies between 0.01 Hz and 1 Hz. Eye movements are monitored by an electronystagmograph. Usually, participants exhibit a nystagmus which is a spontaneous eye movement in response to the rotation. A nystagmus consists of a fast phase movement in the direction of the rotation followed by a slow phase movement in the opposite direction. Different parameters can be extracted from this testing procedure: gain, phase, symmetry and time constant.

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Gain is the relation of the peak slow phase velocity of the nystagmus and the head velocity.

This parameter is often considered to be an indicator of general functioning of the vestibular system.

Phase is the correspondence of the slow phase velocity of the nystagmus with the alternating chair velocity. At low frequencies, phase lead is significantly different between healthy individuals and individuals with vestibular dysfunction.

The *symmetry* is determined by comparing the slow phase velocities during clockwise and counterclockwise rotation. This is an indicator of equal functioning of the semicircular canals in left and right ears.

Finally, the *time constant* is a measurement of time until the amplitude of the nystagmus declines to 37% of the peak amplitude during rotation. After the end of a rotation, the so-called velocity storage keeps up the nystagmus despite the peripheral vestibular system returning to normal. This typically lasts up to 10 to 20 seconds after the rapid stop of the rotation and is an indicator of the velocity storage of the vestibular system. In sinusoidal oscillation, phase lead is directly related to the time constant. The shorter the phase lead, the longer the time constant.

In the *caloric test*, hot (usually above 40°C) or cold (usually below 30°C) water of a pre-specified volume is inserted into the ear canal (see Furman & Wuyts, 2012). The water either warms up or cools down the endolymph in the semicircular canal resulting in an expansion or contraction of the endolymph. Thus, the cupula is deflected and the participant feels as if he or she is rotating. Similar to the VOR, the caloric stimulation leads to a nystagmus in healthy individuals. The caloric test can detect vestibular dysfunction in case the nystagmus fails to appear at an extremely low water temperature of 17°C or below and can further determine asymmetric functioning of the semicircular canal or the superior vestibular nerve. This asymmetry is called canal paresis and is calculated by comparing the slow phase velocity of the caloric nystagmus in right and left ear during hot and cold water stimulation.

The third common but relatively novel testing procedure for vestibular functioning is the measurement of *vestibular evoked myogenic potentials* (VEMP; see Colebatch, Halmagyi, & Skuse, 1994). There are two different types of VEMP: the cervical VEMP (cVEMP) and the ocular VEMP (oVEMP).

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For cVEMP, auditory burst stimuli of high intensity are applied to the ear. The otolithic organs (sacculae and utricle) are sound sensitive and send a signal on the vestibular nerve to the brainstem on strong stimulation. This signal is relayed to the neck muscles. The cVEMP is typically assessed as an inhibitory potential with an electromyogram at the sternocleidomastoid muscle. It is generally assumed that cVEMP is reflecting the sacculae and inferior vestibular nerve functioning.

In contrast, the oVEMP is collected with an electromyogram below the eyelid to detect the contraction of the extraocular muscles. The oVEMP is thought to primarily reflect responses from the utricle and superior vestibular nerve.

VEMP output waves usually include a P1 and N1 component. Parameters extracted from VEMP waves include absolute latencies, inter-peak latencies, peak-to-peak amplitudes and an asymmetry ratio between left and right ear using the respective peak-to-peak amplitudes.

Twenty-two studies in the publication sample investigated inter-individual differences in vestibular function and susceptibility to motion-related sickness. With one exception, all studies investigated motion sickness or motion sickness history. Only one study investigated VIMS.

The first studies from the 1960s compared the incidence of motion sickness in labyrinthine defective patients and healthy individuals during parabolic flight (Kellogg, Kennedy, & Graybiel, 1964) and at sea (Kennedy, Graybiel, McDonough, & Beckwith, 1968). In both studies, labyrinthine defectives with a loss of vestibular functioning did not show any signs of motion sickness while the majority of healthy participants showed severe sickness symptoms. Therefore it was concluded that labyrinthine defectives are practically immune to motion sickness and that vestibular functioning plays the key role in explaining differences in motion sickness susceptibility. In a different study, the resistance of labyrinthine defective participants to motion sickness was replicated in a laboratory setting with a rotating chair. However, labyrinthine defectives were not completely immune but showed significantly decreased levels of sickness compared to healthy controls (Murdin et al., 2015). This could be attributed to residual vestibular functioning in the labyrinthine defectives.

As labyrinthine defectives did not experience any or at least very low motion sickness, differential functioning of the vestibular system was considered as source of individual susceptibility in non-pathological participants as well.

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Eleven studies in my publication set investigated vestibular functioning with VOR. VOR was assessed prior to the sickness inducing stimulus and in some cases during the exposure to assess the effects of habituation.

The best predictor across all VOR parameters was the time constant. Six studies identified a significant relationship between the VOR time constant and measurements of motion sickness (Clément & Reschke, 2018; Dai, Raphan, & Cohen, 2007; DiZio & Lackner, 1991; Gordon et al., 1996; Hoffer et al., 2003; Quarck, Etard, Darlot, & Denise, 1998). The effects found were medium ($\eta^2 = .20$; Clément & Reschke, 2018) to large ($r = .59$; Quarck et al., 1998). The time constant strongly depends on the integration of velocity information in the central vestibular system, the velocity storage. It seems as if more susceptible individuals have a more effective velocity storage and thus a prolonged time constant (Quarck et al., 1998). This assumption is supported by the fact that labyrinthine defectives not experiencing any motion sickness symptoms also had a reduced time constant (Dai et al., 2007). Furthermore, as described above, motion sickness symptoms usually decrease with habituation. The VOR time constant similarly decreases during extended exposure to a sickness inducing stimulus (e.g. at sea) and enhanced habituation (Clément & Reschke, 2018; Dai, Kunin, Raphan, & Cohen, 2003; Schwarz & Henn, 1989; Shupak et al., 1990).

Another parameter considered for predicting individual differences in motion sickness susceptibility is VOR gain. Two studies found gain to be related to motion sickness with higher gain for more susceptible individuals (Gordon et al., 1996; Shupak et al., 1990) while three studies reported insignificant relationships (Clément & Reschke, 2018; Dai et al., 2007; Quarck et al., 1998). The authors of those studies finding associations of VOR gains and motion sickness argued that the increased VOR gain indicates that motion sickness susceptible individuals have generally more intense vestibular responses (Gordon et al., 1996). Ventre-Dominey, Luyat, Denise, and Darlot (2008) proposed an interaction of time constant and eye velocity (i.e. gain) on the susceptibility of motion sickness.

Besides VOR, which primarily assesses functioning of the semicircular canals, VEMP are used to determine functioning of the otolithic organs. Five studies have investigated VEMP in relationship to motion sickness. All five studies used cVEMP while only one study additionally

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investigated the relationship with oVEMP. Three studies report a higher VEMP threshold (Singh, Pandey, & Mahesh, 2014; Tal et al., 2013; Tal, Hershkovitz, Kaminski, & Bar, 2006), two studies observed higher asymmetry ratios (Fowler, Sweet, & Steffel, 2014; Singh et al., 2014) and one study reported higher cVEMP amplitudes for susceptible individuals (Fowler et al., 2014). One study did not find any relationship of cVEMP parameters or canal paresis from a caloric test with motion sickness history (Buyuklu, Tarhan, & Ozluoglu, 2009). Singh et al. (2014) provided the only study investigating both cVEMP and oVEMP and reported the same results for both, an increased threshold and asymmetry ratio in motion sickness susceptible participants.

Lower VEMP thresholds have been suggested to indicate a broader dynamic range of the vestibular system facilitating adaptive modifications to maintain postural stability and enhance habituation to unusual motion conditions (Tal et al., 2013).

The findings of higher asymmetry ratios being related to motion sickness (Fowler et al., 2014; Singh et al., 2014) match previous results of increased torsional asymmetries in astronauts more susceptible to space motion sickness (Diamond & Markham, 1991, 1992) and stronger asymmetries in ocular counterrolling to left and rightward tilts (Lackner, Graybiel, Johnson, & Money, 1987). It is suggested that asymmetric otolithic functioning is well compensated during normal motion conditions. However, under extreme or unfamiliar motion conditions, this compensation fails, leading to a sensory conflict which in turn produces motion sickness (Singh et al., 2014). Despite the evidence, the authors acknowledged that otolith asymmetry is only one and might not be the main causative factor in motion sickness susceptibility (Lackner et al., 1987).

As mentioned earlier, only one study investigated the relationship of the previously described measurement methods with sickness induced solely by visual stimuli. In contrast to the findings for motion sickness, W. H. Johnson, Sunahara, and Landolt (1999) were able to induce VIMS in unilateral and bilateral labyrinthine defectives. Due to the low number of bilateral defectives in this study, it is unclear whether labyrinthine defectives are as susceptible to VIMS as healthy individuals. The fact that severe VIMS could have been induced in these patients shows, however, that the vestibular system plays a different, probably much smaller role in the genesis of visually-induced motion sickness including cybersickness.

More research has to be conducted to determine the exact relationship of the functioning of the vestibular system and cybersickness. For motion sickness, a relationship of general sensitivity of the vestibular system and/or the asymmetry of functioning is likely. However, the inconsistent results demonstrate that this relationship is only one of several factors of motion sickness.

Visual aspects.

The first attempt to link ocular aspects to the sensation of motion sickness was conducted by Reason (1968, 1969a) using the spiral after-effect (SAE). For this type of measurement participants are instructed to fixate a point in the middle of a constantly rotating spiral disc. After terminating the rotation of the disc, many participants experience a persisting movement, the SAE. The time until the participant indicates that the SAE has vanished is recorded with a stopwatch.

Reason (1968, 1969a) found that the SAE was related to individual motion sickness history ($r = .43$ in Reason (1968) and $r = .42$ in Reason (1969a)). Furthermore, he observed the SAE to be correlated with a labyrinthine after-sensation which was similarly assessed with a rotating chair and self-reported persistence of any after-sensations. Based on these findings, Reason (1968, 1969a) proposed his 'receptivity' hypothesis in which he suggested that individual susceptibility would differ in association with general receptivity to sensory input. In this theory, he linked the sensitivity to visual or vestibular stimulation to personality constructs like extraversion-introversion (Reason, 1968, 1969a).

However, two subsequent studies on the SAE could not reproduce the high correlations with motion sickness history and reported non-significant correlations of $r = .21$ (Croucher & Hindmarch, 1973) and $r = .09$ (Keinan, Friedland, Yitzhaky, & Moran, 1981).

In a sense, the SAE is very similar to the optokinetic after-nystagmus which will be introduced below. However, unlike the optokinetic after-nystagmus, the SAE relies on self-report and thus on the subjective experience of the participants. The persistence was measured with a stopwatch, another source of possible unreliability, to the nearest 0.5 second which is a rather coarse temporal resolution.

As a more objective measurement and similar to the vestibulo-ocular nystagmus used for the prediction of motion sickness, the optokinetic nystagmus (OKN) was investigated in relation to

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motion-related sickness and especially with regards to VIMS and cybersickness. In contrast to the vestibulo-ocular nystagmus which is induced by vestibular stimulation utilizing the VOR, the OKN is the result of visual stimulation. Theoretically, OKN can be induced by any kind of constant angular visual stimulation such as a VR scenery. In practice, OKN are usually triggered by optokinetic drums similar to those used for inducing VIMS.

The OKN resembles the nystagmus induced by vestibular stimulation. Keinan et al. (1981) showed that the slow phase velocity of the OKN is related to motion sickness history of seafarers suggesting a possible interplay of vestibular and visual systems in the mediation of motion sickness.

More recently, the OKN was investigated in relation to VIMS. The parameter of interest was the time constant in form of the optokinetic after-nystagmus (OKAN). OKAN can be assessed when abruptly ending the visual drum stimulation (e.g. by switching off the light). The nystagmus induced during visual stimulation usually upholds for some time after ending the stimulation. OKAN is analogously to the VOR time constant the time until the slow phase velocity decays to 37 % ($1/e$) of the peak velocity during visual stimulation.

Two studies investigated the relationship of OKAN and VIMS (Guo, Chen, Wei, So, & Cheung, 2017; Guo, Ji, & So, 2011) and found significant relationships between OKAN and nausea ($\rho = .48$; Guo et al., 2011) and OKAN and total sickness ($r = .51$; Guo et al., 2017). The authors argued that the velocity storage mechanism, which was also supposed to affect the VOR time constant, stores information during OKN and discharges them after termination of the visual stimulation. The duration of the OKAN would reflect the amount of stored information which in turn seems to be related to the individual susceptibility to VIMS (Guo et al., 2017).

OKAN is a promising new approach to predict the susceptibility to visually induced sickness (including VIMS, cybersickness and to some extent simulator sickness) using the sensory afferents involved in the genesis of the syndrome. The findings are especially intriguing in light of the results by W. H. Johnson et al. (1999) who were able to induce VIMS in bilateral labyrinthine defective patients and thereby limiting the importance of the vestibular system for VIMS.

Taking together the findings for the vestibular system (especially VOR) and OKAN, it is possible that the velocity storage is in fact a key mechanism in the genesis of motion-related sickness.

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The velocity storage is a process of multisensory integration of different motion cues from the vestibular and visual systems and gains significance only in those situations in which either vestibular or visual signals are missing (or are highly incongruent), hence those situations in which motion-related sickness generally occurs. Laurens and Angelaki (2011) describe that the time constant of velocity storage is lengthened to a practical relevance only in those situations. It is possible that the time constant can be increased either by vestibular cues in absence of visual cues or vice versa and thus can be triggered by either one of these two systems. This could explain why labyrinthine defective patients are immune to motion sickness elicited by vestibular stimulation but can experience VIMS induced by visual stimulation.

Concerning other ocular aspects, two studies investigated the influence of vision acuity on cybersickness. Both studies were not able to show a relationship between cybersickness scores and stationary 3D vision acuity (Allen, Hanley, Rokers, & Green, 2016) or stereo vision acuity (Hale & Stanney, 2006). However, Allen et al. (2016) found participants with greater sensitivity to moving visual cues reporting higher sickness scores and aborting the VR at a higher rate. The authors argued that greater sensory ability in the form of better 3D vision enables the participants to more easily recognize visual motion cues incongruent to the vestibular reality and experience more discomfort as a result. So far, this study is the only publication on this relationship. Further research should determine if this relationship can be replicated.

Jackson and Bedell (2012) investigated differences in vertical phoria and VIMS. Phoria describes the alignment of both eyes during resting. Heterophoria (= misalignment of both eyes) can usually only be observed when both eyes are dissociated and single vision is prohibited, for instance by covering one eye. In this study, the vertical deviation of both eyes resting positions correlated to VIMS ratings resulting from an optokinetic drum exposure. According to the authors, sickness could be caused either by fatigue resulting from constantly aligning both eyes to single vision or reduced postural stability of participants with greater vertical phoria. However, it is also possible that vertical heterophoria itself is not causing higher sickness susceptibility but is merely a symptom of otolith asymmetry which could, as described above, also be related to motion-related sickness.

Postural instability.

One area that has often been studied in connection with motion-related sickness and is related to both vestibular and visual function is postural instability. Studies in this area were inspired by the postural instability theory of motion sickness, stating that motion sickness is triggered by a prolonged loss of postural stability. The theory also emphasizes that postural instability is not the result but the reason for motion sickness genesis (Riccio & Stoffregen, 1991).

In studies concerning postural instability, body movements were usually detected by optical or electromagnetic sensors attached to the abdomen or head or by means of a force platform. Parameters commonly used to study postural instability include postural variability (standard deviation), velocity of sway, range of sway and the alpha parameter of a detrended fluctuation analysis which determines the self-affinity of a signal.

Several studies (e.g. Koslucher, Munafo, & Stoffregen, 2016; Smart et al., 2002) have shown that people who are exposed to an adverse movement stimulus sway more and exhibit greater variability in postural control before they report experiencing motion sickness. In the context of this review, the question arises whether postural stability without being exposed to a motion stimulus can also predict motion-related sickness in a motion environment. Or in other words: do people who later experience motion-related sickness have a higher postural instability even before exposure? 21 studies have investigated this question in the current publication set.

Seven studies found a significant difference in spontaneous sway between those who felt motion-related sickness and those who remained well, in the sense that sick participants showed greater postural instability (Chen et al., 2012; Koslucher, Haaland, & Stoffregen, 2014; Shahal et al., 1999; Stoffregen, Chen, Varlet, Alcantara, & Bardy, 2013; Stoffregen & Smart, 1998; Stoffregen, Yoshida, Villard, Scibora, & Bardy, 2010; Yokota, Aoki, Mizuta, Ito, & Isu, 2005). Six studies could not detect any difference (Bonnet, Faugloire, Riley, Bardy, & Stoffregen, 2006; Cobb, 1999; Macefield & Walton, 2015; Munafo et al., 2017; Smart et al., 2002; Tal, Bar, Nachum, Gil, & Shupak, 2010). The studies mentioned above dealt with motion sickness, VIMS, cybersickness and simulator sickness and showed no specific effect for one of the mentioned sickness types.

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Many studies found inconsistent results with interaction effects and more complex movement pattern differences between well and sick participants. These results could be the subject of a review of their own and shall only be presented here in brief.

Some studies found significant relationships between postural instability and motion-related sickness, but only for part of the sample or only under certain conditions and observed no or opposite results for the rest. Interaction effects were determined with the gender (Koslucher, Haaland, & Stoffregen, 2016), stance width (Chen et al., 2013) and the axis in which sway was measured (Villard, Flanagan, Albanese, & Stoffregen, 2008). Chang, Chen, Kung, and Stoffregen (2017) reported that participants who got sick in a car simulation showed less postural variability than well participants if they were the driver and more if they were not the driver.

The inconsistent results indicate that a linear relationship of standard parameters (postural variability, speed), measured during spontaneous sway, with symptoms of motion-related sickness cannot be found reliably. Other studies followed the approach that it is not generally the postural instability during spontaneous sway that distinguishes people getting sick and those who do not, but the strategy with which postural balance is established.

In two studies, participants who became sick achieved a higher ratio of lateral to pivotal head movements, suggesting that well participants are better at stabilizing their head (Séverac, Bessou, & Pagès, 1994; Séverac Cauquil, Dupui, Costes Salon, Bessou, & Güell, 1997).

In an in-depth study, Laboissiere et al. (2015) examined the power spectrum of sway in the anteroposterior axis and found a greater proportion of high-frequency components in people with a high motion sickness history, as well as a greater proportion of low-frequency components in sick participants who were exposed to visual motion stimuli. Because sway in a specific frequency range is associated with postural control by a particular sensory system, the authors concluded that people with a low motion sickness history tend to regulate posture by using visuovestibular signals. With the actually induced VIMS, the correlations were exactly the other way around. In contrast to the motion sickness history, it has been suggested that people who have become sick make more use of visual stimuli in the regulation of postural balance.

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This obvious contradiction is explained by possible differences in the questionnaires used in the collection of motion sickness history and actual symptoms or differences in the types of motion stimuli needed to induce motion sickness (actual motion) and VIMS (visual motion).

Some of these results coincided with previous studies (Yokota et al., 2005) but some did not (Shahal et al., 1999). Caillet et al. (2006) found that people who did proprioceptive physical sports (e.g. gymnastics, skiing or archery) for a long time were less susceptible to motion sickness and explained this by a learned regulation of posture with proprioceptive and less reliance on visuovestibular signals.

Postural stability has a strong foundation for explaining motion sickness (Riccio & Stoffregen, 1991). However, postural stability in spontaneous sway in the absence of motion stimuli, i.e. general postural stability, seems to be an unreliable predictor for individual differences in the experience of motion-related sickness. Strategy differences in the regulation of postural balance with the analysis of sway frequency bands offer a new possibility to elucidate individual susceptibility to motion-related sickness. Still, these results differ in some analyses without these differences being sufficiently theoretically explainable, yet.

Migraine.

One common disorder mentioned in the context of vestibular disturbances and motion sickness is migraine. Migraine is usually associated with unilateral headache with or without additional neurological symptoms (aura). However, many migraine patients also suffer from vertigo, other vestibular disturbances and nausea. Fourteen publications in the publication set investigated the relationship between migraine (or associated disorders) and sickness symptom ratings or general motion sickness history.

Earlier studies comparing migraine patients and healthy controls found higher susceptibility to motion sickness assessed by self-report questionnaire for adults (Golding, 1998; Kuritzky, Ziegler, & Hassanein, 1981; Sharma & Aparna, 1997) and children (Barabas, Schempp Matthews, & Ferrari, 1983) with migraine.

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Grunfeld and Gresty (1998) investigated motion sickness of participants of a yacht race over a period of nine months and found a higher incidence of motion sickness for those indicating experience with migraine prior to the race. Importantly, motion sickness and headache did not occur together. Thus, motion sickness was not a mere symptom of a migraine attack.

When investigating migraine patients within an optokinetic drum eliciting VIMS, migraine patients did show significantly elevated general sickness ratings but only higher scores on the nausea and dizziness sub-scores (Drummond, 2002). Similarly, migraine patients only indicated a higher incidence of motion sickness in some but not all motion vehicles (e.g. cars and buses but not trains) in comparison to controls (Drummond, 2005).

Since the mid-2000s, research on the topic made a distinction between regular forms of migraine and vestibular migraine (VM) which is not yet an official diagnosis. In contrast to migraine, the main symptoms of VM are dizziness and nausea which must not necessarily be accompanied by headache. The distinction between VM and regular migraine (or other migraine variants) yielded promising results: most of the studies investigating VM patients observed significantly higher sickness history scores for VM patients in comparison with healthy controls and regular migraine patients (Bolding, Ljostad, Mygland, & Monstad, 2011; Jeong, Oh, Kim, Koo, & Kim, 2010; Sharon & Hullar, 2014; Wang & Lewis, 2016). Only one study did not find significant differences between VM and regular migraine patients, neither in motion sickness history nor in actual symptom ratings following rotating chair exposure (Murdin et al., 2015).

Two studies additionally investigated the relationship of motion sickness history and Menière's disease (MD) which is a disease of the inner ear leading to vertigo and vestibular disturbances. MD is very similar to VM and difficult to differentially diagnose. Both studies observed drastically elevated susceptibilities to motion sickness for MD (Golding & Patel, 2016; Sharon & Hullar, 2014). The change in motion sickness susceptibility from childhood (before the onset of the disease) to the time of assessment even was the best predictor for an MD diagnosis (Golding & Patel, 2016).

Generally, most studies agreed on the following pattern for motion sickness susceptibility: general population < migraine < vestibular migraine/ Menière's disease.

There have been several attempts to explain the relationship between migraine and motion-related sickness. Most of them argue that migraine is accompanied by visual (e.g. impaired motion perception) and vestibular (e.g. impeded balance and vertigo) dysfunctions which increases the sensory conflict during unusual movements and thus leads to increased motion sickness (Drummond, 2005; Golding & Patel, 2016). Another tentative explanation states that both motion sickness and migraine are associated with serotonergic deficits. This hypothesis was supported by findings of migraine symptoms augmented by decreased serotonin synthesis and reduced VIMS for healthy and migraneous participants after consuming a drink with L-tryptophan which is a serotonin precursor (Drummond, 2006).

Although the exact mechanisms underlying the association need further clarification, the relationship between migraine (especially VM) and motion-related sickness is well established.

Fitness and sympathetic activity.

Aerobic fitness is related to the amount of physical exercise an individual is carrying out. More frequent physical exercises lead to an increase of VO_2^{\max} , the maximum oxygen uptake which is often used as a measurement of aerobic fitness. High VO_2^{\max} is important for endurance during prolonged exercise and is often considered as a sign of good health. Five studies investigated motion sickness and aerobic fitness and assessed or validated aerobic fitness with VO_2^{\max} . All of these studies used an exposure and reports of actual motion sickness as indicator of susceptibility.

Three studies found a positive relationship of aerobic fitness and motion sickness scores (Banta, Ridley, McHugh, Grissett, & Guedry, 1987; Cheung, Money, & Jacobs, 1990; Rawat, Connor, Jones, Kozlovskaya, & Sullivan, 2002), in the sense that participants with greater aerobic fitness showed more motion sickness symptoms during exposure to a rotating chair. While two studies used cross-sectional analyses, Cheung et al. (1990) administered an 8-week aerobic fitness program and longitudinal data with three rotating chair exposures prior and three exposures after the fitness program. Successful training was validated by increases in VO_2^{\max} in all participants. Despite a certain degree of habituation to the rotating chair that is common with a longitudinal design, all participants had an increase of motion sickness ratings accompanying the elevated aerobic fitness.

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It is yet undetermined why aerobic fitness correlates with motion sickness susceptibility. An increase in aerobic fitness is characterized by adaptive cardiovascular and metabolic adaptations of the body which could lead to an increase in susceptibility (Cheung et al., 1990). Rawat et al. (2002) hypothesized that increased aerobic fitness leads to higher tonic levels of certain hormones such as vasopressin or adrenocorticotrophic hormone which might reduce the efficacy of acute release of these hormones in a motion situation.

However, aerobic fitness was not predictive in all environments. Dobie et al. (2001) did not find a relationship between the amount of self-reported physical activity and motion sickness susceptibility, without assessing VO_2^{\max} . Jennings, Davis, and Santy (1988) did not observe a significant correlation of aerobic fitness and the level of space sickness in astronauts flying to the International Space Station. It is possible that the metabolic changes for aerobic fitness do not apply at weightlessness. It must, however, also be noted that astronauts typically show drastically reduced variance in aerobic fitness compared to the general population.

Three studies furthermore investigated parameters of baseline salivary secretion of individuals who were susceptible and those who were tolerant to motion sickness. These studies found higher salivary amylase (Harm & Schlegel, 2002), higher amylase activity (Gordon et al., 1992), higher total protein concentration (Gordon et al., 1988) and higher secretion rate (Gordon et al., 1988; Gordon et al., 1992) for susceptible participants. The exact parameters predicting motion sickness susceptibility in these three studies were rather inconsistent. However, all three studies concluded that their results reflect increased sympathetic tone for those susceptible to motion sickness. None of these publications presented a possible explanation for these relationships.

At first glance, the results from salivary secretion contradicted the previously mentioned studies on aerobic fitness to some extent as the latter is often associated with decreased resting sympathetic activity.

Further research with larger sample sizes is needed to clarify the role of aerobic fitness and the mechanism of differences in baseline hormone balance and put the findings into the context of a theoretical framework. Those studies could determine if the increased sympathetic tone is the result of

acute or chronic stress which is triggered by increased physical activity and if stress is also affecting motion sickness susceptibility.

Heritability and genetic factors.

Environmental factors such as habituation have been discussed in a previous section. Despite the influence of the environment, a considerable genetic contribution to the occurrence of motion-related sickness has been considered in previous research. The studies in the publication set investigating genetic factors can be categorized into studies of ethnic differences (5 studies), heritability (4 studies) and a genom-wide association study (1 study).

Research on ethnic differences has focused on an increased susceptibility within those of Chinese ethnicity. More precisely, four of the five studies investigating the ‘Asian hypersusceptibility’ to motion sickness observed increased sickness reports of participants with Chinese ancestry. These studies include both self-reported motion sickness history (Ji, So, & Cheung, 2009; Klosterhalfen et al., 2005) and symptom ratings after the exposure to an optokinetic drum (Stern, Hu, LeBlanc, & Koch, 1993; Stern et al., 1996). Furthermore, one study found a similar pattern for ethnic Chinese, but American-born participants (Stern et al., 1996). Participants of African ethnicity showed comparable levels of symptom ratings as Caucasians (Stern et al., 1993).

Conversely, Klosterhalfen et al. (2006) observed the reverse results of lower motion sickness history and fewer symptom ratings in an optokinetic drum among their Chinese participants. Interestingly, as a behavioral measurement, total tolerance time, i.e. the time until participants aborted each sequence on request, was significantly lower among those same Chinese participants, indicating an earlier or more severe onset of VIMS symptoms. The authors stated that these contradictory results may be caused by a lack of awareness of motion sickness symptoms or a socially and culturally based response bias. Moreover, fewer symptom ratings could have been the result of shorter average exposure duration as Chinese were aborting sequences sooner (Klosterhalfen et al., 2006).

In summary, an increased susceptibility of Chinese to motion-related sickness seems likely. The reasons for these ethnic differences are yet undetermined. Stern et al. (1996) suggested that ‘Asian hypersusceptibility’ has a genetic reason. Chinese would either have a lower threshold for the

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detection of toxins in the body or differ in their physiological systems, e.g. in the release of stress hormones such as vasopressin which they found to be elevated in Chinese during drum exposure.

Besides differences between ethnicities, heritability was investigated by assessing consistency in motion sickness susceptibility between parents and their (biological) children and comparing concordance rates between monozygotic and dizygotic twins. Three studies reported a significant increase in susceptibility of children if at least one of their parents indicated severe experiences of motion sickness (the criterion was dichotomic) (Sharma, 1980; Yanus & Malmstrom, 1994), and even higher when both parents indicated severe sickness (Abe & Kajiyama, 1970). Concordance rates of monozygotic twins were significantly higher than concordance rates of dizygotic twins (Reavley, Golding, Cherkas, Spector, & MacGregor, 2006; Sharma, 1980). Yanus and Malmstrom (1994) estimated the heritability of motion sickness to be at around 59 % while Reavley et al. (2006) estimated the heritability at 57 %. All studies were clearly indicating a genetic contribution to motion sickness susceptibility. The influence of genes is probably highest at a younger age as the concordance rates of monozygotic twins was highest at childhood (70 %) and decreased at a higher age when environmental factors are probably playing a bigger role (Reavley et al., 2006).

As for the question which genes play a role in motion-related sickness, Hromatka et al. (2015) conducted a very large study involving 80,494 individuals. Unfortunately, motion-related sickness was assessed by a single item asking for experience of motion sickness in cars. This could have severely restricted the generalizability of the results. Due to the large sample size, gene sequences that were related with a p -value smaller than 5×10^{-8} (corresponds to a Bonferroni correction) were considered significant. By this procedure, 35 genes were identified to be related to motion sickness susceptibility. These genes were associated with a number of different phenotypes. The gene with the (by far) lowest p -value was PVLR3 which is involved in the development of the eye. Loss of PVLR3 expression leads to ocular defects in mice and humans. Many other genes were related to inner ear development, balance, glucose homeostasis, insulin homeostasis or were also found to be related to migraine. These results support the emphasis on research for vestibular and ocular aspects in sickness prediction.

Other physiological factors.

Some additional physiological factors for the genesis of motion-related sickness have received only little attention. Although some might inherit valuable insights into the genesis of motion-related sickness or are able to explain why individual susceptibility varies to a great extent, most of the following factors are based on only three or less publications (some additionally with small sample sizes) and might need some further validation.

Three studies investigated baseline levels of stress hormones, namely cortisol (Koch et al., 1990; Meissner et al., 2009) or adrenocorticotrophic hormone (ACTH; Kohl, 1985) which is involved in the production of cortisol. It must be noted that baseline levels of these stress hormones are generally difficult to attain as these parameters highly depend on the daytime due to fluctuations with the circadian rhythm and could be influenced by the context of the (possibly stress-inducing) laboratory setting.

Higher baseline cortisol levels were associated with increased tolerance to an adverse rotation stimulus. However, this relationship was only found in female participants. Men, whose cortisol levels were not related to motion tolerance, might have had increased willingness to meet social standards which masked the relationship (Meissner et al., 2009). Similarly increased ACTH baseline levels were also associated with fewer motion sickness symptoms during motion stimulation (Kohl, 1985). The direction of relationship surprises at first glance as this means that a higher level of baseline stress hormone activity is related to decreased sickness during stressful motion stimulation. Although the authors do not imply any causative relationship and speculate about the involvement of other related hormones (e.g. vasopressin or corticotrophin releasing factor) in the formation of the observed results, they hypothesized that participants with greater baseline levels of stress hormones more readily adapt to stressful motion stimuli, have greater responsivity of the endocrine system and are able to resolve environmental stress such as sensory conflict more easily (Kohl, 1985). However, contradictory results have been reported as well. Koch et al. (1990) observed higher baseline cortisol levels for participants who later became sick in an optokinetic drum and attributed these differences to higher anticipatory stress and anxiety which in turn compromised well-being during drum exposure.

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Due to the controversial findings, the predictive validity of baseline stress hormones for motion-related sickness remains unclear.

Another aspect is regular smoking or more precisely the influence of nicotine. Golding, Prosyankova, Flynn, and Gresty (2011) observed that regular smokers are less susceptible to motion sickness when they are deprived of smoking overnight or for several hours. The findings fitted observations of nicotine dosages increasing VIMS susceptibility (Zingler et al., 2007). Nicotine could affect the vomiting center or directly exacerbate sensory conflict by altering vestibular functioning. Furthermore, nicotine is known to increase acetylcholine release which activates muscarinic receptors. Thus, nicotine deprivation indirectly reduces muscarinic receptor activation which is similar to the effect of anti-emetic drugs such as scopolamine (Golding et al., 2011). Unfortunately, no non-smoking control group was included to test whether nicotine deprivation protects against motion-related sickness or if regular smokers are generally more susceptible and return to a usual level when deprived from smoking.

In two studies, Bosser and colleagues were able to link the susceptibility to vasovagal syncope to the susceptibility to motion sickness in children (Bosser, Gauchard, Brembilla-Perrot, Marcon, & Perrin, 2007) and adults (Bosser, Caillet, Gauchard, Marcon, & Perrin, 2006). Vasovagal syncope is a brief loss of consciousness caused by a sudden drop of heart rate and blood pressure. As this relationship is also observable in family members of the participating children, the authors suggest a common genetic foundation for both motion sickness and vasovagal syncope, emphasizing the link of motion sickness and the autonomic system (Bosser et al., 2007).

Catanzariti et al. (2016) found elevated levels of motion sickness history in patients with adolescent idiopathic scoliosis (AIS), a medical condition of curvilinear deformation of the spine during adolescent growth. AIS is often accompanied by difficulties of postural control, attributed to either a deficit in sensory modalities or inadequate central integration of multiple sensory inputs.

According to the evolutionary hypothesis (Treisman, 1977), motion sickness is a residual symptom of a toxin detector excreting substances that evoke similar symptoms as motion sickness. Thus, motion sickness was investigated in relation to other mechanisms of detecting possibly toxic constituents like unpleasant odors, (bitter) tasting or food aversions.

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Sharma, Sharma, Sharma, and Singh (2008) observed that super-tasters of phenylthiocarbamide which is essentially bitter tasting were also reporting the highest motion sickness history, although the relationship was non-linear and normal tasters had the lowest susceptibility. In a more recent study, Benson, Hooker, Koch, and Weinberg (2012) found somewhat contradicting results in non-tasters being the group with the highest motion sickness history. But again, the relationship was not linear. They suggested that susceptibility to nausea may have co-evolved with bitter tasting in the sense that nausea as a response to ingested toxins is unnecessary if normal bitter tasting serves as protector against toxic substances. In a different study, individuals who preferred sweet over salty taste and who were more sensitive to unpleasant odors were more susceptible to motion sickness (Sharma & Aparna, 1997). Motion sickness history has also been shown to correlate with the number of food aversions a person indicates (Fessler & Arguello, 2004). Kohl, Lacey, and Homick (1983) did not find significant baseline differences in vitamin B12 blood concentration for susceptible and non-susceptible participants.

Phenotypical analysis in the large study by Hromatka et al. (2015) discovered correlations of motion sickness susceptibility and poor sleep quality. Insomnia patients displayed more symptoms during a driving simulator, although it must be noted that the insomnia patients were not well matched to the controls in terms of age or psychological variables such as anxiety and depression and consisted of females only (Altena et al., 2018). However, the results suit findings of increased motion sickness severity of sleep deprived participants in rotating devices (Dowd, Moore, & Cramer, 1975; Kaplan et al., 2017). The results indicated that the VOR time constant is prolonged for those who are sleep deprived and that fatigue could compromise the ability to adapt to adverse motion environments. Thus, poor sleep quality could yield chronic fatigue and a chronically extended VOR time constant, exacerbating motion sickness susceptibility (Kaplan et al., 2017).

Lastly, there seem to be differences in white matter diffusion along a tract (inferior fronto-occipital fasciculus) connecting the right visual motion processing area (MT/V5) and the right anterior insula between susceptible and non-susceptible individuals (Napadow et al., 2013). However, the causation, whether increased white matter integrity led to increased motion sickness or the elevated integrity is a result of frequent nausea experience, is unclear.

Psychological aspects

Anxiety.

Anxiety is the most often investigated personality trait in relationship to motion-related sickness. The object of investigation ranged from state anxiety to trait anxiety, a general tendency to be more anxious in various situations, and neuroticism, a similar concept with additional aspects of impulsivity and depression.

Studies assessing state anxiety either right before (Kiernan, Soykan, Lin, Dale, & McCallum, 1997; Pot-Kolder, Veling, Counotte, & van der Gaag, 2018; Viaud-Delmon, Warusfel, Seguelas, Rio, & Jouvent, 2006), during (Golding et al., 2017; Pot-Kolder et al., 2018) or after an exposure (Kim et al., 2005; Viaud-Delmon et al., 2006) to an actual or visual motion stimulus predominantly observed relationships between the level of state anxiety and expressed sickness severity. On the other hand, two studies did not provide significant correlations. However, one lacked in sample size (Kiernan et al., 1997) and the other (Golding et al., 2017) investigated the response to parabolic flight and thus might have had a very restricted sample as probably only those people would voluntarily participate who are generally not particularly anxious. Apart from that, state anxiety, although influenced by trait anxiety (Spiegelberger, Gorssuch, Lushene, Vagg, & Jacobs, 1983), is thought to be highly dependent on environmental factors and not very stable across multiple situations and therefore will not be discussed in more detail.

The other publications assessed anxiety as trait anxiety, neuroticism or as something in between state and trait anxiety referring to states of anxiety within a predefined time frame such as two, four or six weeks prior to the assessment. In the interest of simplicity, these will in the following be referred to as ‘anxiety’ despite the disparity in meaning. The questionnaires employed in this process of assessing anxiety are manifold: State-Trait Anxiety Inventory (STAI-T; Spiegelberger et al., 1983; used in 6 studies), Eysenck Personality Inventory (EPI; Eysenck, 1963; 4 studies), Taylor Manifest Anxiety Scale (TMAS; Taylor, 1953; 2 studies), 16PF Questionnaire (Cattell, Eber, & Tatsuoka, 1970; 1 study), Eysenck Personality Questionnaire (EPQ; Eysenck & Eysenck, 1975; 1 study), Hamilton Anxiety Scale (HAS; Hamilton, 1959; 1 study), Maudsley Personality Inventory

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(MPI; Jensen, 1958; 1 study), NEO Personality Inventory Revised (NEO-PI-R; Costa & McCrae, 1992; 1 study), Self-rating Anxiety Scale (SAS; Zung, 1971; 1 study) and a self-made anxiety questionnaire.

Nine studies provided information on 14 relationships between different measurements of (trait) anxiety and sickness severity or history. Four studies did not provide sufficient information for the computation of effect sizes of which two, however, stated to have found a significant relationship between anxiety and motion sickness history (Collins & Lentz, 1977) or cybersickness (Solimini, Mannocci, Di Thiene, & La Torre, 2012) while two did not find a significant relationship (Dobie & May, 1990; Kottenhoff & Lindahl, 1958).

Figure 5 presents the effect sizes of the remaining publications with indications of the test employed. The effect sizes were remarkably concordant and most of them range in between $r = .26$ and $r = .41$. Ten of the fourteen tests resulted in a significant relationship between anxiety and motion-related sickness. Slightly lower and non-significant was the relationship with the 16PF. Fox and Arnon (1988) used three scales from the 16PF: C (affected by feelings – emotionally stable), O (self-assured – apprehensive) and Q4 (relaxed – tense). Possibly these three scales do not reflect trait anxiety as good as other measures and are therefore only weakly related to sickness scores. Standing out on both extremes of the list are the two correlations reported by Bick (1983), obtained separately for men and women. For women, he found the highest correlation of all correlations reported ($r = .62$) while the effect was absent in men ($r = .06$). He concluded that motion sickness might be primarily related to neuroticism in women and to vestibular disturbances in men. In a way, the results refuted the hypothesis of gender differences being caused by social demand as there should have been a higher correlation for men due to equally high social demands on males presenting themselves as not anxious. It needs to be mentioned that the sample size in the study by Bick (1983) was fairly small and the effects for men and women comprise of only 12 participants each. The range of the confidence intervals shows that the gender differences could also be much smaller (Figure 5).

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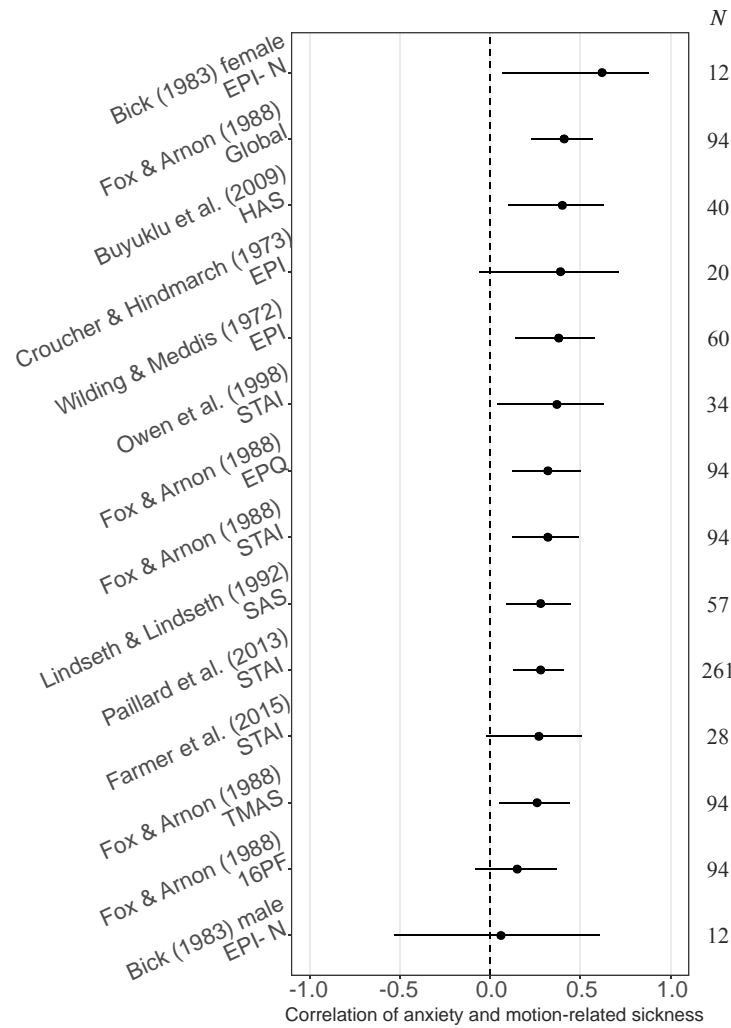


Figure 5. Effect sizes and 95% confidence intervals for all studies investigating (trait) anxiety and motion-related sickness.

Apart from the effect for females reported by Bick (1983), the highest correlation was attained by Fox and Arnon (1988) who used four different measurements to assess anxiety. From the scores of all four measurements, they computed a composite global score of anxiety. This global score, probably due to its increased reliability, was best at predicting individual motion sickness scores of their participants ($r = .41$).

In a subsequent analysis, I pooled the correlation coefficients from all studies providing sufficient information with Hedges-Olkin fixed effects (Hedges & Olkin, 1985). From the study by Fox and Arnon (1988) only the correlation of the global score was included as the study would be overrepresented otherwise if all five correlations had been adopted. The pooled correlation resulted in

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$r_{pooled} = .33$ (95%-CI: .26 - .40). However, it must be noted that the studies differ considerably in the assessment of motion-related sickness and anxiety and this was not taken into account in the calculation of the pooled correlation.

In summary, most studies supported the notion of a relationship between anxiety and motion-related sickness. However, only few were giving a proper rationale to explain why anxiety could be related to the genesis of motion sickness. Some symptoms of motion-related sickness may be intrinsic to anxiety as well, although nausea is usually not one of them (Fox & Arnon, 1988). Owen, Leadbetter, and Yardley (1998) suggested that anxiety directly affects postural balance and leads to deficiencies in postural control and hence to increased motion sickness susceptibility.

It is also possible that anxious individuals may tend to be more attentive or alert to internal states of the body and might also facilitate the appearance of symptoms of motion-related sickness (Fox & Arnon, 1988). This latter hypothesis was part of studies 2 and 3 of this project in form of pain catastrophizing and body awareness.

Psychological disorders.

Virtual realities gained increased attention by phobia research due to its great potential for use in exposition therapy. As cybersickness is a common side-effect of virtual reality exposure, some studies investigated if cybersickness might be problematic when used in therapy or generally if phobic patients have an increased risk of getting sick when exposed to motion-related stimuli. Of course, phobias are closely tied to anxiety.

Three studies investigated different specific phobias and their relation to motion-related sickness using visually presented stimuli. Two of them used a VR (Robillard, Bouchard, Fournier, & Renaud, 2003; Viaud-Delmon et al., 2006) and one induced VIMS by means of a moving room (Faugloire, Bonnet, Riley, Bardy, & Stoffregen, 2007). Unfortunately, these three studies had some methodological issues. For this reason, the validity and generalizability of the results may be compromised.

Faugloire et al. (2007) found that claustrophobia was related to the level of VIMS when participants were restrained during exposure. In contrast, there was no relationship when participants

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were unrestrained. However, Faugloire et al. (2007) measured claustrophobia as a condition that comes very close to state anxiety in a restrained condition. This assumption is supported by the fact that more people without symptoms of sickness disclosed to have experienced claustrophobia in the past. Also, the authors suggested that claustrophobia (during the restrained condition) might cause an increased susceptibility to experience sickness. It seems equally likely that symptoms of sickness cause claustrophobia when restrained and impeded from withdrawing.

In another study, Robillard et al. (2003) matched non-phobic controls to patients with different specific phobias. The participants were then exposed to a virtual reality depicting the content of the respective phobia or the phobia of the matched patient. Phobic patients were showing higher cybersickness with a medium effect size. These results, however, could be explained by elevated state anxiety of phobic patients when exposed to the fear-inducing stimulus alone. Given the largely diverging levels of trait anxiety between phobic and control groups, a specific effect of phobia on cybersickness is unlikely.

The third study observed a relationship of agoraphobia and cybersickness during combined audio and visual stimulation but not when exposed to visual stimuli alone (Viaud-Delmon et al., 2006). The increase in cybersickness among phobic patients was accompanied by higher state anxiety during audiovisual compared to just visual stimulation. An explanation for these results could be impaired multisensory integration ability among agoraphobic and anxious patients.

Finally, Sharma and Aparna (1997) found a significant correlation between acrophobia (fear of heights) and motion sickness history ($r = .43$).

The interpretation of these studies with regard to the role of phobias is difficult as phobic groups were confounded with elevated trait and state anxiety. Future studies should balance anxiety levels between phobic and control groups in order to determine if there is a specific effect of phobia on sickness levels or if the relationship is caused by increased vulnerability of phobic patients for fear responses under certain conditions.

For other psychological disorders, the works of Charles Mirabile are pivotal. Mirabile was the only researcher to investigate psychological disorders and motion sickness history in more detail as he was trying to establish motion sickness as an objective predictor of various psychological disorders. In

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all of his studies, he used a motion sickness history questionnaire to attain a spectrum of differential motion sickness susceptibilities by disorder. Some psychological disorders were overrepresented at different points of the spectrum: passive-aggressive personality disorder as well as alcohol and heroin addicts have a low susceptibility; schizophrenia patients have medium-high susceptibility; emotionally unstable and antisocial personality disorders had the highest susceptibility (Mirabile, 1972; Mirabile & Glueck, 1980; Mirabile, Glueck, & Hedberg, 1981).

In a later study, Mirabile and Glueck (1993) found that patients with a seasonal affective disorder (SAD) were more likely to be susceptible to motion sickness, an effect which was not present in non-seasonal affective disorders. Furthermore, patients with SAD who were also highly susceptible to motion sickness were more responsive to light therapy than motion sickness resistant patients. Thus, they suggested that common sensory (dys)function might play a role in SAD as well as in motion sickness.

One criticism against the studies by Mirabile and colleagues is that most studies, except the latest (Mirabile & Glueck, 1993) did not incorporate healthy controls but only used a psychiatric sample with various different disorders. This complicated estimation whether patients of certain psychological disorders were having an increased susceptibility to motion sickness or lied in the normal range of susceptibility. Furthermore, despite assuming neurobiological causes, Mirabile and colleagues do not offer explanations as to why certain psychological disorders should be related to motion sickness and others not.

Overall, the practical benefit of motion sickness to predict or identify psychological disorders is very limited. Some disorders might be related to motion sickness history but the reasons are unknown.

Personality.

Thirteen studies in the publication sample investigated personality in relation to motion-related sickness (excluding those only investigating anxiety/neuroticism or personality disorders). The idea of personality influencing the susceptibility to motion-related sickness was first raised by the *receptivity hypothesis* which claims that individuals who have a generally higher sensory receptivity

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are also more prone to become motion sick (Reason, 1968, 1969a). This theory, referring to the cortical inhibition theory by Eysenck (1955) stating that introverts are having greater neural response given the same sensory input than extroverts, suggested that introverts should also be experiencing stronger sensory conflict while exposed to motion-related stimuli. However, out of nine studies investigating extraversion, only three found significant relationships between extraversion and motion sickness, in the sense that introverts were more susceptible (Collins & Lentz, 1977; Kottenhoff & Lindahl, 1958; Nichiporuk, 2013). Six studies were not able to replicate any relationship between extraversion and susceptibility to motion-related sickness (Bick, 1983; Croucher & Hindmarch, 1973; Dobie & May, 1990; Farmer et al., 2015; Gordon et al., 1994; Wilding & Meddis, 1972).

Since extraversion did neither show a relationship to the spiral after effect (Croucher & Hindmarch, 1973), the receptivity theory has been generally considered disconfirmed. Most studies were conducted prior to the 1990s and investigated the relationship to motion sickness severity or history. However, two newer studies using visually presented motion likewise found no relationship (Dobie & May, 1990; Farmer et al., 2015).

Keinan et al. (1981) assessed the tendency to cope with stress on the repression-sensitization scale (Byrne, 1961). Repressors tend to ignore and avoid facing stressors while sensitizers try to actively cope with the stressor at hand. In this study, repressors reported greater motion sickness while at sea.

Leimann Patt, Baistrocchi, and Moia (1988) observed that participants scoring higher on alexithymia, i.e. the inability to identify emotions in oneself and others, were experiencing more motion sickness, probably misinterpreting bodily signals and somatizing emotional distress. This suggested that participants, who are ignoring bodily stressors during motion-related stimulation, either by personal tendency or by inability, are experiencing somewhat greater motion-related sickness. The effect of awareness to bodily signals on the degree of motion sickness was also investigated in studies 2 and 3 of this project.

Some other personality constructs were part of only one or two studies in the current publication sample. From those, higher motion sickness history was assessed for participants who had low psychoticism (Gordon et al., 1994), low perfectionism (Nichiporuk, 2013), low sensation seeking

(Alley, Willet, & Muth, 2006) and low obsessiveness (Leimann Patt et al., 1988). Other constructs did not yield significant relationships with motion-related sickness: locus of control (Collins & Lentz, 1977; Keinan et al., 1981), validity scales (Royal, Jessen, & Wilkins, 1984) and most scales of the 16PF failed to show linear relationships, except social boldness, perfectionism and the primary factor extraversion (Nichiporuk, 2013).

Perception (Field dependency).

The majority of studies in the area of perception were conducted on field dependency. Field dependency is defined as a perceptual style in which the perception of an object is either strongly dependent on the object environment (field dependent) or independent of it (field independent) (Witkin & Goodenough, 1977).

There are generally two different procedures for measuring field dependency. In the first method, participants must recognize geometric shapes embedded in more complex contextual shapes which ought to be ignored (embedded figures). In the second method, the participants sit in a tiltable chair within a darkened room and look at an illuminated frame with a rod in the middle (rod and frame test). Chair, frame and rod are vertically deflected and the participant cannot touch the ground. The task is to rotate the rod to a vertical position relative to the physical ground, ignoring the orientation of the frame and the own body. Task performance is determined by the deviation from the optimal vertical position (true vertical). Participants who can complete this task well are considered to be field independent.

In the present set of publications, seven studies were conducted, which examined the rod and frame test in connection with motion sickness, four used the embedded figures test and one study used a test that was similar to the rod and frame test.

Of the seven studies with the rod and frame test, six reported that there was a significant correlation between the result in the rod and frame test and the severity of motion sickness (Barrett & Thornton, 1968; Barrett, Thornton, & Cabe, 1970; Long, Ambler, & Guedry, 1975; Neimer et al., 2001; Yardley, 1990). One study (Mirabile, Glueck, & Stroebel, 1976) did not find a significant relationship, neither did the study that used a similar test to the rod and frame test (Pitblado &

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Mirabile, 1977). Cian, Ohlmann, Ceyte, Gresty, and Golding (2011) found an interaction of field dependency with off-vertical axis rotation in light or in the dark. Field dependent individuals were generally not more susceptible to motion sickness but exhibited more sickness when the adverse rotation was administered in the dark without any visual cues.

Unfortunately, both studies not finding a linear relationship between the rod and frame test and motion sickness history did not report sufficient data of the linear relationship to compare them to the other studies. The pooled correlation of the remaining five studies with Hedges-Olkin fixed effects resulted in $r_{pooled} = .47$ (95%-CI: .36 - .58).

For the embedded figures test none of the publications listed here could determine a significant connection with motion-related sickness (Barrett, Thornton, & Cabe, 1969; Bick, 1983; Deich & Hodges, 1973; Long et al., 1975). Although the rod and frame test and the embedded figures test should measure the same construct, the correlation between the two tests often does not seem to be higher than $r = .50$ (Long, 1972). A different study achieves a correlation of $r = .61$ (Arthur & Day, 1991), which is higher, but with a shared variance of 37 % there is low evidence for measuring the same construct.

Both tests are considered indicators of the ability to correctly perceive a stimulus in the presence of a conflicting context. With the embedded figures, both the stimulus to be perceived and the context are purely visual. In the rod and frame test, the conflicting context is generated both visually and vestibularly. Therefore, even theoretically it is much more likely that the rod and frame test is more closely related to sickness caused by a sensory conflict.

Another aspect that has only been investigated in one study so far is autokinesis. Autokinesis is a phenomenon in which a small visual point of light that is actually stationary is perceived as moving. The study found a significant link to motion sickness history and concluded that both motion sickness and autokinesis were related to a vestibular system dysfunction (Mirabile, Glueck, Stroebel, & Pitblado, 1977). Unfortunately, no attempts have yet been made to replicate the found connection.

Cognitive performance.

The relationship between parameters of cognitive performance and motion sickness was investigated in two studies, in the sense that cognitive performance can predict future motion-related sickness or motion sickness history. In the first study, cognitive performance was measured in the form of a concentration test in Taiwanese boxers before and motion sickness after a boxing bout (Chen et al., 2013).

Boxers who did not report motion sickness after the bout also achieved a significantly better result in the concentration test before the bout. The result is doubtful in several respects. The authors speak of motion sickness, since the head and body were exposed to several passive movements (i.e. enemy blows) during the bout. However, it is much more likely that the sickness was not caused by movement alone, but by injuries to the head, such as a concussion. It is therefore questionable whether this can still be called motion sickness. In addition, the correlative relationship leaves questions about the causal relationship between the two variables. It is quite possible that boxers with a lower concentration performance also showed worse performance in the ring and had to take correspondingly more enemy blows, meaning the number and strength of punches was not standardized. The value of the results for predicting motion sickness is therefore rather low.

The second study investigated the predictive power of spatial perception on motion sickness history (Levine & Stern, 2002). A significant correlation was found in men but not in women. The correlations were explained by a possible greater sensitivity for the vertical upright in those who had higher spatial abilities. This explanation is reminiscent of field independence. Since there are no further studies on the subject and the correlations could only be determined in men, it remains unclear to what extent spatial ability can predict motion sickness and go beyond field dependence.

Summary

The compilation of the results has shown that many of the presented interrelationships were based on only a few or somewhat controversial results. Further studies are necessary to determine replicability and to eliminate contradictions in the relationships found. Unfortunately, more systematic

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(or meta-analytical) methods could often not be applied, as the conditions and measuring methods were too different or the necessary data were not available.

However, the review of the literature has also found some promising predictors for motion-related sickness. The possible predictors and their obtained relationship with motion-related sickness are summarized in Table 5. Although most results suggested that sickness caused by physical motion (i.e. motion sickness) shows the same correlations as visually induced sickness (i.e. VIMS, cybersickness and simulator sickness), there were some meaningful exceptions such as age or labyrinthine defectiveness. Therefore, the findings for these two categories are presented separately. This approach also illustrates that some aspects that were predictive of motion sickness have never been investigated in the context of visually induced sickness.

The most reliable findings for predicting motion sickness are gender, vestibular function, especially the length of the VOR time constant, the presence of migraine, the susceptibility of close relatives, great anxiety (both trait and state anxiety), field dependence, a high sympathetic tone and habituation to the adverse stimulus.

There is less certainty about predictors for visually induced sickness (VIMS, cybersickness and simulator sickness). Gender, habituation, anxiety and possibly OKAN are the best predictors of visually induced sickness.

As the study by Hromatka et al. (2015) has shown, there seems to be a genetic link between the development of the vestibular and visual systems affecting susceptibility to motion sickness. In *what way* genes are affecting the susceptibility to motion-related sickness remains unclear.

Finally, there is probably a significant environmental impact on susceptibility, most likely represented by varying degrees of habituation. It is still unclear to what extent habituation for similar stimuli and different types of motion-related sickness can be achieved, even if results suggested certain generalizability. Anxiety as a general tendency to deal with aversive experiences may also influence susceptibility to motion-related sickness.

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Table 5. Summary of the results of the literature review.

	<i>Motion sickness</i>	<i>Visually induced sickness</i>
Demographic variables		
Gender	▲	(▲)
Menstrual cycle (peri-menstrual phase)	(▲)	—
Age	(▼)	(▲)
Habituation	▼	▼
Handedness	(●)	—
Body mass index (BMI)*	(●)	(●)
Alcohol consumption*	(●)	—
Hangover severity*	(▲)	—
Physiological variables		
Labyrinthine defect	▼	(●)
Vestibular ocular reflex time constant	▲	—
Vestibular ocular reflex gain	(●)	—
Vestibular evoked myogenic potential threshold	(▲)	—
Vestibular evoked myogenic potential asymmetry	(▲)	—
Spiral after-effect	(●)	—
Optokinetic after-nystagmus	—	(▲)
Vision acuity	—	(●)
3D vision	—	(▲)
Vertical phoria	(▲)	(▲)
Postural instability	(▲)	(▲)
(Vestibular) Migraine	▲	—
Aerobic fitness	(▲)	—
Higher sympathetic tone	▲	(▲)
Chinese ethnicity	(▲)	(▲)
Susceptible relatives	▲	—
Baseline Cortisol / Baseline ACTH	(▼)	(▲)
Nicotine-deprived smokers*	(▼)	—
Vasovagal syncope	(▲)	—
Adolescent idiopathic scoliosis (AIS)*	(▲)	—
(Bitter) Taste sensitivity	(●)	—
Food aversions*	(▲)	—
Bad sleeping quality	(▲)	—
Psychological variables		
State anxiety	▲	▲
Trait anxiety	▲	▲
Phobia	(▲)	(▲)
Extraversion	●	(●)
Repression (repression-sensitization)	(▲)	—
Psychoticism	(▲)	—
Perfectionism	(▼)	—
Sensation Seeking*	(▼)	—
Obsessiveness*	(▼)	—
Locus of control*	(●)	—
Social desirability*	(●)	—
Field dependency (RFT)	▲	(▲)
Field dependency (EFT)	●	(●)
Autokinesis*	(▲)	—
Mental rotation ability	(●)	—

Note: ▲ = increased susceptibility; ▼ = decreased susceptibility; ● = no relationship; — = not yet investigated; () = three or less studies and/or mostly contradictory results; * = only one study.

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This review illustrates that despite being a long known phenomenon, individual susceptibility to motion-related sickness is still not fully elucidated. Although many indications pointed to physiological or biological differences, there is also reason to investigate psychological factors causing the large inter-individual differences. In addition to the influence of video games as a possible habituation for VR in Study 1 and Study 3 (unpublished result), catastrophizing and body awareness are examined as possible psychological factors on the expression of motion-related sickness in studies 2 and 3.

Cognitive Impairments

The possibility of experiencing sickness in VR is in itself an undesirable consequence of the use of such virtual environments. However, there may be even more hazardous repercussions if the use of VR and the emergence of cybersickness have a negative effect on (cognitive) performance. In any case, it is a safety-relevant issue whether driving a car or using other means of transportation is possible without any restrictions after using a VR, especially if one has developed cybersickness symptoms. The same naturally applies when VR is used by surgeons in the operating room, pilots or other flight personnel or by anyone else in high stake situations whenever VR is to be used.

The manufacturers of VR equipment recommended that the use of vehicles or machines (generally all activities that are visually or physically demanding) should be avoided until all symptoms of cybersickness have subsided (Oculus, 2018). Since studies showed that these symptoms can last the whole day or in an attenuated form even for several days (Champney et al., 2007; Gower & Fowkles, 1989), the use of VR could lead to considerable restrictions in everyday life. In a U.S. Navy study investigating the effects of flight simulators, some participants still experienced symptoms of simulator sickness over several days, which is why the authors recommended not to drive a car one to two days after the exposure to the simulator (Kennedy, Lilienthal, Berbaum, Baltzey, & McCauley, 1989). Additionally, flying an aircraft is forbidden for six hours or more after the exposure to a flight simulator (Gower & Fowkles, 1989). Although in practice, these recommendations should be followed as a precautionary measure. It is not yet clear to what extent the use of VR and especially the experience of cybersickness actually leads to limitations of cognitive performance.

Studies using car simulators investigating the effect of simulator sickness on driving ability did not find worse performance in driving tasks (e.g. lane keeping) for those who got sick compared to those who showed less or no symptoms (Helland et al., 2016; Mullen, Weaver, Riendeau, Morrison, & Bédard, 2010; Muttray et al., 2013). However, the simulator sickness caused a more cautious driving style with lower speed and less steering maneuvers (Helland et al., 2016) and thereby probably altering one's own perception of fitness and performance.

Studies that have used flight simulators were also ambiguous as to the effect of simulator sickness on cognitive performance. While some studies similarly did not find any effect on cognitive

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performance (Kennedy et al., 1987; Warner, Serfoss, Baruch, & Hubbard, 1993), others registered an effect on the speed of psychomotor actions (Uliano, Lambert, Kennedy, & Sheppard, 1986) or on concentration tasks (Kennedy, Fowlkes, & Lilienthal, 1993).

Several studies suggested that exposure to an aversive motion environment leads to an increased reaction time (Nalivaiko, Davis, Blackmore, Vakulin, & Nesbitt, 2015; Nesbitt, Davis, Blackmore, & Nalivaiko, 2017; Shattuck, Shattuck, Smith, & Matsangas, 2013). Various approaches could explain the influence of motion-related sickness on this deterioration of reaction time. Motion-related sickness could lead to increased fatigue (a recognized symptom), low motivation or a slower motor response (Wertheim, 1998), which in turn could cause a slower reaction rate. It is also possible, though, that motion sickness has a general effect on cognitive processing speed.

Despite the aforementioned studies on reaction speed, the effects of cybersickness on cognitive performance have not yet been investigated. Since motion sickness has been associated with various cognitive parameters, from mental rotation (Levine & Stern, 2002; Parker & Harm, 1992), to perceptual speed (Golding & Kerguelen, 1992) and working memory (Bos, 2015; Dahlman, Sjörs, Lindstrom, Ledin, & Falkmer, 2009), it is also possible that cybersickness may affect other areas besides reaction speed.

As noted above, decrements in cognitive performance as a result of VR exposure could have serious implications for fitness in any kind of professional activity but especially those which involve vehicles or machines. It is necessary to understand which cognitive abilities are impaired and to what extent by cybersickness in order to be able to take necessary precautions in case someone experiences cybersickness in professional contexts, especially when human safety is at risk.

Research questions

Three main research questions have been extracted from the literature. All these research questions are concerned with the topic of the applicability of virtual environments with HMDs and the syndrome of cybersickness. Two of these questions address the emergence of cybersickness and investigate aspects of the system and characteristics of the individual. The third question examines the consequences of cybersickness on cognitive performance.

To answer all questions, a VR application was developed which is described in further detail in the appendix.

Research question 1

Based on the aforementioned considerations about different hardware components, the first research question concerns the effect of VR hardware on the degree of cybersickness. This question is subdivided into: *What effect do head-mounted displays have compared to large screens and what effect does a more realistic motion control method have compared to a generic control method on the degree of cybersickness?*

These two research question are investigated in Study 1 and Article 1 of this project.

Research question 2

If VRs induce cybersickness then one has to examine the question, *what influence does cybersickness have on the cognitive performance of the user directly after exposure to VR*. This will also be investigated in Study 1 of this project. The results are presented in Article 2.

Research question 3

Finally, as shown in the literature review, anxiety seems to correlate with susceptibility to motion sickness. Since more specific constructs and mechanisms have not yet been investigated, this project will examine: *What is the impact of (pain) catastrophizing and body awareness on individual susceptibility to motion-related sickness.*

This research question is addressed in studies 2 and 3, as in Article 3 of this project.

Article 1 (Study 1)

Mittelstädt, J. M., Wacker, J., & Stelling, D. (2018). Effects of display type and motion control on cybersickness in a virtual bike simulator. *Displays*, 51, 43-50. doi:10.1016/j.displa.2018.01.002

Summary

In the first study (Mittelstaedt, Wacker, & Stelling, 2018) we investigated the influence of the presentation method and the method of motion control on the experience of cybersickness in a virtual environment. We found differences between presentation devices (HMD and large screens) but not between two different control devices (generic and realistic).

Motivation

In this study, the goal was to determine the impact of different hardware on the level of users' cybersickness experience, namely the choice of presentation device and the influence of the control method.

Many previous studies suggested that users of HMDs typically report more cybersickness than users of large screens. Moss and Muth (2011) argue that the difference in inducing sickness between HMDs and conventional presentation media is that HMDs usually hide independent reference points of the physical world, i.e. visual cues that are giving hints about the true vertical orientation of the body. It is important to know whether these effects are specifically triggered by HMDs, making them not fully suitable for every application, or whether the effects are caused by particular differences (such as masking the physical environment) that can possibly be changed with design adjustments.

This study was designed to replicate earlier results of increased cybersickness levels of HMDs and to exclude the possibility that differences are caused by the perception of reference points of physical reality, so participants who were presented with VR on a large screen additionally wore a mask that hid the visual surroundings.

In addition, effects of the motion control method on the development of cybersickness were investigated. It is potentially difficult and costly to physically re-create a control device reflecting the method of locomotion depicted in a VR. Therefore, it is interesting whether a more realistic method of

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motion control reduces the development of cybersickness at all or whether virtual applications can be controlled just as well with a generic control device. More specifically, in this study we compared two types of motion control methods: a realistic motion control method with a bicycle ergometer and a generic motion control method with a commercial gamepad.

Since cybersickness in VRs, presented on HMDs or screens and controlled by gamepads, is possibly related to familiarity with such systems and kinds of applications (Rosa et al., 2016), we have also evaluated the frequency of video game consumption and its influence on sickness.

The aim was to assess the influence of display and control methods and to generate possible design recommendations for future VR applications.

The study was carried out with the virtual bicycle application, which was developed within the scope of this project (see Appendix). Participants were riding a virtual bicycle along a pre-specified path on a virtual island. With reaching the destination the degree of cybersickness was surveyed. The participants were assigned to one of three conditions with alternating presentation devices (HMD vs. large screen) and motion control method (bike ergometer vs. gamepad).

Results and discussion

The results of this study showed that participants experiencing the VR with the HMD as presentation device experienced more cybersickness than those using a large screen with a mask. These results support earlier findings that HMDs induce more sickness than other presentation devices such as large screens (Sharples et al., 2008) and stand in contrast with the assumption that the higher cybersickness found in connection with HMDs can be explained by the masking of independent reference points in the visual surroundings that occurs in HMDs (Moss & Muth, 2011). In addition, the results contradict findings by Keshavarz et al. (2011) that there was no difference between HMD and large screen when the field of view was limited to an equal degree. However, other than in the aforementioned studies, participants had active control over their virtual movements and did not just watch a three-dimensional movie. Despite being told to keep looking straight ahead, small movements of the head in those wearing an HMD could have disrupted the internal reference frame and elicited a sensory mismatch.

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As a second result, no difference between the two motion control methods (realistic vs. generic) was found. This finding contradicts some of the previous research (Jaeger & Mourant, 2001) which found a difference between walking on a treadmill and generic control method. However, walking on a treadmill involves vestibular feedback by physically walking forwards. This vestibular feedback was absent in the virtual bicycle application which could have caused the divergence of findings between these two studies. The results dovetail more recent findings, in part also using treadmills, which were not able to determine differences in cybersickness induction regarding the method of motion control (Aldaba et al., 2017; Lee et al., 2017).

As a final result, there was a correlation between the frequency of video game use and cybersickness susceptibility but only in the condition with HMD and generic motion control. The literature review presented above suggests a considerable effect of habituation on the susceptibility to motion-related sickness but was indefinite about the degree of generalizability of habituation across multiple vehicles or motion-relevant contexts. The correlations found may be a small indicator that the habituation to virtual environments by frequent interaction with video games can be generalized to a certain extent on the susceptibility to cybersickness in VR. Still, another interpretation, namely that people who are less susceptible to cybersickness more often opt for leisure activities such as video games, is also conceivable.

This article only described cybersickness that was experienced during the immersion and right after ending the immersion. Many users of VR, however, complain about lingering symptoms for a prolonged period after termination of the exposure. These and possible implications of those aftereffects for cognitive performance were investigated in Article 2.

Article 2 (Study 1)

Mittelstädt, J. M., Wacker, J., & Stelling, D. (under review). VR aftereffect and the relation of cybersickness and cognitive performance. *Virtual Reality*

Summary

This article (Mittelstaedt, Wacker, & Stelling, under review) discusses short-term aftereffects of cybersickness and the use of virtual realities on basal cognitive performance. People exposed to virtual reality showed a relative deterioration in reaction times compared to a control group. This deterioration seems to be only partially related to cybersickness and may be a more general effect of VR exposure.

Motivation

Article 1 investigated the influence of system variables such as the choice of presentation device and motion control method on the degree of cybersickness. The topic of the second article was potential aftereffects of cybersickness and the use of VR in general on cognitive performance.

As outlined above, there have been findings of deteriorated cognitive performance for individuals affected by motion-related sickness. Especially reaction speed seems to slow down in individuals affected by symptoms of motion-related sickness after the exposure to adverse motion stimuli (Nalivaiko et al., 2015; Nesbitt et al., 2017; Shattuck et al., 2013). However, since there are also contradictory results and it has not yet been investigated to what extent other parameters of cognitive performance are affected by cybersickness, the aim was to determine the changes in performance before and after exposure to a cybersickness-inducing VR.

The results regarding reaction time were to be replicated with several reaction time tasks (simple and choice). In addition, other tests on various cognitive parameters which were already discussed in connection with motion sickness were performed: processing speed, spatial comprehension and short-term memory.

Results and discussion

The results in our study replicate the deterioration of reaction speed of those previously exposed to a VR in different tasks compared to a control group. However, the changes in response time were only slightly related to the degree of reported cybersickness and were also observable in participants who were exposed to the less symptom inducing method (large screen condition). In the study, the reaction times of all three groups exposed to VR worsened compared to a control group that rested between data collections. This suggests that exposure to VR in general may lead to a drop in performance, regardless of the degree of cybersickness induced.

It is possible that certain features of the VR application, such as input or presentation delays inherent to the system, have caused users to adapt, slowing down processing and/or response.

These results correspond to previous research by Muth (2009), who also observed deterioration in performance regardless of the degree of motion sickness, and to some extent also to the study by Nesbitt et al. (2017) whose significant correlation was primarily based on the data of an influential outlier.

In most cases, the intra-individual differences, i.e. the individual deterioration of reaction times were significantly lower than the inter-individual variance measured before the exposure to VR. Affected individuals do not drop to a level that no longer allows them to perform well and thus the cognitive performance will be practically not very impeded.

Likewise, none of the participants experienced a significant drop in performance, despite some severe symptoms of cybersickness which were even exhibited a while after ending the immersion. However, it must be mentioned that a decline in performance may be greater if the period of use is significantly longer.

Besides reaction time, none of the other three parameters of cognitive performance (perceptual speed, spatial ability and working memory) deteriorated. In fact, the performance in the working memory and spatial ability tests somewhat improved after exposure but was not different between conditions or related to cybersickness and is thus attributable to an effect of practice. In summary, our results indicate that cognitive performance, besides reaction time, is not impaired by cybersickness or exposure to VR.

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After the results reported in Article 1 showed that parameters of the VR system like the presentation device are affecting cybersickness scores, I was interested in factors influencing individual cybersickness susceptibility. For this I referred to the literature review depicted above and extended its results to investigate new concepts in relation to motion-related sickness.

Article 3 (Studies 2 & 3)

Mittelstädt, J. M., Stelling, D., & Wacker, J. (in press). Emotional and cognitive modulation of cybersickness: The role of pain catastrophizing and body awareness. *Human Factors: The Journal of the Human Factors and Ergonomics Society*. Published online.

Summary

This article (Mittelstaedt, Wacker, & Stelling, in press) describes the results of studies 2 and 3: The individual tendency to catastrophize (pain) is correlated with increased reports of motion sickness in various motor vehicles and the severity of cybersickness when exposed to VR. This effect seems to be moderated by the ability to perceive and anticipate bodily processes.

Motivation

Regardless of the system used, there are often large inter-individual differences in the expression of cybersickness symptoms, as shown above. The aim of these two studies was to investigate the influence of two psychological constructs related to body perception and the processing of pain which might be similarly involved in the processing of aversive physical stimuli, including nausea and motion sickness (Balaban & Yates, 2017).

Anxiety has often been studied in connection with motion-related sickness and it has mostly been found to be associated with increased occurrence of motion sickness as well as with the severity of sickness symptoms with direct exposure to an aversive motion stimulus (Farmer et al., 2015; Fox & Arnon, 1988; Owen et al., 1998; Paillard et al., 2013).

However, since there are few approaches to explain why anxiety should be related to motion-related sickness, we have used constructs related to body perception (body awareness; Shields, Mallory, & Simon, 1989) and the emotional processing of adverse bodily symptoms (pain catastrophizing; Sullivan, Bishop, & Pivik, 1995). Pain catastrophizing represents the individual tendency to worry and constantly ruminate about adverse stimuli and magnify its symptom sensation. Body awareness describes the ability or sensitivity to perceive subtle bodily changes, e.g. as a result of hunger, illness, or fatigue. Both of these constructs are related to anxiety (Ginzburg, Tsur, Barak-

Nahum, & Defrin, 2014) and could represent to what extent symptoms of motion related-sickness are perceived as threatening.

Differences in the way physical symptoms are perceived and processed could provide a better insight into the development of motion-related sickness symptoms and clarify inter-individual differences in symptom severity.

In Study 3, the same virtual environment was used as in Study 1. This time, however, participants were allowed to explore the virtual island without a pre-specified route. Furthermore, all participants were standing while being exposed to the VR.

Results and discussion

Pain catastrophizing predicted both the indication of motion sickness in various vehicles and the severity of cybersickness during VR exposure. Strong catastrophizers report more motion sickness and worse symptom severity. The ability to perceive bodily changes, i.e. body awareness, had no such linear effect. However, there was an interaction effect on the relationship with pain catastrophizing, in the sense that people who have high catastrophizing and low body awareness report the most motion sickness and worst symptom severity.

Overall, we were able to show that the degree of catastrophizing is related to the degree of motion-related sickness and thus identified catastrophizing as a possible cause for the aggravation of motion-related sickness symptoms. This relationship provides opportunities to plan interventions that increase knowledge about the syndrome, corresponding to the moderating effect of body awareness, and thus reduce the extent of ruminating and catastrophizing of sickness symptoms. This notion fits in with previous research in which simple cognitive distraction (Bos, 2015) or the application of a cognitive-behavioral technique (Dobie, May, Fisher, & Bologna, 1989) have already led to a reduction in motion sickness symptoms.

General discussion

This dissertation project examined cybersickness induced by the use of VR. Within the scope of this dissertation, I investigated the impact of different system design choices (presentation device and motion control method) on the degree of cybersickness, as well as the relationship between cybersickness and inter-individual differences in catastrophizing aversive symptoms and being able to perceive bodily signals. Additionally, I assessed aftereffects of cybersickness and VR usage on cognitive performance.

Overview of the results

Within the project, a VR system and application was created that allows participants to experience and interact with a virtual environment. Although not explicitly intended, this application reliably induces cybersickness in the majority of users and creates large inter-individual variance allowing investigations of relationships and possible causes of cybersickness in a VR. As a side note, the application allows the retrieval of items *within* the immersion, which according to our knowledge, has not been done before.

The findings of the first study demonstrate that HMDs induce more cybersickness than large screens, even if the visual surroundings of the screen are masked. This confirms the results of earlier studies from which the hypothesis of the present project was derived. (Liu & Uang, 2011; Rebenitsch & Owen, 2017; Sharples et al., 2008; Tan et al., 2015; Tong et al., 2016). The results contradict other studies that have found no difference between the two presentation media, especially when the external environment of the screen is covered (Keshavarz et al., 2011). In this study a 3D movie was used in which participants could not influence the virtual movement. In contrast, our study used an active virtual environment in which the participants were able to control their motion. Perhaps, active control increases immersion, the experience of illusory self-motion (vection) or interacts in a yet unknown way with HMDs in inducing cybersickness. Another difference is that we did not use a chin rest for the purpose of giving the participant active control over the bicycle. Although the participants were requested to move their heads as little as possible and always look straight ahead, even small movements, e.g. as a result of pedaling the bike, may have caused the HMD inducing more

cybersickness, especially because the image presented on the HMD moves along up and down, but remains the same on the large screen, thus perhaps providing an implicit visual frame of reference (Lin et al., 2002).

Apart from the display technology, we were not able to determine any difference in the motion control method. Thus the hypothesis that a realistic control method leads to less cybersickness could not be confirmed.

This supports past findings which also failed to establish a connection between the degree of realism of the motion control method and the extent of cybersickness (Aldaba et al., 2017; Bhandari et al., 2017; Lee et al., 2017; Tregillus et al., 2017). Consequently failing to replicate the contradicting proposition of an ameliorating effect of a realistic control method on cybersickness found in some of the previous studies (Jaeger & Mourant, 2001; Llorach et al., 2014). I will discuss some system restrictions in the limitations that might explain this discrepancy.

After examining the hardware design factors, we investigated the inter-individual differences in susceptibility to cybersickness. We were able to demonstrate a consistent relationship between (pain) catastrophizing and motion-related sickness. This correlation was evident both when the participants were asked to report their motion sickness experiences in various means of transportation from the past, and similarly when they had to assess the severity of cybersickness symptoms as a result of VR exposure. Furthermore, this connection between catastrophizing and motion-related sickness was consistently moderated by body awareness. Those with high catastrophizing and low body awareness were particularly susceptible.

We were thus able to show that the tendency to catastrophize perceptions of aversive bodily signals is related to the severity of motion-related sickness and that catastrophizing motion sickness symptoms is perhaps a central mechanism in the mental and emotional processing of these symptoms. It is unlikely that these processes cause motion-related sickness, but it seems quite possible that cognitive and emotional processing is involved in the further progression of motion-related sickness and thus in its severity.

Furthermore, we examined the question to what extent the experience of cybersickness affects cognitive performance after the termination of VR exposure. Our data showed that the participants

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who were exposed to VR, regardless of the presentation device and motion control method used, suffered losses in reaction speed compared to a control group. Thus, we were able to replicate previous results of worsened reaction time as a result of motion-related stimulation (Nalivaiko et al., 2015; Nesbitt et al., 2017; Shattuck et al., 2013). However, unlike in other previous studies, the observed deterioration in our study was only partly correlated with symptoms of cybersickness. Thus, our hypothesis that cognitive performance is impeded by cybersickness was largely disconfirmed.

This result suits previous observations that performance losses are not necessarily explained by motion sickness, but by the exposure to extreme motion experiences per se (Muth, 2009). Moreover, the result does not necessarily contradict the two studies finding relationships of reaction speed deterioration and cybersickness (Nalivaiko et al., 2015; Nesbitt et al., 2017), since in both studies the reaction times of almost all participants, including those who have not gotten sick, deteriorated and significant correlations were largely based on the influence of single outliers.

For the other abilities (especially spatial abilities and working memory) no deterioration could be observed as a result of VR exposure or cybersickness symptoms. Most importantly, even those participants who complained about severe symptoms during immersion, and still felt them after the termination of the exposure, showed no major loss of performance.

Limitations

As has been mentioned in the previous section, there may be an inadequacy of the utilized system regarding vestibular force feedback that serves as possible explanation for the missing effect of the control method.

The bicycle ergometer lacks any vestibular feedback, relevant when accelerating, braking, turning or in case of a changing slope, i.e. beginning to cycle up or downhill. The latter was anecdotally reported to have the highest impact on disorientation by some of the participants. This missing degree of reality might have prevented the bicycle ergometer to have an alleviating effect on cybersickness genesis. This rationale seems possible as the two studies arguing in favor of a positive effect of a realistic motion method used walking with actual locomotion (treadmill or walking in open space) as navigation method in VR while others did not use actual forward movement (e.g. walking in

place). However, there are also studies that could not find an effect even though a treadmill was used (Aldaba et al., 2017).

Either way, providing the bicycle with additional vestibular feedback on the visually represented movements would increasingly blur the boundary to a simulator. A simulator, e.g. a full-flight simulator, does not only provide detailed and life-like control armatures but also moves physically like the simulated vehicle and in accordance with control inputs. For reasons of cost and practicality, it must be assumed that VR application will be limited to visual presentation and has to operate without vestibular feedback at home or in professional contexts.

In addition, like so many other studies in behavioral research, the experiments involving the actual induction of cybersickness in VR was conducted using predominantly student samples or at least samples of young people. Since the above presented review of the literature indicates an effect of age on the susceptibility to cybersickness, the generalizability of the results of this project across all age groups is questionable. Currently, there is no reason why the obtained relationships should not be valid for older people, however, the mere circumstance of higher cybersickness severity for older people or the unfamiliarity with the technology might influence the relationships investigated in this project.

Practical implications

As described in the Introduction, VR offers many possibilities for use in professional contexts, for example as supporting devices for surgeons in the operation room, for remotely operating flying objects, or in physical and cognitive rehabilitation. The present research results are of importance in different respects for the design and use of VR in these contexts.

First, whenever motion is incorporated in the VR application and cybersickness prevention is more important than other aspects such as immersion, e.g. to increase motivation in rehabilitation, fixed screens are preferable to HMDs so that cybersickness does not negate the positive influence of VRs in these contexts. This naturally also restricts interactivity, since one advantage of HMDs is that the virtual environment changes intuitively with the movements of the head. A solution could be provided by so-called Augmented Reality glasses which offer similar interactivity to HMDs but at the

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same time have transparent displays and may be less sickness inducing due to the independent visual background of the physical reality. However, similar research with Augmented Reality glasses is still missing.

Second, aside from the system used, people who catastrophize bodily symptoms seem to be particularly susceptible to high levels of motion-related sickness. Likewise, low sensitivity to body symptoms seems to be additionally disadvantageous for high catastrophizers. In addition to a standard screening procedure for potentially susceptible individuals with a motion sickness history questionnaire, the assessment of catastrophizing and body awareness could identify those who are likely to develop high levels of cybersickness. These individuals may be selected for interventions that strengthen the awareness of the symptoms that may occur, e.g. by explaining the physiological reactions and symptoms and by reducing the extent of rumination and worry, as an approach by Dobie et al. (1989) has previously attempted to do.

Third, although the increase in response time as a result of VR exposure was consistently observed over several tests and a similar trend was discovered in the test for processing speed, the intra-individual variance in performance between pre- and post-test measurement was significantly lower than the inter-individual variance that can be observed in pre-tests. Hence the data on losses of cognitive performance collected in the present project does not suggest the need to refrain from controlling machines (e.g. cars) following a sickness inducing VR.

Therefore, the data presented here do not support that driving a car or operating a machine following the use of VR should be avoided, as cognitive performance does not seem to be substantially reduced. This is line with simulator driving performance not being impeded by simulator sickness (Helland et al., 2016). However, other studies have shown that there is still the possibility of experiencing spontaneous symptoms even hours after the termination of VR (LaViola, 2000) that can at least distract, if not, in the case of dizziness, lead to loss of balance or blackouts, so that affected individuals still need to remain cautious.

Future research

Since the results presented here lead to the assumption that cognitive and emotional processes may influence the course of symptoms of motion-related sickness, future studies should investigate to what extent the actual severity of symptoms is determined by biological (e.g. otolith asymmetry) and respectively by cognitive or other influencing factors. This reflects, in a way, the question whether motion sickness is more of a medical or a psychological syndrome.

In the past four years of this doctorate, there have been enormous technical changes, but also with regard to media attention and the social acceptance of VR. More and more tangible areas of application for VR are emerging that were not foreseeable four years ago. Future studies should focus more on the systems and applications that will eventually be used in specific situations.

VR applications, for example for the support of surgeries, have completely different requirements than those that help pilots to remotely control a flying object. The field of research and the number of scientists dealing with this topic has grown to such an extent that in the future it will be possible to study all these different application domains separately. Studies in the settings and with the systems that will eventually be used, should enhance the ecological validity of the results.

The literature review on individual differences in susceptibility to motion-related sickness revealed that the determination of causes and exact prediction of these differences is still challenging. Specifically, many findings from research on motion sickness are not validated using visually induced sickness including cybersickness. Since there are some predictors that seem to be valid for both motion sickness and visually induced sickness (gender, anxiety), but others do not seem to apply to all types of motion-related sickness (age, labyrinthine defectives), an investigation of these factors is a worthwhile area of research.

In general, Table 5 contains many brackets indicating either three or less studies on a given relationship or mostly contradictory results. Replication of these controversial relationships is needed to underpin their actual significance or to resolve conflicting results.

Conclusion

In this dissertation project I reviewed and combined the vast literature on motion sickness and the relative young science on cybersickness. In three studies I carried out experiments that try to replicate previous results and explore new research questions.

Virtual reality is a new technology that, although often used for entertainment purposes, can also support professionals in their working environment as a useful tool. At present, the negative effects of cybersickness might prevent this useful application of the technology. Still, cybersickness incidences might decrease, similarly to the decrease of motion sickness in aviation throughout the 20th century, when the technology will become more established within the general population. Consequently, exploring the possibilities, difficulties and dangers of this technology is necessary to apply it in a beneficial manner. The findings of this project will help to better understand the development of cybersickness caused by VR and its consequences for human performance.

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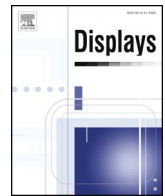
Appendix

Article 1

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Effects of display type and motion control on cybersickness in a virtual bike simulator[☆]



Justin Mittelstaedt^{a,*}, Jan Wacker^b, Dirk Stelling^a

^a German Aerospace Center (DLR), Sportalle 54a, 22335 Hamburg, Germany

^b University of Hamburg, Von-Melle-Park 5, 20146 Hamburg, Germany

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ABSTRACT

Cybersickness is an ongoing issue in VR usage. Effects of display types and different means of a virtual avatar's navigation control on the degree of sickness are disputed or sparsely investigated. In the present study, participants were instructed to ride a virtual bike across a virtual island. Participants used either a head-mounted display (HMD) or a large TV screen for VR presentation and a bike ergometer or a gamepad for motion control. Cybersickness in three different conditions, each with 20 participants, was assessed with the SSQ prior, on multiple occasions during and after VR immersion. Results indicated higher sickness scores with the HMD than in the large screen condition. However, no differences between the means of control were observed. Additional correlation analyses revealed significant relationships between the sickness scores with past motion sickness history in the conditions using the bike ergometer. Sickness scores in the gamepad condition were not related to past motion sickness but showed a significant negative correlation to video game usage. Possible reasons for missing differences between means of control are discussed. Effects of different virtual vehicles on user expectations regarding motion control should be investigated. The study provides a new approach to the relationship of cybersickness and demographic variables.

1. Introduction

Virtual reality (VR) and head-mounted displays (HMD) have become increasingly popular over the past few years as lower costs allow for their use in the consumer market and more in-depth applications in professional contexts. Despite various efforts and technological improvements, one common issue continuously associated with VR is the feeling of illness and discomfort during and after the experience of VR technology. In the current literature, the term *cybersickness* has been established to describe this phenomenon.

The reported symptoms of cybersickness are associated with those commonly described for motion sickness and simulator sickness. *Motion sickness* is a well-known physiological response to extreme environments in which visually perceived cues are in disagreement with movements perceived by the vestibular system. Affected individuals suffer from symptoms such as vertigo, disorientation, nausea, vomiting, headache, sweating and the sopite syndrome which includes drowsiness, fatigue and mood changes, each to varying degrees [1]. *Simulator sickness* describes a similar syndrome which is oftentimes observed in different kinds of simulators, especially flight simulators, fixed-based or

full-motion [2] and is explained with a sensory conflict between incongruent cues in the visual and vestibular systems.

As conceptual delineation from the other two ailments, cybersickness is defined as the experience of motion sickness-like symptoms, caused by the presentation of virtual environments on different displays like HMDs or screens, but with the absence of vestibular motion [3]. It must be noted that this distinction is sometimes ambiguous as some applications, such as a fixed-based flight simulator, fit the definitions of both simulator and cybersickness.

Although cybersickness shares many characteristics with motion and simulator sickness, evidence indicates that the three syndromes cannot be considered the same as distinct symptom profiles show some significant differences in symptom and overall severity [4]. In comparison to motion sickness and simulator sickness, cybersickness induces relatively more symptoms of disorientation and fewer in the oculomotor system. The overall symptom severity tends to be higher for cybersickness than for simulator sickness [5], but lower in comparison with motion sickness; emetic responses are, for instance, very rarely observed [6].

The prevalence of cybersickness has varied considerably in different

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* Corresponding author.

E-mail addresses: Justin.mittelstaedt@dlr.de (J. Mittelstaedt), jan.wacker@uni-hamburg.de (J. Wacker), dirk.stelling@dlr.de (D. Stelling).

studies, possibly due to differences in sample composition and virtual environment setup. Reported incidence rates of cybersickness symptoms range between 35% [7] and 79% [8]. This variability can be attributed to a great extent to differing VR presentation systems and displays. Chen, Dong, Hagstrom and Stoffregen [7] used a large TV screen to expose their study participants to the virtual environment, while Kim, Kim, Kim, Ko and Kim [8] utilized a less common, but much more immersive computer-aided virtual environment (CAVE) system that has been shown to induce significantly more cybersickness than desktop versions of the same virtual environment [9]. Sharples, Cobb, Moody and Wilson [10] also found a greater instance of cybersickness for virtual environments presented on an HMD in comparison with a desktop screen.

The relationship between display type and cybersickness is well documented, although there are some contradicting results [11]. Thus, the present study aims to replicate previous results on the effect of display type on cybersickness.

1.1. Vection and cybersickness

One of the most discussed antecedents of nauseous experiences in virtual environments is vection, a visually induced sensation of illusory self-motion in absence of real (vestibular) motion. Vection has been shown to be more prevalent among those who experienced higher levels of simulator sickness in a fixed-based flight simulator [12].

Subsequently, vection was investigated in relation to visually induced motion sickness (VIMS) by using apparatus like an optokinetic drum [13,14] and its relationship to sickness symptoms was further supported. However, the relationship between vection and VIMS does not seem to be determined by the absolute magnitude of experienced vection, but rather by the *change* in experienced vection [15]. That is similar to the vestibular sensation of movement that is only felt with accelerating motion and not at constant speed.

There have also been contradicting results and an ongoing debate regarding the relation between vection and sickness. Some studies did not find any significant relationship between vection and self-reported sickness symptoms [16,17]. Nonetheless, Keshavarz, Riecke, Hettinger and Campos [18] conclude that vection does not deterministically cause sickness in virtual environments, but is rather a “necessary prerequisite” that must be experienced alongside other factors, e.g. sensory conflict, for the development of nauseous symptoms, so that cybersickness can develop. Some of these additional factors potentially contributing to differences in cybersickness genesis are discussed in the next section.

It is almost unanimously accepted that some kind of visually presented motion (linear or rotational) which produces an optic flow is a prerequisite for cybersickness. Some studies, especially those investigating VIMS, use abstract visual imagery like an optokinetic drum to create optic flow. In virtual environments, this optic flow is usually attained by altering the user’s position, i.e. applying locomotion.

The issue of means of locomotion in VR is oftentimes critical as the scope of virtual space does usually not match the size of the available physical space due to limitations like small laboratory rooms or cables attached to presentation displays. Many studies therefore use passive movement, for example a virtual rollercoaster ride while being seated on a chair [19,20], motion is controlled with video game related devices such as joysticks or gamepads [21,22] or head-controlled navigation [23].

Motion control resembling its real life counterpart is used however in simulators, like driving [24] or flight simulators [25].

Control devices for non-motorized motion, like walking or riding a bike, are, however, rarely used, although these methods may provide important benefits like improved ecological validity and an enhanced sense of presence while being in the virtual environment [26]. Jaeger and Mourant [27] suggested that a more natural, dynamic motion control mitigates the degree of cybersickness as users of a treadmill to

control virtual walking showed fewer sickness symptoms than users that navigated statically by pressing a mouse button. This notion is also in line with differences between cybersickness and simulator sickness. As suggested earlier, simulator sickness tends to be lower in severity than cybersickness. Therefore it can be assumed that devices that more closely resemble real-world navigation in VR, like a treadmill for real walking, induce less cybersickness than the same scenario controlled with a less intuitive device (e.g. a gamepad). Similar results were observed by Llorach, Evans and Blat [28]. However, evidence is sparse and was only collected using walking as navigation method.

1.2. Individual differences

Considerable differences on the effects of sickness symptoms exist between different systems, display technologies and scenario features. But even when these technical parameters are disregarded, substantial inter-individual differences persist. There have been some efforts to explain which individuals are more susceptible to sickness in VR and which are more tolerant to aversive, sickness-inducing stimuli [29].

Two often discussed variables in relationship to sickness are gender and age. Similar to motion sickness, women tend to be more susceptible to sickness symptoms than men [6,27]. However, age has been found to be positively correlated with the magnitude of reported cybersickness [30], whereas motion sickness is usually negatively correlated with age [1]. This adds to the notion that cybersickness and motion sickness are actually different syndromes.

Motion sickness history, ascertained from subjective reports about past occasions of experienced motion sickness in a variety of vehicles (e.g. travelling with airplanes or ships, using funfair rides) has been shown to predict cybersickness in different virtual environments [29,31,32]. In fact, past motion sickness history seems to be one of the best predictors of future cybersickness in virtual environments.

Virtual environments are often similar to what many people experience when playing video games, especially those incorporating a first-person view. But in contrast to the assumption that frequent video game users are more used to virtual environments and may therefore be more resistant to cybersickness, it has been shown that video game usage actually correlates positively with cybersickness [27,33], so that frequent video game players tend to develop more sickness in VR.

1.3. Hypotheses

This study investigates cybersickness severity in a virtual bike VR application presented with different displays (HMD vs. large screen) and controlled by means varying in closeness to reality (bike ergometer vs. gamepad). We hypothesize that:

- H1: HMDs induce significantly more cybersickness than large screens.
- H2: The use of the bike ergometer induces less cybersickness than the use of the gamepad due to lower sensory conflict.
- H3: The severity of cybersickness is related to the self-reported incidence of motion sickness in other contexts (motion sickness history).
- H4: The severity of cybersickness is related to the video game usage frequency.

2. Methods

2.1. Participants

60 volunteers (40 female, 20 male) with a mean age of 25.62 years (SD = 9.34 years) participated in the study. They were randomly assigned to one of three conditions: twenty participants to the *Bike/HMD* condition (13 female, 7 male, mean age = 25.65 years, SD = 9.40 years), *Gamepad/HMD* condition (12 female, 8 male, mean age = 24.40 years,

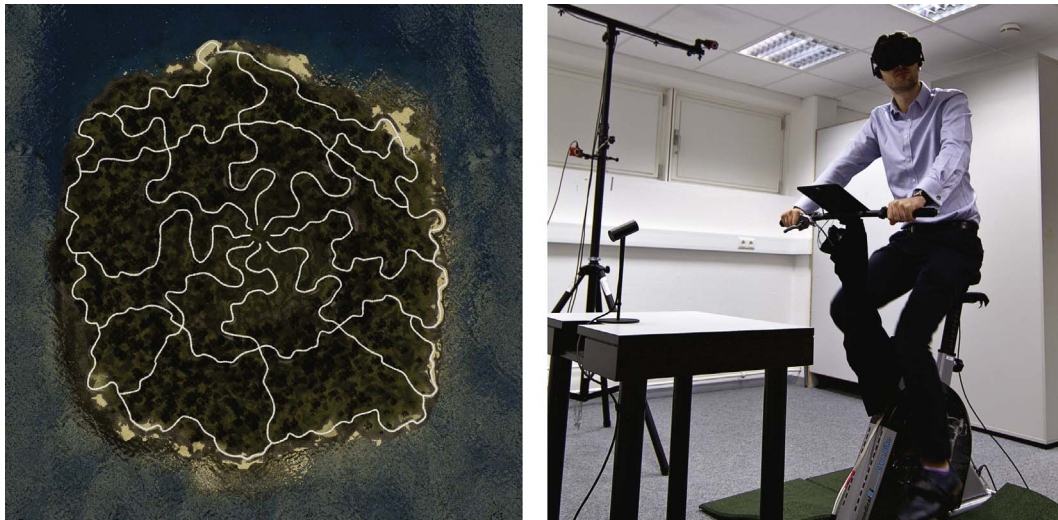


Fig. 1. Map of the island layout. White lines mark paths (left). Experimental setup with bike ergometer and HMD (right).

SD = 8.95 years) and *Bike/Screen* condition (15 female, 5 male, mean age = 26.80 years, SD = 9.98 years), respectively. All participants had normal or corrected to normal vision by using contact lenses. Glasses were excluded from the study since some eyeglass frames do not fit under the head-mounted display.

Study protocol was approved by the Ethics committee of the German Psychological Association (DGPS; JM 012017).

2.2. Apparatus

2.2.1. Head-mounted display

In the *Bike/HMD* and in the *Gamepad/HMD* condition, the virtual reality was presented on an Oculus Rift Consumer Version 1 head-mounted display (HMD). The Oculus Rift had two separately rendered displays with a screen resolution of 1080×1200 pixels for each eye with a refresh rate of 90 Hz. Consequently, it allowed stereoscopic vision with a 110° horizontal field of view. To track head position in a three-dimensional space, the Oculus Rift was equipped with an accelerometer, a gyroscope, a magnetometer and an additional constellation tracking camera. The inter-pupillary distance of both lenses was adjustable in a range from 57 mm to 71 mm. Participants were instructed to adjust the distance between lenses until they suited their respective inter-pupillary distance.

2.2.2. Large screen

The *Bike/Screen* condition used a large screen (Sony Bravia HX75) instead of the HMD with a 55 in. (140 cm) screen size that was placed approximately 1 m in front of the participant sitting on the bike ergometer. The screen has a resolution of 1920×1080 pixels and a refresh rate of 400 Hz. While using the virtual bike, participants wore a prepared mask that imitated the head-mounted display. The mask was applied with a strap band similar to the Oculus Rift and offered two rounded apertures at the position of the eyes to look through. This limited the field of view to a similar extent as with an HMD. Additional weights were attached to the mask to give it approximately the same weight on the forehead as the Oculus Rift (470 g).

2.2.3. Bike ergometer

The *Bike/HMD* and the *Bike/Screen* conditions used a bike ergometer for navigation in the virtual environment. Movements from the pedals of the ergometer were translated into electrical signals and mapped to the acceleration of the virtual bicycle. The rotation of the handlebar was tracked with an OptiTrack Flex 3 optical motion capture system with a standard error of around 0.1 mm and transferred to the

orientation of the virtual handlebar. A handbrake, attached to the right side of the handlebar, offered the possibility to decrease speed and coming to a halt.

2.2.4. Gamepad

The *Gamepad/HMD* condition used an Xbox One Controller to control the virtual bike. Right and left shoulder triggers were used for acceleration and braking respectively. The left joystick was used for steering the handlebar. Instead of directly flipping to the direction given by the input of the left joystick, the virtual handlebar gradually adjusted its orientation towards the inputted direction to make the control easier and smoother.

2.3. Scenario

Virtual scenery was built in-house using the Unity game engine (v5.4.0p3). The virtual environment depicted a small island with realistic environmental models and texture for trees, stones and grass. A network of equidistant paths, delimited by fences, was spread over the island layout which was exclusively used for navigation. The participant's view was from an avatar's head position on the virtual bike. From that position, participants were also able to see part of the avatar's body and of the virtual bike. The map layout and the experimental setup can be seen in Fig. 1.

Participants completed three sessions (*Ses1*, *Ses2* and *Ses3*). Each session included navigation from a starting point to a pre-specified target. The routes were predetermined, all alternative pathways were inaccessible, and scenarios were always completed in the same fixed sequence. These three routes were of equal distance and had a similar vertical profile as well as a similar number of curves that needed to be navigated through. However, while the routes in Session 1 (*Ses1*) and Session 3 (*Ses3*) were predominantly downhill paths, the route in Session 2 (*Ses2*) was a track that led primarily uphill.

Participants were instructed to use the delimited paths for navigation and to adjust their navigation speed to suit their own preferences. However, to guarantee a minimum time spent in the VR, the virtual speed was capped so that at a certain point a faster cycling did not result in increased virtual speed.

2.4. Cybersickness measurement

Previous efforts to detect cybersickness with objective, i.e. physiological methods, [8,19,34] yielded inconsistent results. Heart rate, for instance, has been observed to predict cybersickness in one study [19],

but was unrelated in another [34]. Thus, most of the studies concerning cybersickness use self-report questionnaires or symptom checklists to identify the severity of sickness in VR despite the obvious shortcomings of the self-report method in this context (response tendencies, demand characteristics etc.).

Different questionnaires have been used in the research literature on cybersickness, although none has been specifically designed for cybersickness. Some have been developed to assess motion sickness like the Motion Sickness Assessment Questionnaire [35] or the Nausea Profile [36] while the Simulator Sickness Questionnaire [SSQ; 37] was developed to assess simulator sickness experienced in military simulators.

The SSQ was originally developed to assess the degree of simulator sickness in different flight simulators. Although there is evidence that simulator sickness and cybersickness differ in the symptoms they induce [4], the SSQ is the most popular self-report questionnaire for both simulator and cybersickness.

It consists of 16 symptoms which are rated on a four-point scale (“none”, “slight”, “moderate” and “severe”) that translate into a rating of 0 to 3. Scores on each rating were aggregated to form a total score of sickness (SSQ-T) and three sub-scores: Nausea (SSQ-N), Oculomotor (SSQ-O) and Disorientation (SSQ-D) in accordance with the formulae given by Kennedy et al. [37]. The symptoms and rating labels of the SSQ were translated into German.

One disadvantage all checklists have in common is that they are usually assessed after the VR immersion has ended, because they are filled in as paper-pencil versions. Keshavarz and Hecht [38] addressed this issue by developing a one-item motion sickness scale that was answered by giving a verbal statement of the currently experienced motion sickness ranging from 0 to 20. On the one hand, this provides significantly less information than the previously mentioned instruments; on the other, because it can be answered while being immersed in the virtual environment and while the potential symptoms are experienced, this procedure has superior ecological validity.

In the present study, we solved this issue by developing a virtual version of the SSQ that is answered within the VR immersion. While the SSQ was administered with a paper-pencil version prior to and after the VR immersion, items were presented within a virtual hologram inside the VR in order to cope with poor ecological validity of assessments after the completion of the immersion. Ratings were made either by pressing two buttons placed on the handlebar or by using the shoulder buttons on the gamepad to increase or decrease the rating. Ratings were confirmed by pulling the handbrake on the bike or by pressing the ‘A’ button on the gamepad.

2.5. Procedure

Before commencing the study, participants filled in an informed consent and a short demographic data sheet which included two items regarding their frequency of bike and video game use and three items on self-reported sickness in cars, at sea or due to alcohol or excessive food consumption. Afterwards, participants filled in a pre-immersion measurement of the SSQ.

Then, participants were briefed on the experimental set-up in their respective condition, either on the head-mounted display or the mask and large screen and either on the bike ergometer or the gamepad controls. Before the start of the immersion, participants were reminded that they could abort the experiment at any time without giving any reasons but especially if they felt unwell or nauseous.

At first, participants received a 90 s trial (*Acqu*) in which they were set on the island and could familiarize themselves with the virtual environment by looking around but without the possibility to move the virtual bike.

Subsequently three sessions followed in which participants were instructed to ride from a starting point to a given target point. Upon arrival at the target and at the end of the familiarization trial, participants gave ratings on the SSQ symptoms.

After the completion of the immersion, participants filled in a paper-pencil version of the SSQ.

2.6. Analysis

For the SSQ scores, linear mixed models (LMM) with maximum likelihood estimation were computed separately for the Total Scores and all sub-scores Nausea, Oculomotor and Disorientation. As fixed effects, condition (Condition) and time of measurement (i.e. pre and post; Time) were included in the model with the participant as random effects.

All post hoc tests were Tukey *p*-adjusted. The α -level for all statistical tests was $\alpha < 0.05$.

Data were analyzed with R 3.3.2 [39]. For the LMM the R package `lme4` [40] was used. [41] Graphics were created with the `ggplot2` package [42].

3. Results

3.1. Cybersickness differences

Due to severe nauseogenic symptoms 4 of the 60 participants prematurely terminated the immersion. Two of them were in the Bike/HMD and the other two were in the Gamepad/HMD condition. None of the participants in the Bike/Screen condition had to abort the immersion.

We compared durations of exposure and speed of motion between conditions by computing means of all three motion trials for every participant. Analyses of variance did not reveal any significant differences in duration ($F(2,56) = 1.41$; $p = .253$) or speed of motion ($F(2,56) = 2.25$; $p = .115$).

SSQ Total Scores before, during and after the VR immersion are presented in Fig. 2 broken down by condition. In both the Bike/HMD and the Gamepad/HMD conditions an almost linear increase in sickness during the phases of VR immersion is discernible with a maximum average score of 51.53 in the last assessment within VR for the Bike/HMD group.

As Condition and Time were treated as categorical variables, Wald

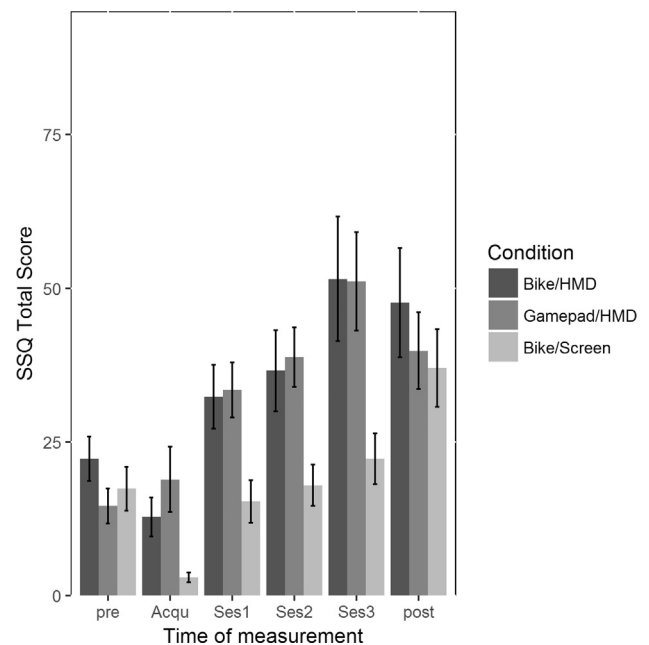


Fig. 2. Mean SSQ Total Scores for all times of measurements broken down by condition. Error bars indicate the standard error. *pre* = before the VR immersion; *Acqu* = familiarization phase inside VR (without motion); *Ses1–Ses3* = three consecutive navigation sessions; *post* = after the VR immersion.

Table 1
Results of Wald tests for each predictor of the LMM of SSQ Total Scores.

Model 1: SSQ Total Score			
Predictor	df	F-value	p-value
Intercept	(1,220)	118.01	< .001
Time	(4,220)	33.426	< .001
Condition	(2,57)	4.47	.016
Time:Condition	(8,220)	2.46	.014

tests were computed for each main effect and the interaction effect on the SSQ Total Score in the LMM. Results of these analyses are presented in Table 1.

For the SSQ scores within the VR, results showed significant main effects for Time and Condition, and a significant interaction effect. Upon further investigation of the Time effect with pairwise *t*-tests, significant differences were observed for all pairwise comparisons except the difference between *Ses1* and *Ses2* ($t(220) = 0.40, p = .995$) and between *Ses3* and the post-immersion measurement ($t(220) = 1.53, p = .547$). These results and the trend depicted in Fig. 1 indicate that sickness scores increased with immersion duration and virtually simulated motion, which was not present in the familiarization phase.

For the Condition, significant differences between the Bike/Screen condition and both HMD conditions (with Bike/HMD: $t(57) = 2.56, p = .034$; with Gamepad/HMD: $t(57) = 2.66, p = .027$) were observed in post-hoc comparisons.

As for the interaction effect, Fig. 2 shows that there were no significant differences between conditions in the pre or the post-immersion measurements while there were significant differences in ratings given within the VR.

The same procedure was repeated for the three sub-scores Nausea, Oculomotor and Disorientation. Mean scores and standard errors can be seen in Fig. 3. The analyses yielded a similar pattern for each sub-score as for the Total Score.

Results show significant main effects of Time and Condition for all three sub-scores of the SSQ. For Time, significant differences between most pairwise comparisons were observed with some exceptions. The comparisons between *Ses1* and *Ses2* did not reach significance in any sub-score. Additionally, for Nausea, the comparison between *Ses3* and the post-immersion measurement was not significant. For Disorientation, differences between *Ses1* and *post*, *Ses2* and *post* and between *Ses2* and *Ses3* did not reach significance.

For Condition, Nausea and Oculomotor scores were significantly

Table 2
Pearson correlation coefficients of the maximum SSQ Total Score with the frequency of bike or video game usage and motion sickness history by condition.

	Maximum SSQ Total Score		
	Bike/HMD	Gamepad/HMD	Bike/Screen
Video game use	-0.41	-0.50*	0.08
Sickness (car)	0.48*	-0.02	0.54*
Sickness (sea)	0.53*	-0.02	0.64*
Sickness (alcohol/food)	0.02	0.01	0.42

df = 18
* $p < .05$

different only between the Bike/HMD and the Bike/Screen conditions. Disorientation scores were significantly different between the Gamepad/HMD and the Bike/Screen conditions.

The interaction effect was similar for all three sub-scores with significant differences between the Bike/Screen condition and the two HMD conditions within VR in absence of significant differences in pre- and post-immersion measurement.

3.2. Cybersickness predictors

To investigate individual characteristics in relation to the degree of sickness experienced, participants were asked about their frequency of bike and video game use as well as about their susceptibility to sickness symptoms in cars, at sea and as a result of alcohol or excessive food consumption.

Pearson correlation coefficients were computed with the maximum reported SSQ Total Score within the immersion separately for each condition. Results are presented in Table 2. Correlations showed a reasonably strong relationship between self-reported motion sickness susceptibility in cars and at sea and the experienced sickness in both conditions involving the bike ergometer. However, there was no significant relationship between the self-reported motion sickness susceptibility and the experienced sickness in the Gamepad/HMD condition. Instead, this condition showed a significant correlation with video game use i.e. that the higher the frequency of video game usage the less participants experienced sickness.

4. Discussion

4.1. Display type

The first issue investigated in this experiment was the question of

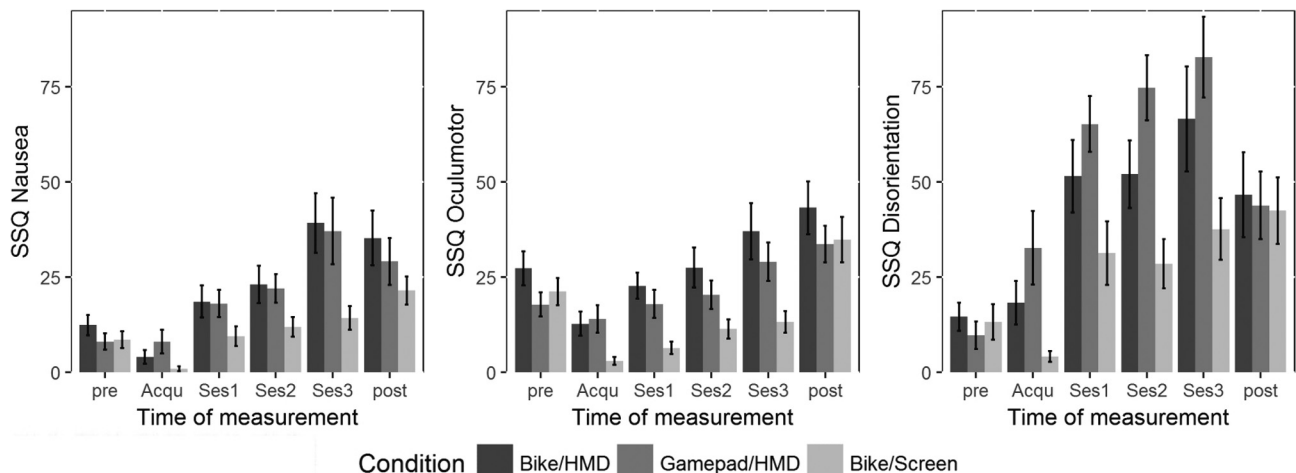


Fig. 3. Means and standard errors of the SSQ sub-scores Nausea (left), Oculomotor (center) and Disorientation (right). *pre* = before the VR immersion; *Acqu* = familiarization phase inside VR (without motion); *Ses1*–*Ses3* = three consecutive navigation sessions; *post* = after the VR immersion.

the degree of cybersickness induced by two different display types, namely HMDs and large screens. Analyses showed considerable differences between both HMD conditions and the large screen condition in terms of cybersickness which suggests that HMDs induced substantially more cybersickness than screens in the present study. These results are in line with the current literature [3,10].

It is possible that the heightened immersion provided by the HMD, elicited higher levels of cybersickness. Another possibility is the influence of independent visual backgrounds. We additionally had the participants in the large screen condition wear a face mask to limit the field of view and to exclude cues from the real world, analogous to an HMD [43,44] while not fixating their head position or orientation. Consequently, it was possible for participants to turn their view and perceive cues outside the VR which in turn reduced the adverse effect of the virtual environment. Independent visual backgrounds, cues from the real world or other constant visual cues, independent from the optic flow of the VR, are promising as an approach to ameliorate cybersickness. In fact, a grid overlay as independent visual frame has been shown to reduce symptom severity [45]. If those cues are eliminated, display types do not seem to make any difference as Keshavarz, Hecht and Zschuschke [11] observed no difference in cybersickness symptoms between HMDs and screens after masking out the environment. So it is possible that the difference found in the present study is caused by visual cues from the physical environment which participants in the large screen condition were able to see if they moved their heads far from the center of the screen.

4.2. Motion control

There were no significant differences in sickness scores between the Bike/HMD and Gamepad/HMD conditions, indicating that the more realistic motion control with the bike ergometer did not mitigate cybersickness in VR. This is even more remarkable in light of postural stability considerations. The bike provided the possibility for participants to sit and to hold on to the handlebar and thus support their postural stability, an approach which has been found to alleviate sickness in past studies [43,46]. Anecdotal observations from the present study suggested some participants experienced problems with postural stability as considerable sway was observed in the Gamepad/HMD condition, especially in the fore-aft axis. This might have caused the comparatively higher scores on Disorientation in the Gamepad/HMD than in the Bike/HMD condition. Participants in the conditions using the bike ergometer were able to hold on to the handlebar and thus did probably not experience as many feelings of vertigo and losing postural stability as the participants in the Gamepad/HMD condition who were standing throughout the immersion.

However, one possible explanation for the missing general effect is that the bike ergometer did not meet user's expectations of real world bike control sufficiently. The utilized ergometer lacked the possibility to lean into turns and did not provide rotational feedback. Any violation of these expectations could lead to sensory conflict and cybersickness without further regard to the closeness to reality of the remaining setup.

Prior studies found the exposure duration [47] and visual optic flow [48] affecting degrees of cybersickness. Analyses of mean durations of VR exposure as well as average speed, equaling linear optic flow showed no significant differences in the three conditions. Hence, neither of them can be used as an explanation for the observed effects or the absence of differences between motion control devices.

An interesting question is whether the sensory conflict would persist if a different virtual vehicle that did not generate similar expectations (like a tricycle) was simulated using the same setup.

4.3. Cybersickness in general

The conditions using the HMD induced high SSQ scores relative to other studies that used the SSQ. Levels of sickness increased with

duration in all three conditions. What is noticeable is that the level of sickness did not substantially decline after the end of the immersion. On the contrary, in the Bike/Screen condition, sickness scores continued to increase after the immersion so that post-scores were at the same level as the other two conditions. Disorientation, however, showed a considerable decline in the Gamepad/HMD condition between the last measurement within VR and the post-immersion measurement. These results suggest that sickness assessments within VR and post-immersion assessments by using paper-pencil versions yield slightly different ratings. Due to the higher temporal proximity to the measured symptoms, it is reasonable to assume that within VR assessments possess greater validity.

Scores may also have been influenced by demand characteristics. Young, Adelstein and Ellis [49] previously observed that post-immersion SSQ ratings were higher when a pre-test was administered before the immersion. In the present study, we handed out the SSQ on six different occasions, two paper-pencil and four virtually in VR. It is likely that the repeated administration of the SSQ affected symptom ratings and triggered higher responses.

This issue, however, cannot be completely eliminated when investigating the development of cybersickness at different points in time with repeated measurements. Future studies should investigate the influence of repeated measurements on cybersickness beyond pre- and post-measures on the demand characteristic of symptom checklists.

4.4. Motion sickness history and video game usage

Past motion sickness history is known to be one of the best predictors for cybersickness [29,31]. We assessed motion sickness history in two means of transportation, i.e. by car or at sea, and with sickness as a result of excessive alcohol or food consumption. In addition, we asked for the frequency of video game usage which was correlated positively with cybersickness in previous studies as well [27,33].

Self-reported motion sickness in cars and at sea were significantly related to cybersickness in the present study, however, only in the conditions that used the bike ergometer for motion control. The level of cybersickness in the Gamepad/HMD condition did not correlate with motion sickness history, but was negatively related to frequency of video game usage.

The navigation using the bike ergometer was very intuitive and similar to a real bike whereas the controls of the gamepad were probably only intuitive for those participants regularly engaging in video games. This additional demand might have presented further strain especially on those individuals who were unfamiliar with the use of a gamepad. Not exactly knowing how an input on the gamepad affects the virtual scenery is like not being in control. Past studies have shown that active control is one way to reduce sickness severity [7,50].

For the conditions employing the bike ergometer, we assumed that all participants were familiar with bikes and knew how to use them. The intuitiveness of control might therefore have led to the activation of a more general sickness susceptibility that is responsible for an adverse reaction in different contexts.

5. Conclusion

The present study confirmed results suggesting HMDs to be more sickness inducing than presentation displays such as large screens [10]. However, we were not able to confirm that a more realistic motion control (bike ergometer) induces less cybersickness than more generic means of motion control (gamepad) as has been previously found with walking [27,28]. Relationships with motion sickness history and video game usage provide an interesting approach to different connections of cybersickness with demographic variables depending on the motion control devices utilized to navigate in VR. Results further demonstrate the importance of using sickness assessments while participants are immersed in the virtual environment.

Future studies should investigate effects of different virtual vehicles on expectations regarding motion control and in turn on cybersickness. More research is needed on why display types induced different levels of cybersickness within VR and why these differences disappeared in the post-immersion assessment. The influence of demand characteristics in multiple assessments of cybersickness has to be determined.

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Declaration of conflict of interest

The authors do not have to declare any conflict of interest.

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Justin Mittelstaedt studied Psychology at the University of Hamburg (M.Sc. in 2014) and has been working in the selection of aerospace personnel at the DLR department of Aviation and Space Psychology since 2014. His recent research interests include the effect of different VR applications on cybersickness and cognitive performance, as well as personality assessment in astronaut selections. In 2016, he was part of the team for the psychological selection of female space flight participants (SFPs).



Professor Jan Wacker studied Psychology at the University of Marburg (Diploma: 2001; PhD: 2005). Since 2013 he is professor of Differential Psychology and Psychological Assessment at the University of Hamburg, where he is currently research dean of the Faculty of Psychology and Human Movement Science. He serves on the editorial boards of the European Journal of Personality, the Journal of Research in Personality and the newly founded journal Personality Neuroscience. His research is concerned with the biological foundations of major personality traits and the improvement of Psychological Science.



Dirk Stelling studied Psychology at University of Hamburg with special emphasis on clinical neuropsychology and organisational psychology where he did his PhD with the thesis “Teamwork in Man-Machine-Systems (1999). At the German Aerospace Center (DLR), in the department of Aviation and Space Psychology (DLR) his activities include computerized teamwork assessment, selection, aviation problem cases and he is head of the DLR Crew Performance & Transport division and deputy of the department. He is lecturer for personality psychology at university and registered Aviation Psychologist EAAP (European Association for Aviation Psychology) since 1999, where he worked as a lecturer in international courses.

Article 2

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VR aftereffect and the relation of cybersickness and cognitive performance

authors:

Justin Maximilian Mittelstaedt¹, Jan Wacker², Dirk Stelling¹

¹ German Aerospace Center (DLR), ² University of Hamburg

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Correspondence address:

Justin Maximilian Mittelstaedt
German Aerospace Center (DLR)
Sportallee 54a
22335 Hamburg

Abstract

The purpose of the study was the investigation of VR induced aftereffects on various basic cognitive abilities and its relationship with cybersickness. Previous studies suggest an adverse effect of VR exposure on simple reaction times. Aftereffects on other basic cognitive abilities have rarely been studied.

Sixty participants performed a test battery, consisting of five different tests, prior and after the immersion into a VR bike application. Participants were assigned to three different experimental conditions using different kinds of displays, motion control devices. Twenty additional participants acted as a control group.

Reaction times of simple ($\chi^2(3) = 140.77; p < .001$) and choice reaction tasks (two choice: $\chi^2(3) = 66.87; p < .001$; four choice: $\chi^2(3) = 55.48; p < .001$) deteriorated after VR exposure but remained stable or improved in the control group not exposed to VR. Changes in performance were only weakly related to degrees of cybersickness ($.04 < r < .28$).

We propose a general aftereffect of VR exposure on reaction times that is only slightly related to subjective degrees of cybersickness. Taken together, however, usage of VR systems, even if inducing moderate levels of cybersickness, leads only to minor decrements of cognitive performance.

Keywords: cybersickness, cognitive performance, head-mounted displays, reaction times

1. Introduction

Cybersickness, i.e. becoming ill and experiencing symptoms of nausea and disorientation in virtual environments (McCauley and Sharkey 1992), remains an issue in spite of the enormous technological improvements over the course of the last decade.

Apart from the relatively new phenomenon of cybersickness in virtual realities (VR), motion sickness is a long known adverse physiological and psychological reaction to different means of transportation, e.g. ships, cars and airplanes (Reason and Brand 1975). Symptoms include nausea, disorientation, headache, sweating, drowsiness, fatigue, mood changes and vomiting. Motion sickness is caused by a sensory conflict between the visual and vestibular senses or more precisely by a vestibular sensation of movement in absence of any supporting visually perceived cues (Bertolini and Straumann 2016).

Similar symptoms have also been observed in different kinds of vehicle simulators, such as fixed-based, full-motion flight (Kolasinski 1995) or driving simulators (Helland et al. 2016). Simulator sickness is explained by the incongruence between the simulated visual and vestibular signals or by a deviation from the expectancy of real-life motion (Johnson 2005). Its symptoms are similar to motion sickness, although often less severe.

Cybersickness is defined as sickness induced by virtual environments presented on head-mounted displays, screens or projector systems. Unlike motion sickness, it is caused by the presentation of visual cues of motion in absence of any vestibular indicators (Rebenitsch and Owen 2016). Symptoms of cybersickness are also similar to motion sickness and typically focus on three main symptom clusters: nausea (e.g. stomach awareness, vomiting), disorientation (e.g. vertigo, dizziness) and oculomotor symptoms (e.g. eyestrain, blurred vision) (Kennedy et al. 1993b).

To this day, cybersickness remains an ongoing problem and probably the greatest limitation to the further dissemination and wider use of VR technology.

1.1. Cybersickness and performance

Cybersickness in itself is an adverse experience that people naturally avoid by aborting the sickness-inducing application. However, there might be situations in which such applications cannot

be avoided, are experienced for the first time or are deliberately used to develop a certain degree of habituation to the adverse stimulus (Howarth and Hodder 2008). In these cases it is important to be aware of the possible consequences of cybersickness even after the end of immersion. It is often assumed that cybersickness would decrease cognitive performance, although this assumption has rarely been investigated.

1.2. Performance in simulators

The issue of cognitively impairing effects has been primarily investigated in driving and flight simulators. In driving simulators, results do not suggest any negative effects on the ability to drive a simulated car. Mullen et al. (2010) found no significant performance differences in a driving simulator between those participants who were able to finish the simulation in comparison with the drop-outs who needed to abort the simulation prematurely because of simulator sickness. Participants who reported higher levels of sickness also did not perform worse in lane keeping or other indicators of driving performance (Helland et al. 2016; Muttray et al. 2013). However, participants who became sick tended to drive more safely, turned the steering wheel less often and reduced their average speed (Helland et al. 2016).

In flight simulators, there were more, sometimes contradictory, findings on the relationship between sickness and performance. Some studies (Uliano et al. 1986) suggested a decrease in performance, for example by slowing down control inputs, as a result of experienced sickness while others could not find a significant relationship (Warner et al. 1993). In a study using a pattern comparison, grammatical reasoning and a speed tapping test, practice effects (i.e. performance gains through repeated exposures) of participants who were exposed to a flight simulator in between test administrations were in the normal range of practice effects of controls, indicating no significant performance loss due to the simulator exposure and the degree of sickness (Kennedy et al. 1987). However, in a similar study using the same three tests, those who were exposed to a flight simulator had practice effects smaller than the control group in the grammatical reasoning and pattern comparison tests (Kennedy et al. 1993a) suggesting that simulator exposure attenuated the practice effect.

Given the previous findings, it remains undetermined if simulators and induced simulator sickness does impair cognitive performance as an aftereffect. Because some studies may not have been able to determine any effects due to the complexity of the tests performed, we limited the investigation of adverse effects of VR exposure to basic cognitive abilities.

1.3. Basic cognitive abilities

There are results suggesting a detrimental effect of cybersickness on *basic* cognitive abilities. Nalivaiko et al. (2015) observed a significant relationship between the degree of cybersickness and an increase in simple reaction time. This result has been further confirmed (Nesbitt et al. 2017). Nevertheless, there is a reservation that the two rollercoaster scenarios used in the two studies induced different levels of cybersickness, but did not influence increases in response time differently. The relationship of reaction time and cybersickness was just found within users of the same virtual environment, suggesting that the relationship does not persist across multiple applications.

In addition to reaction time, there are other cognitive domains that have been studied in the context of cybersickness and need to be considered for possible aftereffects.

Mental rotation ability has been suggested to predict motion sickness susceptibility, although results seem to be unreliable as most effects differ by gender and some of them point in opposing directions (Levine and Stern 2002; Parker and Harm 1992).

Findings from a paradigm of motion sickness induced by horizontal or vertical linear oscillations report a decrease in response rate in a Visual Search task which was weakly related to self-reported motion sickness ratings (Golding and Kerguelen 1992). However, possible impairments of perceptual speed in a state of cybersickness can similarly be expected but have not yet been investigated.

Results from a different study suggest a decline of (verbal) working memory in participants who needed to abort the exposure to an optokinetic drum (Dahlman et al. 2009). Similar results for auditory working memory and exposure to an adverse motion stimulus were found (Bos 2015). On both occasions, the assessment of working memory was administered during the exposure to the optokinetic drum and did not include the investigation of any possible aftereffects on working

memory. Nevertheless, the results indicate an effect of cybersickness on working memory which could potentially extend to the period following a VR exposure.

Despite the delineated results which present a connection between the individual level of cybersickness and the rate of performance loss, Muth (2009) was similarly observing performance losses which were, however, unrelated to the expression of motion sickness. His study investigated aftereffects on cognitive functioning as a result of the exposure to uncoupled motion. Performance decrements of different cognitive capacities were observed up to two to four hours after ending the immersion. Based on the underlying data, the impairments in this study could not solely be explained by individual levels of motion sickness.

In sum, whereas results from simulator studies indicate no performance loss in more complex tasks like a driving or flying simulator, a decrease in performance in more basic cognitive tasks was observed. The association with individual levels of cybersickness led to mixed results.

With the present study, we seek to replicate previous findings of increased reaction times as a result of VR exposure and try to clarify the impact of VR immersion on other basic cognitive abilities which have partly been shown to be affected by similar environments inducing motion sickness-related symptomatology. The selection of the test procedures follows the findings of previous research, in which the areas of reaction time, mental rotation ability, perceptual speed and working memory were specifically associated with cybersickness. For each of these areas we have selected a test (two tests for response time) that uses a well-known standard paradigm.

As there might be specific effects of input devices on performance and aftereffects (Muth 2009; Walker et al. 2007), we used two different motion control as well as two different display devices.

We expected a performance decrease in various cognitive tasks after VR exposure. In addition, VR setups inducing more cybersickness (i.e. one using HMD rather than a large screen) (Mittelstaedt et al. 2018) should be associated with more pronounced performance decreases and individuals reporting more cybersickness should perform worse. We used three different VR setups, inducing varying degrees of cybersickness.

2. Methods

2.1. Apparatus

We incorporated three experimental conditions using different presentation and motion control devices. In two conditions, the virtual environment was presented on a head-mounted-display (HMD) with one using a bike ergometer (Bike/HMD) and the other a generic gamepad (Gamepad/HMD) as means of motion control. Participants in the third condition experienced VR on a large TV screen while controlling motion on the bike ergometer (Bike/Screen).

Analyses of cybersickness-inducing effects of these conditions can be found in Mittelstaedt et al. (2018).

A fourth condition acted as control group. Participants of this group were not exposed to VR and rested instead.

2.2. Head-mounted display

For the HMD conditions, we used an Oculus Rift Consumer Version 1HMD to present the virtual reality scene. The Oculus Rift has a 110° horizontal field of view presented by two separately rendered displays with a screen resolution of 1080x1200 pixels per eye and a refresh rate of 90Hz. Head position is tracked within three-dimensional space by the Oculus Rift's accelerometer, a gyroscope, a magnetometer and an additional constellation tracking camera. Both eye lenses of the HMD were adjustable within a range of 57mm to 71mm and participants were instructed to set the distance according to their respective inter-pupillary distance.

2.3. Large Screen

Instead of using the HMD, participants in the Bike/Screen condition were seated in front of a large screen (Sony Bravia HX75) TV with a 140cm screen size, placed approximately in a distance of 1 meter. The screen has a resolution of 1920x1080 pixels and a refresh rate of 400Hz.

Participants wore a prepared mask with two rounded eye apertures, applied with a strap band to provide a similarly limited field of view to the HMD. Additional weights were attached to the mask to give it approximately the same weight on the forehead as the Oculus Rift (470 grams).

2.4. Motion control

Bike conditions used a bike ergometer to control navigation in the virtual environment. Pedaling on the ergometer was translated into electrical signals and mapped to the acceleration of the virtual bike. Steering the handlebar of the ergometer resulted in direct translation to the steering of the virtual handlebar.

The Gamepad/HMD condition used an Xbox One Controller to control the virtual bike. Right and left shoulder triggers were used for acceleration and braking respectively. The left joystick was used for steering.

2.5. Participants

Fifty-one females and twenty-nine males ($M = 25.62$ years, $SD = 9.34$ years) participated in the study. The total of 80 participants were evenly split into the four conditions including *Bike/HMD* (13 female, 7 male, $M = 25.65$ years, $SD = 9.40$ years), *Gamepad/HMD* (12 female, 8 male, $M = 24.40$ years, $SD = 8.95$ years), *Bike/Screen* (15 female, 5 male, $M = 26.80$ years, $SD = 9.98$ years) and a *Control* group (11 female, 9 male, $M = 24.00$ years, $SD = 4.68$ years).

Age did not differ significantly between the four groups ($F(3,76) = .445$; $p = .72$). The first three groups were used for the analyses of effects of display type and means of motion control. These analyses showed that an HMD induces more cybersickness than viewing a TV screen with a mask that covers the entire physical environment and that cybersickness levels did not differ between two different means of control, i.e. a bike and a generic gamepad controller. Results of these analyses can be found in Mittelstaedt et al. (2018).

All participants gave additional information on their amount of video game play and their sickness history in cars and other modes of transportation such as ships or planes. The groups did not differ in video game play ($F(3,76) = .759$; $p = .52$), sickness in cars ($F(3,76) = .038$; $p = .99$) or in other modes of transportation ($F(3,76) = .441$; $p = .72$).

All participants had normal or corrected to normal vision by using contact lenses. Glasses were excluded from the study since some eyeglass frames do not fit under the head-mounted display.

This research complied with the tenets of the Declaration of Helsinki and was approved by the Ethics committee of the German Psychological Association. Informed consent was obtained from each participant.

2.6. Simulator Sickness Questionnaire

A German version of the Simulator Sickness Questionnaire (SSQ; Kennedy et al. 1993b) was used. It consists of 16 symptoms which are rated on a four-point scale from 0 to 3 (“none”, “slight”, “moderate” and “severe”). Symptom ratings were aggregated on three sub-scores Nausea (SSQ-N), Oculomotor (SSQ-O) and Disorientation (SSQ-D) which in turn were accumulated to form a total score of sickness (SSQ-TS) according to the formulae given by Kennedy et al. (1993b).

Prior to the immersion and after each test in the post immersion test battery, a paper-pencil version of the SSQ was completed. In between trials within the VR immersion SSQ symptoms were presented on a virtual hologram. Participants gave ratings by either pressing buttons placed on the handlebar or using the shoulder buttons on the gamepad.

2.7. Test Battery

All tests were based on standard paradigms from the psychological literature and were programmed in PsychoPy2 (v1.84.2; Peirce 2007). Participants responded by using a prepared keyboard or, in case of the Corsi Block Tapping Task, a standard mouse that they were instructed to arrange in an appropriate manner to reach the required input device comfortably. Tests were always presented in the same order as described in the following. This order was determined according to the principle that no two tests with a similar requirement follow each other, e.g. no two tests in a row in which it is important to react as quickly as possible. Furthermore, the Deary-Liewald task was performed first to reproduce the exact conditions of the study by Nesbitt et al. (2017). The average duration of each test is given in Table 1.

[insert Table 1 here.]

2.7.1. Deary-Liewald Reaction Time Task

The Deary-Liewald Reaction Time Task was developed by Deary et al. (2011) and comprises two tasks to assess simple reaction time as well as choice reaction time. In the simple reaction time

task (SRT), participants were required to monitor a white box and to respond as quickly as possible with a button press as soon as a black cross appeared within the white box.

The choice reaction time task (CRT) used four horizontally aligned boxes in which a black cross appeared at random. The keyboard response buttons were arranged in the same layout as the layout of the four boxes on the screen. Depending on the location where the cross appeared the respective button had to be pressed as fast as possible.

Forty test trials of both the SRT and CRT were administered. Latencies (1 to 3 seconds) and the location of the target stimulus were randomized.

2.7.2. Mental Rotation

The Mental Rotation Task used the paradigm originally published by Shephard and Metzler (1971) and assesses spatial abilities or more specifically mental rotation ability. Test material was obtained from Ganis and Kievit (2015). Participants were required to determine if two horizontally arranged figures were vertically mirrored or not. In relation to the left figure, the right figure was also vertically rotated between 0° and 150° . Prior to the test, two example items were given which were required to be answered correctly to continue with the 40 test items. Mirroring and rotation were randomized.

2.7.3. Visual Search

As a measurement of perceptual speed, a Visual Search Task was used (Treisman and Gelade 1980). Stimulus material was similar to the one that was used by Stoet (2011). Target stimuli were upright orange T's which needed to be identified among five to twenty distractor stimuli consisting of upright blue T's and upside down orange T's. Participants were instructed to answer as quickly as possible as soon as they identify a target orange T. In one third of the 36 trials no target stimulus was presented in which case participants had to wait until the next trial. Prior to the test trials, 12 practice trials were given.

2.7.4. Corsi Block Tapping Task.

In this study a digitized version of the Corsi Block Tapping Task (Corsi 1972) was used to assess (visual) working memory. Nine blocks were randomly arranged on the screen. Participants had to click on the blocks following the same order that had been previously presented to them. If at least

two of the four sequences with a given length were rendered correctly, four new sequences with a one block increase in length were given until either fewer than two sequences were correctly reproduced or the final four sequences of nine blocks length were given.

The Total Score is the product of the maximum sequence length the participant was able to reproduce and the total number of correctly reproduced sequences (Kessels et al. 2000), thus can vary between 0 and 288 in the present study.

2.7.5. Arrow Task.

The Arrow Task was another choice reaction time task with two possible choices. Following a fixation cross, an arrow was presented inside a white circle indicating either left or right. As a response, the participant had to press one of two buttons which were congruent in location with the direction to which the arrow was indicating. This part consisted of 40 test trials with six practice trials beforehand. This test serves as an addition to the Deary Liewald test, which already measures a simple and a 4-choice reaction time.

2.8. Procedure

Before commencing the study, participants filled in an informed consent form. Subsequently, participants started the pre-immersion test battery in which they were instructed to take a short break between tests if necessary. However, all participants completed the battery in approximately 25 minutes. Afterwards, participants filled in a pre-immersion measurement of the SSQ.

Then, participants were briefed on the experimental set-up in their respective condition, either on the head-mounted display or the mask and large screen and either on the bike ergometer or the gamepad controls. Before the start of the immersion, participants were reminded that they could abort the experiment at any time without giving any reasons but especially if they felt unwell or nauseous.

The virtual environment was developed with the Unity game engine (v5.4.0p3) and depicted an island with a network of paths which were used for movement of a virtual bike.

The task was to complete three trials of riding from a starting point to a pre-specified target which lasted for approximately 90 seconds. Upon arrival at the target, participants gave ratings on the SSQ symptoms. Together with a familiarization phase in which the participants were able to

familiarize themselves with the virtual world and the completion of the SSQ items within VR, the participants spent a total of about 10 minutes continuously in VR.

Less than a minute after the completion of the immersion, participants began the same test battery in the same order as before the immersion. Participants were explicitly told to spend the same amount of effort as in the pre-immersion testing. In between tests, participants filled in a paper-pencil version of the SSQ.

Members of the control group were not exposed to the VR and rested for 15 minutes instead. Before and at the end of the rest period they gave their rating on the SSQ. These ratings were compared with the ratings given by the experimental groups within the VR.

2.9. Analysis

For the test results, generalized linear mixed models (GLMM) with Laplace approximation were used to test the effect of condition (Condition), the time of measurement (Time) and the degree of cybersickness assessed right after the test administration (SSQ). Condition, Time, SSQ and the interaction between Condition and Time were included as fixed and participants as random effects in the model. First, Wald χ^2 -Tests were used to determine the general effect of a given factor. With a significant Wald Test, post hoc pairwise *t*-tests with TukeyHSD correction were performed if the factor consisted of more than two levels.

As reaction times tend not to be normally distributed, a gamma function was used to fit the distribution of the GLMM of reaction times (Lo and Andrews 2015). Those test results with a dependent variable other than a reaction time, i.e. percentage correct in the Mental Rotation Task and the Corsi Total Score, were analyzed using a logistic linear mixed model with binomial distribution (percentage correct) or a linear mixed model with Gaussian distribution (Corsi Total Score).

To further investigate the relationship between cybersickness and changes in test results, two Pearson correlation coefficients were computed for each dependent variable and each SSQ score. The first correlated the change in test score with reported SSQ scores right after the respective test was completed. For the second, the test scores were correlated with the maximum reported SSQ scores within the immersion.

All post hoc tests were Tukey *p*-adjusted. The α -level for all statistical tests was $\alpha < .05$.

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Data were analyzed with R 3.3.2 (R Core Team 2016). For the GLMM the R package `lme4` (Bates et al. 2015) was used and graphics were created with the `ggplot2` package (Wickham 2009).

3. Results

Four participants had to abort the immersion because of severe nauseous symptoms. Two of them were in the Bike/HMD and two in the Gamepad/HMD condition. All participants were nonetheless able to complete post-immersion cognitive testing.

3.1. Descriptive statistics

Means and standard deviations for all tests divided by test administration are presented in Table 2. For the sickness, SSQ ratings are given in Table 3.

[Insert Table 2 here.]

[Insert Table 3 here.]

3.2. Mixed models

Performance in pre- and post-immersion measurements were compared and investigated for the effect of condition and/or cybersickness with GLMM. Results are shown in Table 4 in case of reaction times as dependent variables and in Table 5 in all other cases.

[Insert Table 4 here.]

3.2.1. Deary-Liewald Task

For the SRT, the main effect for Time was significant. Post-immersion reaction times were higher in each condition. The analysis also revealed a significant effect of cybersickness measured with the SSQ and a significant interaction between Time and Condition. Wald χ^2 -Tests of the interaction terms revealed significant interaction effects for all conditions with the highest in the control group ($z = 11.57$; $p < .001$). After reviewing Figure 1, the reaction times increased in all four groups. However, reaction times in the control group remained comparatively stable and were just slightly increased, revealing a significantly stronger effect for the groups exposed to the VR.

In the CRT, the main effect for Time was significant. The effect for cybersickness (SSQ) just missed significance. A significant interaction between Time and Condition was found. Together with Figure 2, this effect is mainly due to the fact that the reaction times in the control group decrease, while they increase in all experimental groups.

[Insert Figure 1 here.]

[Insert Table 5 here.]

[Insert Figure 2 here.]

3.2.2. **Mental Rotation Task**

The main effect for Time suggests a significant reduction in processing time in the post-immersion measurement of the Mental Rotation task of 359ms to 464ms, depending on condition. The rate of correctly resolved items did not differ significantly from the two measurement points.

Additionally, neither the condition, nor the degree of cybersickness had any influence on performance in this task.

3.2.3. **Visual Search Task**

Reaction times in the Visual Search task did not show any significant differences between conditions, the times of measurement, or cybersickness. Although the interaction between Time and Condition was not significant, Figure 3 indicates a trend where the control group shows a stronger improvement of reaction times from the first to the second administration of the test than the other conditions.

3.2.4. **Corsi Block Task.**

The GLMM for the Corsi Total Score did not show any significant main effect of Condition, Time or cybersickness or an interaction effect of Condition and Time.

3.2.5. **Arrow Task.**

For the Arrow task, the GLMM indicated a significant main effect for Time and a significant interaction effect between Time and Condition. Further analyses revealed a significant interaction in the in the control group ($z = 6.11$; $p < .001$). Figure 4 shows that the reaction times of the control group participants have decreased from the first to the second administration, while the reaction times of the other conditions have noticeably increased.

3.3. **Cybersickness and cognitive performance**

Finally, to further analyze possible relationships between sickness scores and cognitive performance, correlation analyses between Δ performance (i.e., change in performance parameter from pre to post measurement) and both the maximum SSQ score within VR and the SSQ scores

immediately after their respective tests were completed were computed. Correlation coefficients are presented in Table 6.

[Insert Table 6 here.]

Cybersickness was significantly correlated with increases of reaction time in the Deary Liewald CRT, both the baseline corrected SSQ score immediately after the test and the maximum score measured within the immersion. Additionally, the baseline corrected maximum SSQ score within VR was correlated with increases in reaction time in the Arrow Task. However, this could not be replicated for the SSQ score that was collected immediately after the test was performed.

All other performance differences showed no significant correlation with the degree of cybersickness.

4. Discussion

In this study we investigated the effect of VR exposure with different motion control and display devices on cognitive capacities and the relationship of performance change with the degree of cybersickness.

Post-immersion measurements of the Deary-Liewald SRT showed a significant interaction with the condition. Response times of the groups exposed to VR increased while response times of the control groups remained almost unchanged. A similar effect was found in the Deary Liewald CRT and in the Arrow Task, each with decreasing response times in the control group. The Visual Search Task showed a similar pattern of change, but this did not become significant. Taken together, the results indicate a significant negative influence of VR exposure on the response time in basic reaction times. The effect may decrease in more complex tasks, such as the Visual Search Task.

Furthermore, analyses that considered the influence of the degree of cybersickness showed that although cybersickness had a significant influence on the response time increase in the Deary Liewald SRT, it could only be replicated to a limited extent in the Deary Liewald CRT and not in the Arrow Task (Table 4).

The results of the correlation analyses, however, showed significant correlations between cybersickness and the reaction time increase in the Deary Liewald CRT and partly also in the Arrow Task (Table 6) but correlations were not significant for the Deary Liewald SRT. The results indicate that cybersickness was at most marginally involved in the performance deterioration and there must be at least one other reason for the performance losses of those who were exposed to the VR.

For other cognitive capacities, we did not find a similar decline in performance. In fact, the performance in the Mental Rotation task, as well as in the Corsi test remained constant and showed no interaction effect with the condition or a connection with cybersickness. Participants were on average somewhat faster in responding to the Mental Rotation Task after they could get used to the task. However, this effect did not differ according to condition and also showed no connection with cybersickness. Thus, we were not able to demonstrate that working memory or mental rotation ability were affected by VR as an aftereffect, despite previous studies reporting a relationship with cybersickness (Bos 2015; Dahlman et al. 2009; Levine and Stern 2002).

4.1. Cognitive aftereffects of Virtual Reality

Findings of increased reaction times after VR immersion in previous studies (Nalivaiko et al. 2015; Nesbitt et al. 2017) were explained with a deteriorating effect of cybersickness on cognitive performance. This assumption is supported by longer reaction times found in situations that may be similar to cybersickness, for instance as a result of respiratory tract illnesses (Smith et al. 2004), sleep deprivation (van den Berg and Neely 2006) or general fatigue (Welford 1980). However, unlike other studies (Nalivaiko et al. 2015; Nesbitt et al. 2017), we found the degree of cybersickness having very little influence on the deterioration of reaction rates. Also, we only found few and low correlations with cybersickness, both with regard to the maximum sickness during the immersion and with regard to the measurement taken directly after the completion of the test.

However, with the results of this study we were able to replicate a *general increase* in the response time for all participants exposed to VR. In this sense, the results are similar to those of Nesbitt et al. (2017), who also found an increase in response times among the majority of their participants, roughly at the same level as in our results. Furthermore, the correlation with cybersickness found by Nesbitt et al. (2017) is primarily based on the very strong performance deterioration of one participant and could not be confirmed by non-parametric correlations.

Therefore, instead of explaining the observed increase of reaction time with the degree of experienced cybersickness, we conclude, based on the present results, a general detrimental effect of VR exposure on reaction time. These findings are in line with previous research suggesting aftereffects of uncoupled motion being unrelated to motion sickness (Muth 2009).

Regarding the question why the reaction time should slow down due to the use of VR as an aftereffect, the previous studies offer no explanation other than cybersickness or motion sickness. Since cybersickness had only very limited influence on the change in performance in the present study, other explanations are necessary.

The drop in performance in response time tasks cannot simply be attributed to the passage time, as possible factors such as motivation loss and boredom may have been the same in all conditions or even greater in the control group.

Another possible explanation could be an aftereffect of visual motor adaptation to the virtual environment. Participants had to adapt to VR as some motor actions may have led to slightly different outcomes as expected (e.g. turning of the handlebar) or visual, proprioceptive and motor senses did not match as well as in reality (e.g. the handlebar is in a different position than expected) which could have affected motor response speed in the reaction time tasks. In line with that, previous research has shown that visual motor adaptation leads to an increase in response time (Fernandez-Ruiz et al. 2011).

In addition, there are latency times, which are inherent in the system, even if they are not created consciously, possibly leading to a temporal adaptation of the participants, expecting a greater latency for visual feedback of their inputs (Sugano et al. 2009; Waltemate et al. 2016). For example, the HMD generates a short latency time from head movement to visual image movement. The steering and acceleration of the bike also reacted with a short, hardly discernable delay. This delay time is about the same as the deterioration of the reaction time (20 to 30 ms).

These conditions may have induced a cognitive adaptation process, expressed in an increased response time after VR exposure. Since this reasoning is still purely speculative at this stage, further research is needed to investigate this hypothesis in more detail.

4.2. Practical implications

A non-trivial conclusion from the present study is that although some individuals indicated severe subjective cybersickness symptoms and some of the participants exhibited visible symptoms like belching even during the second test administration, none of the participants of the study showed a collapse or sharp decline in performance.

Even though we found a significant increase in reaction time immediately following the VR exposure, the average increase of 17ms to 29ms for the simple reaction time is a substantial effect in context of simple reaction times, but its real-world significance is limited. As inter-individual variance was far greater than the intra-individual effect of VR, the present findings suggest that cognitively impairing aftereffects are not of particular practical relevance.

However, before issuing recommendations on security-related questions like driving home or exercising other cognitively challenging tasks following a VR exposure, more extensive research has to be carried out in order to exclude relevant impairments with reasonable certainty.

4.3. Limitations and future research

Due to the fact that the order of the tests was fixed, the time since leaving the VR could have had an influence on the change in performance. However, the degree and thus the difference in cybersickness between the experimental groups and the control group remained relatively stable over 20 minutes after VR (Table 3). Moreover, aftereffects sometimes occur spontaneously and persist only temporarily. Future studies should randomize the order of the tests and investigate the effect of test order.

Another issue is practice effects. Practice effects pose a particularly difficult problem for the investigation of changes in cognitive performance as they are, possibly with the exception of extensive mandatory training, not preventable and could easily mask adverse effects of the treatment (Kennedy et al. 1993a). Likewise in the present study, the improvement of response times of the control group most likely reflects these same practice effects, as otherwise there is no compelling reason why performance should have improved in the control group. Future research could involve extensive prior training to reduce the practice effects in the test phase

About two thirds of the participants were female. Some studies indicated an effect of gender on cybersickness severity like Harm et al. (2007) who proposed that women tend to report more symptoms sooner than men but also recover more quickly after the end of the immersion. However, other studies were not able to consistently replicate gender differences (Klosterhalfen et al. 2008; Ling et al. 2013). We do not expect that the relative imbalance of female and male participants had any influence on the results. However, based on the previous reports of gender differences, we cannot rule out the possibility that men and women are affected differently by VR aftereffects.

4.4. Conclusion

In the present study, we found a significant increase of reaction time after the exposure to a virtual environment and in comparison to a control group. These findings confirm previous results of increased reaction times following a VR immersion (Nalivaiko et al. 2015; Nesbitt et al. 2017).

The performance decrease was, however, only weakly related to subjective levels of cybersickness and was observed in all experimental conditions, not only in those inducing higher degrees of sickness. Thus, the present observations supports a more general effect of VR exposures on

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reaction time which is independent of the degree of cybersickness experience within or after VR immersion (Muth 2009).

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Table 1

Approximate durations for each test. Please note that the duration of the Corsi Test differed between participants because it depended on participant's performance.

Test	Approximate duration
Deary-Liewald Simple Task	2 minutes
Deary-Liewald Choice Task	2 minutes
Mental Rotation Task	3 minutes
Visual Search Task	3 minutes
Corsi	3-7 minutes
Arrow Task	3 minutes

Table 2

Descriptive statistics of cognitive tests by time of measurement. Means and standard deviations in parentheses.

	Bike/HMD	Gamepad/HMD	Bike/Screen	Control	
Pre-immersion	Deary SRT	271 ms (18 ms)	274 ms (29 ms)	281 ms (17 ms)	270 ms (23 ms)
	Deary CRT	425 ms (35 ms)	433 ms (59 ms)	448 ms (74 ms)	415 ms (47 ms)
	Mental Rotation RT	2987 ms (860 ms)	2613 ms (580 ms)	2893 ms (780 ms)	2657 ms (939 ms)
	Mental Rotation %correct	86% (15%)	84% (13%)	83% (13%)	87% (12%)
	Visual Search RT	950 ms (164 ms)	910 ms (119 ms)	1016 ms (225 ms)	951 ms (144 ms)
	Corsi Total Score	122.7 (26)	141.5 (43)	126.2 (47)	133.7 (46)
	Arrow Task RT	379 ms (34 ms)	367 ms (32 ms)	376 ms (40 ms)	356 ms (42 ms)
Post-immersion	Deary SRT	301 ms (24 ms)	292 ms (33 ms)	307 ms (31 ms)	275 ms (26 ms)
	Deary CRT	451 ms (51 ms)	442 ms (69 ms)	460 ms (46 ms)	399 ms (50 ms)
	Mental Rotation RT	2628 ms (893 ms)	2227 ms (508 ms)	2429 ms (638 ms)	2228 ms (941 ms)
	Mental Rotation %correct	88% (14%)	89% (10%)	88% (11%)	87% (15%)
	Visual Search RT	926 ms (159 ms)	893 ms (166 ms)	983 ms (193 ms)	842 ms (126 ms)
	Corsi Total Score	137.0 (38)	146.5 (55)	123.1 (37)	147.6 (45)
	Arrow Task RT	391 ms (34 ms)	380 ms (47 ms)	392 ms (66 ms)	351 ms (38 ms)

RT = reaction time; %correct = percentage of correct responses.

Table 3

Means and standard errors of SSQ Total Scores at different times of measurement.

	Bike/HMD	Gamepad/HMD	Bike/Screen	Control
pre-immersion	22.3 (3.6)	14.6 (2.8)	17.4 (3.6)	19.6 (3.0)
Maximum in VR (or at the end of resting)	54.0 (10.0)	52.6 (8.2)	22.3 (4.1)	11.59 (2.7)
after Deary Liewald	47.7 (8.9)	39.8 (6.3)	37.0 (6.3)	17.8 (2.8)
after Mental Rotation	39.1 (8.0)	35.3 (6.5)	30.0 (6.6)	19.6 (3.0)
after Visual Search	34.4 (7.0)	30.5 (4.9)	29.4 (6.1)	18.9 (3.0)
after Corsi	35.3 (7.0)	28.4 (6.1)	34.4 (7.4)	23.8 (4.3)
after Arrow Task	39.5 (8.1)	37.0 (5.9)	37.4 (8.7)	24.1 (3.9)

Table 4

Results of the GLMM for reaction time related dependent variables. All effects were tested with the

Wald- χ^2 test.

Deary-Liewald SRT			
<i>Predictor</i>	<i>df</i>	χ^2	<i>p-value</i>
Intercept	1	1067.23	<.001
Time	1	304.76	<.001
Condition	3	1.57	.665
SSQ	1	7.10	.008
Time:Condition	3	140.77	<.001
Deary-Liewald CRT			
<i>Predictor</i>	<i>df</i>	χ^2	<i>p-value</i>
Intercept	1	757.95	<.001
Time	1	24.68	<.001
Condition	3	1.84	.607
SSQ	1	3.64	.056
Time:Condition	3	66.87	<.001
Mental Rotation Task RT			
<i>Predictor</i>	<i>df</i>	χ^2	<i>p-value</i>
Intercept	1	299.88	<.001
Time	1	37.38	<.001
Condition	3	3.47	.324
SSQ	1	.13	.719
Time:Condition	3	2.15	.543
Visual Search Task RT			
<i>Predictor</i>	<i>df</i>	χ^2	<i>p-value</i>
Intercept	1	432.27	<.001
Time	1	1.47	.226
Condition	3	2.84	.417
SSQ	1	1.06	.303
Time:Condition	3	5.36	.147
Arrow Task RT			
<i>Predictor</i>	<i>df</i>	χ^2	<i>p-value</i>
Intercept	1	928.36	<.001
Time	1	15.32	<.001
Condition	3	1.23	.747
SSQ	1	.07	.787
Time:Condition	3	55.48	<.001

Table 5

Results of the GLMM for all non-reaction time related dependent variables. All effects were tested with the Wald- χ^2 test.

Mental Rotation Task Percentage Correct			
<i>Predictor</i>	<i>df</i>	χ^2	<i>p-value</i>
Intercept	1	80.87	<.001
Time	1	2.06	.151
Condition	3	2.11	.550
SSQ	1	1.19	.275
Time:Condition	3	5.48	.140
Corsi Total Score			
<i>Predictor</i>	<i>df</i>	χ^2	<i>p-value</i>
Intercept	1	142.53	<.001
Time	1	2.16	.142
Condition	3	4.14	.247
SSQ	1	.01	.926
Time:Condition	3	2.43	.487

Table 6

Pearson correlation coefficients of performance change from pre to post measurement with the change in SSQ Total Score from pre-immersion measurement to either scores assessed after post-test administration or the maximum scores in VR. *P*-values were corrected with the Holm-Bonferroni method.

	Δ SSQ TS after test	Δ max SSQ TS in VR
Δ Deary Simple Task RT	.04	.07
Δ Deary Choice Task RT	.28*	.25*
Δ Mental Rotation RT	-.02	.15
Δ Mental Rotation %	-.05	-.07
Δ Visual Search RT	.21	.13
Δ Corsi Total Score	.09	-.03
Δ Arrow Task RT	.12	.23*

* $p < .05$; TS = Total Score.

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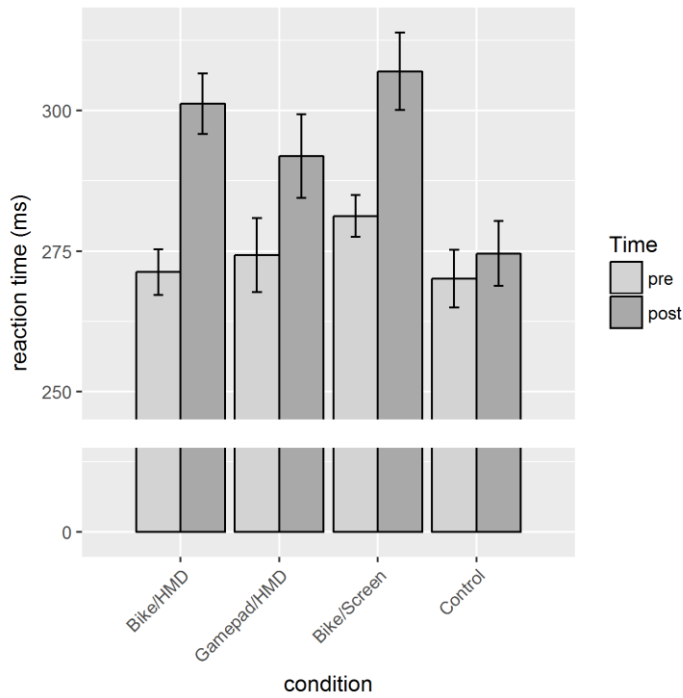


Figure 1. Mean reaction times in the Deary Liewald Simple Task prior and after the VR immersion, separately for the four conditions. Error bars indicate standard errors.

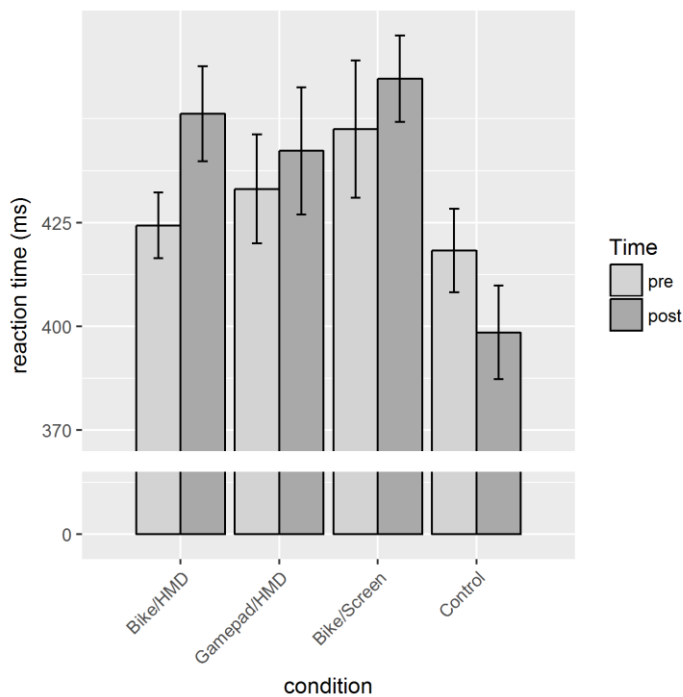


Figure 2. Mean reaction times in the Deary Liewald Choice Task prior and after the VR immersion, separately for the four conditions. Error bars indicate standard errors.

VR aftereffect, cybersickness and performance

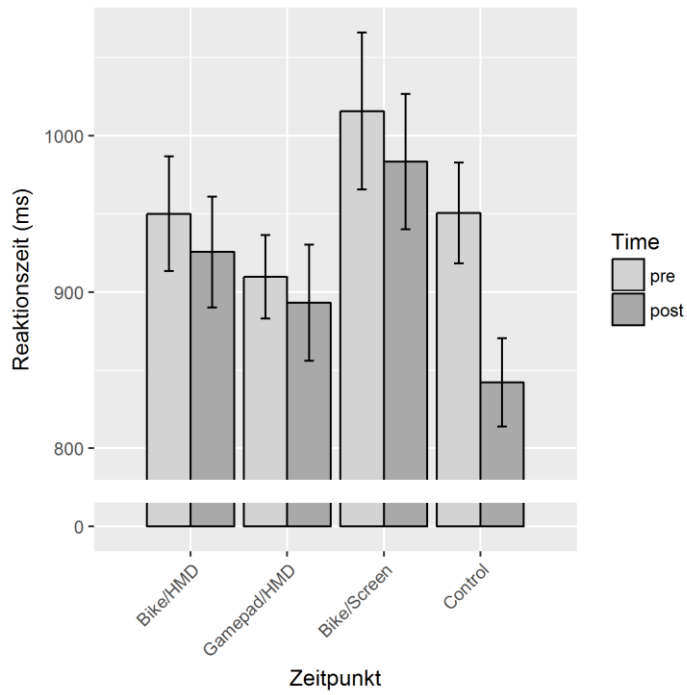


Figure 3. Mean reaction times in the Visual Search Task prior and after the VR immersion, separately for the four conditions. Error bars indicate standard errors.

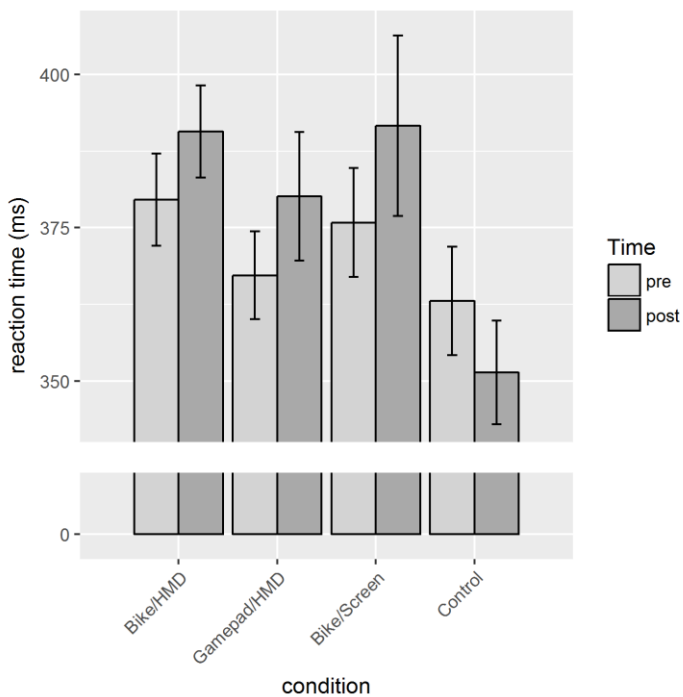



Figure 4. Mean reaction times in the Arrow Task prior and after the VR immersion, separately for the four conditions. Error bars indicate standard errors.

Article 3

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Emotional and Cognitive Modulation of Cybersickness: The Role of Pain Catastrophizing and Body Awareness

Justin Maximilian Mittelstaedt , Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center), Hamburg, Germany, Jan Wacker, Universität Hamburg (University of Hamburg), Germany, and Dirk Stelling, Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center), Hamburg, Germany

Objective: The goal was to investigate the influence of the tendency to catastrophize somatic symptoms and body awareness on motion-related sickness.

Background: Influences of emotional and cognitive-evaluative processes on the genesis of motion sickness or cybersickness have rarely been investigated. Brain imaging studies showed activation during cybersickness, resembling the pattern found for pain processing. Two aspects often investigated in this context are pain catastrophizing and body awareness. The present two studies investigated the relationship of motion-related sickness to two tendencies involved in pain processing: pain catastrophizing and body awareness.

Method: In the first study, 115 participants reported their motion sickness history, pain catastrophizing, and body awareness. In the second study, 40 participants were exposed to a virtual reality and reported their experience of cybersickness as well as their pain catastrophizing and body awareness.

Results: Pain catastrophizing was positively correlated to motion sickness history and cybersickness. Body awareness did not show a linear effect on motion sickness history or cybersickness. However, the interaction effect of pain catastrophizing and body awareness was significant in both studies.

Conclusion: Pain catastrophizing seems to have a detrimental effect on cybersickness symptoms. Body awareness moderated the relationship in the sense that the combination of high pain catastrophizing and low body awareness lead to the highest sickness levels.

Application: Affective and cognitive modulation of cybersickness symptoms should be considered when exposing risk groups to motion-related adverse stimuli.

Keywords: cybersickness, motion sickness, pain catastrophizing, body awareness, attention

Due to the increasing attention for virtual reality (VR) technology in research, entertainment, and professional fields over the past years, the prevalence of illness of users interacting with VR becomes more widely recognized. The symptoms users are experiencing resemble those of motion sickness.

Motion sickness is an often-reported physical response to a sensory conflict caused by incongruent angular and linear vestibular cues or adverse vestibular cues in the absence of or disagreement with cues perceived by the visual system. Affected individuals suffer from symptoms such as vertigo, disorientation, nausea, vomiting, headache, sweating, and the sopite syndrome, which includes drowsiness, fatigue, and mood changes, each to varying degrees (Bertolini & Straumann, 2016).

Cybersickness, in contrast, describes the feeling of illness and discomfort induced by visual stimulation in absence of any vestibular cues. It is often experienced while and after using VR equipment such as head-mounted displays (HMDs), which exclude all visual information from the physical world and provide control of the virtual point of view based on the head movements the user performs. But it can also be observed, to a lesser extent, when using large screens such as TV screens (Mittelstaedt, Wacker, & Stelling, 2018).

Even within the same setting, administering the same sickness-inducing stimuli, vast interindividual differences can be observed. The best way to consistently predict motion sickness or cybersickness has been shown to be general motion sickness history (Golding, 2006), defined as the incidence of motion sickness in different motion vehicles (e.g., cars, planes, fair rides) during youth and adult life. This states that the

Address correspondence to Justin Maximilian Mittelstaedt, MSc, Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center), Sportallee 54A, Hamburg, 22335, Germany; e-mail: justin.mittelstaedt@dlr.de.

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degree of sickness an individual experiences in one vehicle is related to the degree of sickness experienced in a different vehicle, and it also implies an underlying factor causing sickness in different motion-related situations. However, motion sickness history only provides evidence that sickness, induced by motion-related content, is stable across multiple different situations, in various vehicles, and even in the absence of any real motion, when motion is presented visually in a virtual environment or by use of an optokinetic drum. It does not provide explanations as to why some individuals experience more sickness than others.

Repeated evidence suggests gender is a major determinant in explaining individual differences in motion sickness and cybersickness, with females tending to report higher degrees of sickness than males (Dobie, McBride, Dobie, & May, 2001; Munafo, Diedrick, & Stoffregen, 2017), presumably partly because of hormonal variations during their menstrual cycle (Golding, Kadzere, & Gresty, 2005).

Much research focused on physiological indicators to determine differences in susceptibility to motion-related sickness such as otolith asymmetry (Fowler, Sweet, & Steffel, 2014), longer time constant of the vestibulo-ocular reflex (Clément & Reschke, in press), or the time constant of the optokinetic after-nystagmus (Guo, Chen, Wei, So, & Cheung, 2018).

Despite great efforts explaining individual differences with physiological parameters, the exact mechanisms remain unclear, and a considerable impact of psychological aspects seems likely. Among personality factors influencing the susceptibility to motion sickness and cybersickness, anxiety is considered as one of the main contributors. Trait anxiety or more broadly neuroticism has been shown to be related to elevated levels of motion sickness (Fox & Arnon, 1988), cybersickness (Farmer et al., 2015), and motion sickness history (Buyuklu, Tarhan, & Ozluoglu, 2009; Collins & Lentz, 1977; Owen, Leadbetter, & Yardley, 1998). However, why anxiety is related to the genesis of motion sickness is still a matter of debate. Some symptoms of motion-related sickness might be intrinsic to anxiety as well, although nausea is usually not one of them (Fox & Arnon, 1988). Owen et al.

(1998) suggest that anxiety directly affects postural balance and leads to deficiencies in postural control and hence to increased motion sickness susceptibility.

Balaban and Yates (2017) provide a framework for the genesis of nausea, including possible mechanisms of anxiety. This framework comprises automatic sensorimotor processing, cognitive-behavioral processing including cognitive interpretation and affective regulation, as well as interoceptive processing as the interface between the two. According to this model, an internal or external trigger (e.g., an adverse motion stimulus) activates neural pathways (e.g., vestibular or visual pathways), eliciting an autonomous response and interoception with attention toward the autonomous response and an internal representation of the symptoms. On a cognitive level, the perception of symptoms leads to changes in arousal, emotional states (e.g., anxiety), and the interpretation of the triggering stimulus and the perceived symptoms.

Anxiety that is primarily caused by the negative valence and other characteristics (duration, specificity) of the adverse stimulus leads to rumination, worrying about the symptoms, and emotional arousal. This could alter the mode of interoception (i.e., it alters the way the symptoms are perceived), facilitate the experienced symptoms, or generate symptoms in its own right.

The depicted aspects have rarely been investigated in the context of motion-related sickness. Two concepts corresponding to interoception and illness worry and rumination of the aforementioned framework, predominantly used in pain research but not necessarily limited to it, are used in this study to investigate the mechanisms of cognitive and affective modulation in cybersickness: pain catastrophizing and body awareness.

PAIN CATASTROPHIZING

Pain catastrophizing is a well-studied construct in pain research and describes a general negative attitude toward pain and associated sensations. It comprises the three distinct features of rumination, magnification, and helplessness in relation to pain-related thoughts and sensations (Sullivan, Bishop, & Pivik, 1995).

Pain catastrophizing demonstrates a high degree of stability after a 6-week period (Sullivan et al., 1995). Furthermore, studies have shown that dispositional pain catastrophizing is related to pain experience. It exacerbates pain intensity and the overall emotional experience of pain (Sullivan et al., 2001; Sullivan et al., 1995).

However, pain catastrophizing does not seem to be limited to explaining the severity of pain. It was also found to be related to the presence of a weekly headache (Drahovzal, Stewart, & Sullivan, 2006). Devoulyte and Sullivan (2003) showed that pain catastrophizing, assessed on Day 1, predicted the presence and severity of upper respiratory tract illness symptoms over the course of the following week. The authors of both studies conclude that pain catastrophizing may be a general tendency to cope with threatening stimuli and is not necessarily related to pain.

Turner and Aaron (2001) proposed that pain catastrophizing may be more than a pain-specific construct and highlight the relationship between pain catastrophizing and anxiety, neuroticism, or generally negative affectivity. Pain catastrophizing is seen as a tendency to appraise stimuli as threatening in potentially harmful situations.

The main mechanism behind pain catastrophizing is believed to be increased allocation of attention toward the threatening stimulus (Quartana, Campbell, & Edwards, 2009; Sullivan et al., 2001). Empirical evidence supports this claim as pain catastrophizers show more interference of actual or anticipated pain in a mental discrimination task (Crombez, Eccleston, Van den Broeck, Van Houdenhove, & Goubert, 2002). These effects even prevailed after controlling for negative affectivity, supporting the specificity of pain catastrophizing when facing adverse stimuli. Another study suggests that high-pain catastrophizers do not initially allocate more attention to a threatening stimulus than low pain catastrophizers but are rather unable to divert attention from that stimulus (Van Damme, Crombez, & Eccleston, 2004).

Recent experiments indicate a similar role of attention in the genesis of motion-related sickness. Providing mental distraction by giving a

mentally challenging task can ameliorate motion sickness symptoms (Bos, 2015). Reduced attention toward the adverse motion stimulus could also be the reason why controlled breathing (Yen Pik Sang, Golding, & Gresty, 2003) or the additional presentation of pleasant music (Keshavarz & Hecht, 2014) seems to be effective in alleviating sickness severity. Fox and Arnon (1988) hypothesized that a possible explanation for the relationship of anxiety and motion sickness is that anxious individuals may tend to be more attentive or alert to internal states of the body and might more readily perceive symptoms of motion-related sickness.

Based on the above findings, it is assumed that the concept of pain catastrophizing can be considered as a general tendency of not being able to disengage from adverse bodily symptoms. Consequently, we predicted that pain catastrophizers will also show elevated levels of sickness when exposed to an adverse motion stimulus.

Edwards, Haythornwaite, Sullivan, and Fillingham (2004) found gender differences in pain catastrophizing, with females having higher values, and suggested that pain catastrophizing is a mediator for gender differences in pain intensity. Similarly, previous studies found gender differences in susceptibility to motion-related sickness (see Dobie et al., 2001; Munafò et al., 2017). We consequently examined both pain catastrophizing and motion-related sickness for gender differences to determine whether pain catastrophizing is a potential mediator candidate.

BODY AWARENESS

In contrast to pain catastrophizing, which is proposed to affect attention to the adverse stimulus, body awareness is defined as the sensitivity to body cycles and rhythms, the ability to perceive subtle bodily cues and to anticipate bodily reactions to external stimuli (Shields, Mallory, & Simon, 1989). The related concept of interoception (i.e., the perception of bodily signals) has been an integral part of nausea genesis and progression in the framework by Balaban and Yates (2017). Thus, individual differences in perceiving bodily symptoms may have an effect on individual susceptibility to motion-related sickness.

Body awareness is a subjective, nonjudgmental perceptual sensitivity that is not necessarily related to the degree of monitoring of bodily signals or anxiety (Ginzburg, Tsur, Barak-Nahum, & Defrin, 2014). It seems to be a stable trait and generalized across different modalities, such as cardiac or gastrointestinal symptoms (Herbert, Muth, Pollatos, & Herbert, 2012).

When defining body awareness as the aforementioned sensitivity, body awareness has been shown to be beneficial for reducing pain and providing relief in other chronic diseases (Eriksson, Möller, Söderberg, Eriksson, & Kurlberg, 2007). However, this effect of body awareness seems to depend on the mode of attention (i.e., the amount of body monitoring and pain catastrophizing) (Ginzburg et al., 2014).

The sensitivity to bodily cues has been linked to the ability to accurately detect body movements (Tsakiris, Prabhu, & Haggard, 2006), changes in body temperature (Johnston, Atlas, & Wager, 2012), and somatic signals in general (Mehling et al., 2012). VR users who report cybersickness often sway before the advent of sickness (Stoffregen, Faugloire, Yoshida, Flanagan, & Merhi, 2008), have changes in skin temperature (Nalivaiko, Davis, Blackmore, Vakulin, & Nesbitt, 2015), and experience severe nausea (Mittelstaedt et al., 2018). Thus, individuals with high body awareness may be more sensitive to detecting subtle changes in posture, body temperature, or symptoms of the gastrointestinal tract.

Low body awareness (i.e., low sensitivity or ability to detect bodily signals) has been linked to alexithymia, a personality construct comprising difficulties with identifying and regulating emotional states (Zamariola, Vlemincx, Corneille, & Luminet, 2018). Alexithymia has been found to be related to elevated levels of motion sickness in a previous study (Leimann Patt, Baistrocchi, & Moia, 1988). The authors suggest that individuals with high alexithymia somatize their anxiety, thus facilitating motion sickness symptoms. Due to the conceptual and empirical overlaps of the two constructs, it is also possible that individuals with low body awareness fail to emotionally regulate when facing unpleasant environmental cues such as an adverse motion stimulus. In fact, brain imaging indicated that

individuals highly susceptible to visually induced motion sickness have reduced activity in areas associated with interoception (Farmer, Ban, Giampietro, Andrews, & Aziz, 2014).

Taken together, we hypothesized that both pain catastrophizing and body awareness are significant predictors of individual differences in motion- and cybersickness and tested these predictions in two studies. The first study examines the relationship of motion sickness history with body awareness and pain catastrophizing. In the second study, we investigate the relationship of body awareness and pain catastrophizing on cybersickness induced by a virtual bike simulator in a virtual environment.

STUDY 1

As body sensitivity had a beneficial effect in previous studies on pain and other diseases, we expected a negative relationship between body awareness and the severity of motion-related sickness. Furthermore, because pain catastrophizing is a dispositional tendency to magnify somatic symptoms or to allocate more attention to painful or adverse bodily symptoms, we expected it to display a positive association with the perception and the degree of reported motion sickness as well.

Ginzburg et al. (2014) showed a moderating effect of pain catastrophizing on the relationship between body awareness and trait anxiety. Body awareness itself is proposed to be the ability to nonjudgmentally detect bodily sensations and is only maladaptive if combined with a ruminative thinking style being present in pain catastrophizing (Mehling et al., 2009). Therefore, we additionally investigated the interaction effect of body awareness and pain catastrophizing on motion-related sickness.

Methods

Body Awareness Questionnaire (BAQ). The BAQ (Shields et al., 1989) measures attentiveness and sensitivity to body signals and processes such as onsets of physical illnesses, sleep-wake cycles, and bodily reactions to environmental changes. It comprises 18 items that are answered on a seven-point Likert-type scale from *not true at all about me* to *very true about me*.

The authors report reliability measures of an internal consistency of $\alpha = .82$ and a test-retest correlation of $r = .80$ after 2 weeks. In the present sample, the BAQ reached an internal consistency of $\alpha = .85$.

Pain Catastrophizing Scale (PCS). The PCS (Sullivan et al., 1995) assesses negative and exaggerated coping concerning anticipated or experienced painful stimuli (i.e., pain catastrophizing). Thirteen items are answered on a 5-point Likert-type scale and can be divided into three dimensions: Rumination, Magnification, and Helplessness.

Reliability measures for the PCS were reported (Sullivan et al., 1995). The internal consistency of the whole scale was measured as $\alpha = .87$. An investigation of the temporal stability of the PCS resulted in a correlation of two measurements of $r = .75$ after approximately 6 weeks and $r = .70$ after approximately 10 weeks.

In the present sample, the internal consistency of the PCS was $\alpha = .92$.

Motion Sickness Susceptibility Scale (MSSQ). We used the short form of the MSSQ (Golding, 2006), measuring the general susceptibility to motion sickness, by assessing the occurrence of motion sickness symptoms in different means of transportation (e.g., cars, planes, funfair rides) separately for childhood (under the age of 12) and adulthood (last 10 years). The resulting values for childhood (MSA) and adulthood (MSB) are subsequently summed to produce a total MSSQ score. In the present studies, we used the total MSSQ score as a measurement of motion sickness history.

Ratings for experienced motion sickness were given on a 4-point scale (*never*, *rarely*, *sometimes*, and *frequently*). Participants could also indicate that they had not traveled with a transport vehicle in a given time period, in which case this vehicle is not included in the calculation of the total score.

The reliability measures given by Golding (2006) showed an internal consistency of $\alpha = .87$ for the whole scale, with a correlation of $r = .68$ between MSA and MSB. In the current sample, a Cronbach's α of $.87$ with a correlation of $r = .66$ between the two subscales was observed. The mean value in the current sample ($M = 11.1$,

$SD = 8.6$) was slightly lower than in the normative sample ($M = 12.4$, $SD = 9.4$).

Participants and procedure. A total of 115 participants (72 female and 43 male) with a mean age of 29.1 years ($SD = 10.8$ years) filled in the BAQ, PCS, and MSSQ and gave demographic information such as gender and age.

Data analysis. Data were analyzed using R 3.3.2 (R Core Team, 2016) with packages *ez* (Lawrence, 2016) for the computation of ANOVA and *ggplot2* (Wickham, 2009) for creating graphics.

Results and Discussion

Correlation analyses of the BAQ, the PCS, and the MSSQ were performed. Motion sickness history and pain catastrophizing were significantly related ($r = .45$, $p < .01$), while motion sickness history and body awareness did not show a significant relationship ($r = -.09$, $p = .34$). These results suggest a negative effect of pain catastrophizing on motion sickness prevalence in different situations but without any linear effect of body awareness. Pain catastrophizing and body awareness were not significantly correlated in the present sample ($r = .07$, $p = .44$).

The interaction of body awareness and pain catastrophizing. We examined the interaction effects of body awareness and pain catastrophizing by performing a multiple linear regression analysis with main effects for BAQ and PCS and the interaction effect between the two on the MSSQ score. Predictors and outcome variables were *z*-standardized. Results of the regression analysis can be seen in Table 1.

Figure 1 shows the interaction effect between the BAQ and PCS scores on MSSQ scores.

Results show a significant main effect for pain catastrophizing. Participants with a high tendency of pain catastrophizing reported higher incidences of motion sickness in different situations. The analysis also yielded a significant interaction effect between BAQ and PCS. Figure 1 shows that body awareness has an ameliorating effect on motion sickness history but only among participants high on pain catastrophizing.

As Munafo et al. (2017) found significant differences in cybersickness severity between

TABLE 1: Results of the Regression Analysis for Motion Sickness Susceptibility Questionnaire Scores

	β	t	p
BAQ	-.115	1.403	.164
PCS	.463	5.632	<.001***
BAQ \times PCS	-.164	-2.325	.022*

Note. $N = 115$. BAQ = Body Awareness Questionnaire; PCS = Pain Catastrophizing Scale.

* $p < .05$. *** $p < .001$.

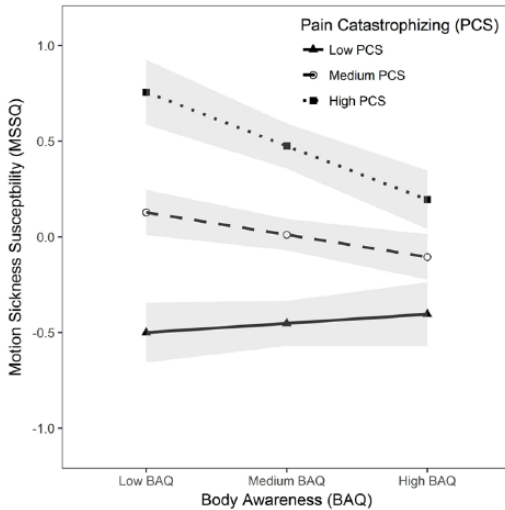


Figure 1. Interaction plot of BAQ and PCS on MSSQ scores. Lines represent fitted values for low (-1 SD), medium (mean), and high (1 SD) degrees of BAQ and PCS. Gray areas indicate standard errors.

gender, we performed the same analysis controlling for gender. The inclusion of gender into the model did not change the effect of pain catastrophizing ($\beta = .46, p < .01$), body awareness ($\beta = -.12, p = .17$), or the interaction between pain catastrophizing and body awareness ($\beta = -.16, p = .02$). The effect of gender was not significant ($\beta = .01, p = .95$). There were no significant differences between male and female participants in pain catastrophizing, $t(69) = 1.325, p = .19$, or motion sickness history, $t(74) = 1.07, p = .29$. However, male participants indicated significantly higher body awareness, $t(83) = 2.15, p = .04$.

Study 1 investigated the relationship between body awareness, pain catastrophizing, and the motion sickness history, which is the frequency

of motion sickness occurrences in the past. However, motion sickness history does not directly assess symptom severity and is based on biographical data.

STUDY 2

In Study 1, we investigated the relationship between motion sickness history and body awareness and pain catastrophizing. As the incidence of motion sickness in various situations had to be recalled from memory, in part from childhood, we investigated the effect of body awareness and pain catastrophizing on ongoing cybersickness induced via VR in a second study.

We expected to find a detrimental effect of pain catastrophizing and a beneficial effect of body awareness on cybersickness severity. Participants with high pain catastrophizing or low body awareness are expected to show higher cybersickness ratings (i.e., more or more severe symptoms) and prematurely withdraw from the immersion more frequently as a result of sickness.

Methods

Participants. Forty volunteers (21 female, 19 male) with a mean age of 23.2 years and a standard deviation of 4.2 years participated in this study. All participants had normal or corrected-to-normal vision using contact lenses. In compensation for participating, they received full monetary remuneration (30€) irrespective of whether they completed the VR immersion or whether they aborted due to sickness symptoms.

This research complied with the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board at German Psychological Association (DGPS; JM 122017). Informed consent was obtained from each participant.

Procedure. Before being immersed in VR, participants filled in an informed consent, the questionnaires (BAQ, PCS, and MSSQ), and a short survey assessing demographic variables like age and gender.

Participants were then briefed on the experimental set-up, consisting of an HMD and a gamepad controller. Before starting the immersion, participants were reminded that they could abort the experiment at any time without decreasing their monetary compensation and without giving any reasons but should do so especially if they felt unwell or nauseous.

The task within VR was to navigate a virtual bike across a virtual island with a continuous movement and thus a constant optic flow.

At first, participants received the opportunity to familiarize themselves with the HMD and the virtual environment by being set on the virtual island and looking around, however without the possibility of moving the virtual bike.

Subsequently, two trials of 5 minutes duration were performed, followed by which the participants were instructed to ride along the virtual island on a path of their own choice. Participants were further instructed to ride at maximum speed at all times (which was easily reached). In case participants slowed down or remained motionless for an extended period of time, they were asked if they wanted to abort the immersion. In the case of continuing, they were requested to return to maximum speed.

After the completion of a 5-minute trial, participants gave ratings on the SSQ symptoms within VR.

Apparatus. HMD. VR was presented on an Oculus Rift Consumer Edition 1 HMD. The Oculus Rift has two lenses that render two separate displays with a screen resolution of 1080 × 1200 pixels, totaling to a 110° field of view. Screens refresh at a rate of 90 Hz. Head position and orientation are tracked with an accelerometer, a magnetometer, a gyroscope, and an additional constellation tracking camera. The interpupillary distance of both lenses was adjustable in a range from 57 to 71 mm. Participants were instructed to adjust the distance between lenses until they suited their respective interpupillary distance.

Virtual scenery. The virtual environment consisted of an island landscape with trees, grass, and stones represented by three-dimensional models and realistic textures. It was built in-house using the Unity game engine (v5.4.0p3) and was used in previous studies (Mittelstaedt et al., 2018).

Participants experienced the virtual scenery from the view of the cyclist's head, which allowed seeing their arms and parts of the cyclist's body as well as parts of the virtual bike, including the handlebars.

Navigation was only permitted on a network of equidistant paths spread across the island, delimited by fences. All possible paths participants were able to take were comparable in terms of the amount of turns and slopes of the track.

Motion control. The virtual bike was controlled with an Xbox One gamepad. The left joystick was used for steering. Right and left shoulder triggers were used for acceleration and braking, respectively. Bike velocity was capped so that all participants were riding at a comparable speed with similar degrees of optic flow. Symptom ratings were given within VR on a virtual hologram using both shoulder buttons and the A button for confirmation of the given rating.

Due to the possible effects of stance and stance width on sickness (Stoffregen, Yoshida, Villard, Scibora, & Bardy, 2010), participants stood in a standardized position while being immersed in VR with their heels separated by approximately 30 cm.

Simulator Sickness Questionnaire (SSQ). The SSQ (Kennedy, Lane, Berbaum, & Lilienthal, 1993) is the most frequently used self-report questionnaire for both simulator sickness and cybersickness. It was originally developed to assess the degree of simulator sickness in different flight simulators and consists of 16 symptoms, which are rated on a 4-point scale (*none, slight, moderate, and severe*). Scores on each rating were aggregated to form a total score of sickness (SSQ-T) and three sub-scores—Nausea (SSQ-N), Oculomotor (SSQ-O), and Disorientation (SSQ-D)—in accordance with the formulae given by Kennedy et al. (1993).

TABLE 2: Means (Standard Deviations) in SSQ Total Scores of Participants Who Aborted and Completed Both Sessions

Session	Aborted Within 5 Minutes ($N = 7$)	Aborted Between 5 and 10 Minutes ($N = 6$)	Completed ($N = 27$)
Session 1	68.4 (30.1)	64.2 (39.3)	35.3 (33.2)
Session 2	—	100.4 (37.4)	48.1 (45.3)

TABLE 3: Means (Standard Deviations) in the MSSQ, BAQ, and PCS for Female and Male Participants

	Female ($N = 21$)	Male ($N = 19$)
MSSQ	10.8 (7.4)	12.7 (11.0)
BAQ	76.4 (16.6)	82.5 (13.2)
PCS	37.8 (7.5)	34.1 (11.1)

Note. BAQ = Body Awareness Questionnaire; MSSQ = Motion Sickness Susceptibility Questionnaire; PCS = Pain Catastrophizing Scale. None of the questionnaire scores differed significantly between female and male participants.

Results and Discussion

Thirteen of the 40 participants decided to abort the immersion prematurely. Of those 13 participants, 7 aborted the immersion within or after the first session—that is, within the first 5 minutes—and six more aborted within in the second session—that is, between 5 and 10 minutes of immersion. Sickness ratings were taken after 5 and 10 minutes, respectively, for each session or at the time the participant chose to abort. Table 2 shows SSQ Total Scores of participants who aborted and of those who completed both sessions.

Ten of the 21 (48%) female participants aborted (6 in Session 1 and 4 in Session 2), while only 3 of the 19 (16%) male participants ended the immersion prematurely (1 in Session 1 and 2 in Session 2). However, SSQ scores in Session 1 ($M_{\text{female}} = 52.7$; $M_{\text{male}} = 37.4$), $t(37) = 1.379$, $p = .176$, and Session 2 ($M_{\text{female}} = 69.8$; $M_{\text{male}} = 47.4$), $t(22) = 1.299$, $p = .207$, were not significantly different between female and male participants, although female participants tended to give higher ratings.

Additionally, we tested for gender differences in motion sickness history, body awareness, and

pain catastrophizing. Means and standard deviations can be seen in Table 3.

Correlation analyses. We conducted correlation analyses for both sessions between SSQ scores (Total Scores and subscores) and the MSSQ, BAQ, and PCS. As cybersickness scores tend to contain outliers in the upper parts of the distribution, we used Spearman rank correlation coefficients. The results can be seen in Table 4.

The BAQ did not show any significant correlation with the Total Score and neither of the subscores. PCS scores were significantly related to sickness ratings in both sessions and for all subscores except Nausea in the second session, probably because of a reduced number of participants as a result of dropouts in the first session.

Furthermore, in an analysis of the interrelations of the predictors MSSQ, BAQ, and PCS, only the MSSQ and the PCS were significantly correlated with each other ($r = .35$, $p = .028$). None of the remaining predictors were significantly related.

The Interaction of Body Awareness and Pain Catastrophizing

First, we tried to replicate the finding for motion sickness history from Study 1. The main effect of pain catastrophizing could be replicated ($\beta = .38$, $p = .02$), however the interaction between pain catastrophizing and body awareness failed to reach significance ($\beta = -.19$, $p = .18$). However, a similar pattern as in Study 1 is discernible in Figure 2. For the sickness severity scores, we performed two multiple regression analyses, one for each session and included the BAQ and PCS as well as the interaction term between the two as predictors. Predictors and outcome variables were z-standardized. Results of the analyses can be seen in Table 5.

TABLE 4: Spearman Rank Correlation Coefficients Between Simulator Sickness Questionnaire Scores and Cybersickness Predictors

	MSSQ	BAQ	PCS
Total Score (Session 1)	.51***	-.08	.42**
Nausea (Session 1)	.59***	-.24	.45**
Oculomotor (Session 1)	.43**	.00	.34*
Disorientation (Session 1)	.38*	-.04	.33*
Total Score (Session 2)	.61***	-.21	.40*
Nausea (Session 2)	.56***	-.15	.33
Oculomotor (Session 2)	.47**	-.20	.37*
Disorientation (Session 2)	.64***	-.19	.40*

Note. $N_{\text{Session 1}} = 40$; $N_{\text{Session 2}} = 33$. BAQ = Body Awareness Questionnaire; MSSQ = Motion Sickness Susceptibility Questionnaire; PCS = Pain Catastrophizing Scale. The MSSQ was strongly correlated to the SSQ Total Score in both sessions and across all subscores.

* $p < .05$. ** $p < .01$. *** $p < .001$.

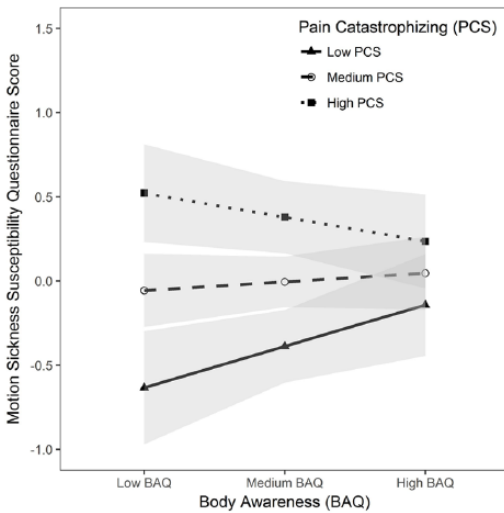


Figure 2. Interaction of BAQ and PCS on the MSSQ scores in Study 2. Lines represent fitted values for low ($-1 SD$), medium (mean), and high ($1 SD$) degrees of BAQ and PCS. Gray areas indicate standard errors.

In both models, the main effect for the PCS was significant. Similar to the correlation analyses, pain catastrophizing was associated with higher levels of cybersickness. The interaction effect between the BAQ and PCS was significant in Session 1. In Session 2, the interaction effect failed to reach significance at an $\alpha = .05$ level possibly due to the reduced sample size and the most susceptible participants aborting

prematurely. The graphical representation of the interaction effect is shown in Figure 3 for Session 1 and in Figure 4 for Session 2.

The interaction plots show that participants with a combination of low body awareness and high pain catastrophizing reported the highest degrees of cybersickness.

Although the interaction term was not significant, the general pattern from Session 1 persisted in Session 2, despite seven participants withdrawing from the immersion before the start of Session 2.

When including gender as a control variable, the overall pattern remains stable, with gender being nonsignificant in both sessions (Session 1: $\beta = -.14, p = .66$; Session 2: $\beta = -.24, p = .47$). However, the interaction effect between BAQ and PCS in Session 1 just misses significance ($\beta = -.27, p = .06$).

We performed two median splits for the BAQ and PCS, respectively, to investigate the group membership of dropouts. Most of the dropouts were from the low BAQ/high PCS group, as can be seen in Table 6. When testing the dropout pattern of the low BAQ/high PCS group against the number of dropouts in the remaining three groups with a χ^2 test, we observed a significantly higher number of dropouts within the low BAQ/high PCS group, $\chi^2(2) = 6.79, p = .03$.

This further supports the suggestion that a combination of high pain catastrophizing and low body awareness has a detrimental effect on the experience of cybersickness.

TABLE 5: Regression Analyses With the Simulator Sickness Questionnaire Total Score as the Dependent Variable in Both Sessions

	β	t	p
Session 1			
BAQ	-.131	.886	.382
PCS	.381	2.597	.014*
BAQ \times PCS	-.280	2.052	.048*
Session 2			
BAQ	-.295	1.736	.093
PCS	.384	2.383	.024*
BAQ \times PCS	-.275	1.806	.081

Note. $N_{\text{Session 1}} = 40$; $N_{\text{Session 2}} = 33$. BAQ = Body Awareness Questionnaire; PCS = Pain Catastrophizing Scale.

* $p < .05$.

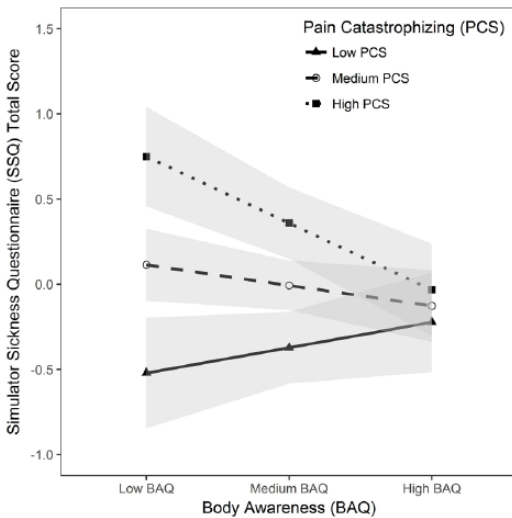


Figure 3. Interaction of BAQ and PCS on the SSQ Total Score in Session 1. Lines represent fitted values for low ($-1 SD$), medium (mean), and high ($1 SD$) degrees of BAQ and PCS. Gray areas indicate standard errors.

GENERAL DISCUSSION

The results reported in the present paper showed a relationship between pain catastrophizing and motion sickness history as well as cybersickness in a VR. Further analyses suggested the relationship to be at least partially

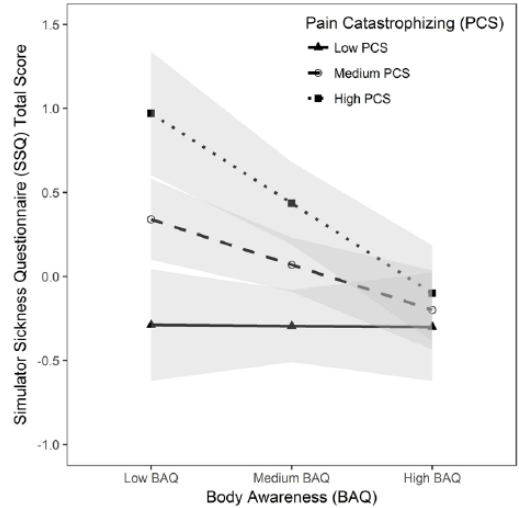


Figure 4. Interaction of BAQ and PCS on the SSQ Total Score in Session 2. Lines represent fitted values for low ($-1 SD$), medium (mean), and high ($1 SD$) degrees of BAQ and PCS. Gray areas indicate standard errors.

moderated by body awareness. The results indicate that people with a combination of high pain catastrophizing and low body awareness are experiencing the most motion sickness on a general basis as well as higher levels of cybersickness when exposed to a VR.

Pain Catastrophizing

The observed negative effect of pain catastrophizing might represent the affective regulation and ruminative thinking about the adverse effects induced by motion-related stimuli suggested by Balaban and Yates (2017). In line with previous research (Van Damme et al., 2004), catastrophizers seem to draw more attention to aversive sickness symptoms and are unable to disengage from them. Since the distraction from the aversive stimulus with mental tasks achieved an improvement in nausea symptoms (Bos, 2015), symptoms seem to worsen as strong catastrophizers keep their attention on the aversive stimulus. Increased attention to the symptoms may lead to an amplification of the symptoms or the appearance of new symptoms.

This role of pain catastrophizing dovetails with findings of relationships of trait anxiety and

TABLE 6: Cumulative Percentage of Dropouts in Relation to Body Awareness Questionnaire and Pain Catastrophizing Scale

	Low BAQ/Low PCS	High BAQ/Low PCS	Low BAQ/High PCS	High BAQ/High PCS
After Session 1	0%	18%	36%	11%
After Session 2	11%	27%	64%	22%

neuroticism with motion sickness severity (Farmer et al., 2015; Fox & Arnon, 1988; Golding, 2006). Several studies have reported large conceptual and empirical overlaps between pain catastrophizing and trait anxiety or neuroticism (Goubert, Crombez, & Van Damme, 2004; Sullivan et al., 1995). All three constructs are known to increase the negative emotional interpretation of events, although pain catastrophizing has been suggested to be a considerably stronger predictor of pain (Sullivan et al., 1995). As it has been assumed that pain catastrophizing is a more general concept also applicable to other adverse stimuli, pain catastrophizing also appears to be a more reliable predictor of motion sickness severity than the more general trait anxiety or neuroticism.

It is highly unlikely that catastrophizing will cause motion sickness. However, in the sense of the definition of pain catastrophizing, it is quite possible that catastrophizing can occur in the perception of physical symptoms, alters the way symptoms are interpreted, and magnifies these by continuous rumination. In the case of past motion sickness history, symptoms of past motion sickness occurrences could have been more severe so that they could be better remembered or high catastrophizers exaggerate the frequency of past incidents and then report them more readily.

The notion that something like catastrophizing is taking place during the experience of motion sickness is supported by correlational brain imaging studies. Investigations of brain activity underlying cybersickness revealed complex patterns of activation, including increased activation in the left amygdala, the pregenual anterior cingulate cortex, the anterior cingulate cortex (ACC), and the right anterior insula (Farmer et al., 2015; Napadow et al., 2013). The ACC also showed differential activation between participants who became sick and those who were resistant to

cybersickness (Farmer et al., 2015). The aforementioned areas are processing stress, emotion, and fear conditioning and support the notion that cybersickness is not a simple bodily reaction to adverse sensory stimuli but undergoes considerable affective and cognitive regulation. Activations of prefrontal areas and ACC have been similarly reported for high catastrophizing individuals when anticipating or directing attention toward pain (Gracely et al., 2004).

The observed relationship of pain catastrophizing and cybersickness (Table 5) or general motion sickness history (Table 1) fits current research on pain processing and supports the assumption that catastrophizing is a general coping tendency in dealing with threatening body perceptions (Devoulyte & Sullivan, 2003).

Since the effects of pain catastrophizing seem to depend on the attribution of the motion stimulus as threatening or not, the influence of catastrophizing can differ depending on the situation. Faugloire, Bonnet, Riley, Bardy, and Stofregen (2007) have found that claustrophobia has a negative effect on motion sickness symptoms but only if the participants were passively restrained. While claustrophobia makes certain situations of passive restraint appear more threatening, (pain) catastrophizing could represent a general tendency of negative interpretation of physical symptoms.

Theoretical Implications

Contrary to our expectation, body awareness did not have a generally beneficial effect on motion sickness severity nor on sickness induced by a VR (Table 4).

However, our results indicate a moderating effect of body awareness on the relationship between pain catastrophizing and sickness, which did not become significant in all analyses.

For high catastrophizing individuals, the results suggest a beneficial effect of body

awareness on the frequency of reportable motion sickness (Figure 1) and the symptom severity of cybersickness (Figure 3). As pain catastrophizing is thought to amplify negative emotional reactions, body awareness might represent the adaptability to such adverse stimuli.

For low catastrophizers, high body awareness as ability to realistically evaluate these symptoms does not seem to have a beneficial effect, probably as there is apparently no negative appraisal to suppress or mitigate.

As with pain catastrophizing, brain imaging studies indicate that interoception takes place during the experience of motion sickness. These studies provided evidence of increased levels of activation in the anterior insula during interoception for heartbeat monitoring (Critchley, Wiens, Rotshtein, Ohman, & Dolan, 2004; Schulz, 2016; Stern et al., 2017), which were similarly found to be activated during increasing levels of nausea induced by visual motion (Napadow et al., 2013). The activation patterns during motion sickness suggest that interoceptive processes contribute to the perception of the syndrome. The present results support the assumption of interoceptive processes being involved in the perception of motion and cybersickness (Balaban & Yates, 2017).

The interaction of body awareness and pain catastrophizing observed in our studies fits an earlier observation on pain and mindfulness, a related but broader construct to body awareness (Mehling et al., 2009). Mindfulness modulated the relationship between pain catastrophizing and pain intensity. Catastrophizing had a stronger adverse effect on pain intensity when mindfulness was low (Schütze, Rees, Preece, & Schütze, 2010). Equally, pain catastrophizing had almost no relationship to pain intensity when participants received a mindfulness-based coping instruction in contrast to being merely distracted from the pain-inducing stimuli (Prins, Decuyper, & Van Damme, 2014).

Individuals with high body awareness might be able to better differentiate between symptoms and to evaluate bodily sensations more realistically. On that note, body awareness and good anticipation of the bodily reaction to motion-sickness-inducing stimuli might suppress a negative appraisal of the symptoms to some extent.

Schütze et al. (2010) proposed that low mindfulness was a precursor for the evolution of catastrophic thoughts about pain. Analogously, low body awareness might be a precursor for the evolution of catastrophic thoughts about sickness symptoms but only among those participants who have a tendency to engage in catastrophic thinking. Therefore, the ability to anticipate the bodily reaction to sickness-inducing stimuli might reduce the negative interpretation of the stimulus.

With regard to gender differences, we were not able to replicate both the catastrophizing (Edwards et al., 2004) and motion-related sickness (Dobie et al., 2001; Munafo et al., 2017) findings. Since we could not identify a gender difference in either measure, it cannot be ruled out that catastrophizing in another sample in which there are differences could be a mediator of gender differences in motion sickness.

Practical Implications

Anxiety and the tendency to catastrophize experienced symptoms of cybersickness should be considered in the application of immersive VRs. Symptoms might be prevented or the severity at least ameliorated if the application of VR in risk groups (e.g., groups with high MSSQ scores) is accompanied by mindfulness interventions highlighting the awareness that these symptoms might occur. A similar cognitive-behavioral therapy approach has already been successfully tested by Dobie, May, Fisher, and Bologna (1989). Participants who are told that motion environments do not necessarily lead to motion sickness and are encouraged to turn their attention away from nausea experienced less motion sickness. Catastrophizers who also have low body awareness may benefit most from such an intervention and can be selected specifically for it.

Future Research

Most importantly, the results presented in this paper are purely correlational. Although there are theoretical approaches to explain the connections found, no causative statements can be made about the exact mechanism associated with catastrophizing, body awareness, and motion-related sickness. Future studies

should try to replicate the present relationships causatively.

Moreover, pain catastrophizing is a construct explicitly targeting the perception and interpretation of pain-inducing stimuli, especially in chronic pain diseases. Symptoms experienced in motion sickness are also adverse but usually not painful. The relationship presented in this paper suggests catastrophizing to be a more general trait in dealing with adverse stimuli, not limited to pain. Future studies should try to incorporate a catastrophizing tendency specific to the symptoms experienced in motion sickness like gastrointestinal or vestibular symptoms.

Finally, body awareness has been assessed with a self-report questionnaire. A different measurement, for instance the ability to correctly estimate one's heart rate, might be considered in future studies to validate the results. Similarly, motion sickness and cybersickness are assessed with self-reports that could be substituted by physiological measurements once they reliably predict motion sickness and cybersickness.

CONCLUSION

Our results suggest that (pain) catastrophizing is a general tendency to appraise adverse and potentially harmful stimuli as more threatening as it is correlated with general motion sickness history and cybersickness severity in VR in the current studies. Furthermore, body awareness seems to modulate the relationship of pain catastrophizing and the experience of sickness.

Catastrophizing and body awareness might be important personal characteristics in modulating experiences and the subjective severity of motion-related sickness.

The results introduce a new concept into the explanation of interindividual differences in motion sickness and cybersickness and show the importance of considering emotional and cognitive modulation.

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KEY POINTS

- Pain catastrophizing is negatively correlated with motion sickness history and actual symptom severity in a VR exposure.
- The relationship of pain catastrophizing and motion-related symptoms is moderated by body awareness. Low body awareness and high pain catastrophizing lead to the highest symptom severity.
- Affective and cognitive modulation of symptoms of motion-related sickness should be considered in the application of potentially adverse stimuli to risk groups.

ORCID ID

Justin Maximilian Mittelstaedt  <https://orcid.org/0000-0002-8419-6842>

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Justin Maximilian Mittelstädt works in the Department of Aviation and Space Psychology at the German Aerospace Center (DLR). He received his MSc in psychology at University of Hamburg in 2014.

Jan Wacker is a professor of psychology at University of Hamburg and received his PhD at the University of Marburg in 2005.

Dirk Stelling works in the Department of Aviation and Space Psychology at the German Aerospace Center (DLR). He received his PhD in psychology at University of Hamburg in 1999.

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Virtual Reality Application

In the VR application the user can ride a virtual bicycle over a small island. This virtual island accommodates a network of paths which have to be used for navigation. The application can be presented either with an HMD or on a normal screen and can be controlled either with a gamepad or a customized bicycle ergometer. In preliminary studies it could be confirmed that it is possible with the application to generate large variance in cybersickness within a short time period of five to ten minutes. Some participants choose to abort the immersion within just a few minutes while others show no symptoms even after ten minutes of exposure.

Display technology.

For the most part, an Oculus Rift Consumer Edition head-mounted display was used to present the virtual environment. The device, also commonly called VR glasses, has two separate displays (one for each eye) with each having a resolution of 1080x1200 pixels and a refresh rate of 90 Hz which totals to a field of view of 110°. The inter-pupillary distance of these two displays is adjustable in a range between 57mm and 71mm which covers the vast majority of the population.

Head-mounted displays have the advantage that physical head movements can be captured using a magnetometer, gyroscope and accelerometer and transferred to the movements of a virtual camera. Thus, in VR, the user always looks in the direction the head is pointing. The Oculus Rift is shown in Figure 6.



Figure 6. The Oculus Rift Consumer Edition head-mounted display.

FACTORS AND COGNITIVE IMPAIRMENTS OF CYBERSICKNESS

Besides the head-mounted display, a large screen was used for one condition in Study 1 of this project. The screen was a commercially available TV screen (Sony Bravia HX75) with a 140cm screen size, a resolution of 1920x1080 pixels and an interpolated refresh rate of 400Hz. While being exposed to the virtual environment on the large screen, participants were wearing a mask with rounded apertures which limited the field of view to a similar degree as the head-mounted display and which masked the physical surroundings of the TV screen. Moreover, the mask was modified with additional lead weights attached to the lower side to match the weight of the head-mounted display. A picture of the mask can be seen in Figure 7.



Figure 7. Mask used with TV screen.

Motion control.

Since the VR application is about controlling a virtual bicycle (see below), a bicycle ergometer was selected as a realistic method of control. The ergometer is a commercially available model that is usually used for training activities. The (magnetic) resistance of the pedals can be adjusted manually via a control computer which also transmits the current pedaling speed of the user. This pedaling speed is then translated by the VR application into the speed of the virtual bicycle. In order to achieve the most realistic riding experience possible, the bicycle rolls out after the pedaling movement has ceased, differently depending on the ascending or descending terrain. The maximum speed is reached at a rather low speed and relaxed pedaling to keep the visual presentation similar for all participants and to exclude the influence of physical exertion. Any pedaling above this maximum speed will not result in an increase of speed.

FACTORS AND COGNITIVE IMPAIRMENTS OF CYBERSICKNESS

Ergometers usually have a fixed handlebar that can be held on to while cycling. In order to enable the steering of the virtual bicycle with the ergometer, a tiltable handlebar has been mounted. Movements of the handlebar are tracked with a motion capturing system, including nine infrared cameras and motion tracking markers at each side and on top of the handlebar, and then translated onto the movements of the virtual handlebar. A handbrake allows the virtual bicycle to be stopped. Figure 8 shows the bike ergometer.



Figure 8. User on the bicycle ergometer.

In addition to the ergometer, the virtual bike can also be controlled with a gamepad (in this case Xbox One). The gamepad has two shoulder triggers, which are located on the upper side and can be conveniently operated with the index fingers. A press on the right shoulder trigger accelerates the virtual bike, while the left trigger can be used for braking. The left analog stick allows the control of the orientation of the handlebar. Since the stick, unlike a real handlebar, often pops back into the neutral position during normal use leading to abrupt riding maneuvers, the virtual handlebar (with gamepad control) programmatically smoothly steers back into straight alignment after a curve was performed.

Virtual application.

The virtual environment was developed using the game engine Unity (v5.4.0p3). Most of the 3D models and textures from the Unity standard distribution were used for the design of the environment and extended by some third party elements. The virtual environment shows an island covered with grass, trees, rocks and a few inaccessible wooden houses. On the virtual island there is a network of sand paths of equal length, delimited by fences on both sides and exclusively intended for navigation by the users. This network can be seen in Figure 9. Users experience this virtual island sitting on the saddle of a bicycle from an ego perspective. The virtual view from the user's perspective is shown in Figure 10.

The virtual bicycle can be moved for navigation as described above and is stopped either as soon as the user has reached a specific destination or the experimenter stops the trial manually. Certain paths can be blocked, forcing the user to follow a specific route, as was done in Study 1.



Figure 9. Path network of the virtual island.



Figure 10. Virtual scenery from the ego perspective of the user.

At the end of a trial, the bike stops and a virtual hologram appears on the handlebar presenting questions that can be answered using either buttons attached to the handlebars or the shoulder triggers on the gamepad (Figure 11). In this project, the questions always consisted of a symptom checklist. However, these can be individually adapted depending on the experiment. This method of querying symptoms during immersion distinguishes this application from most other VR applications used in this research field.

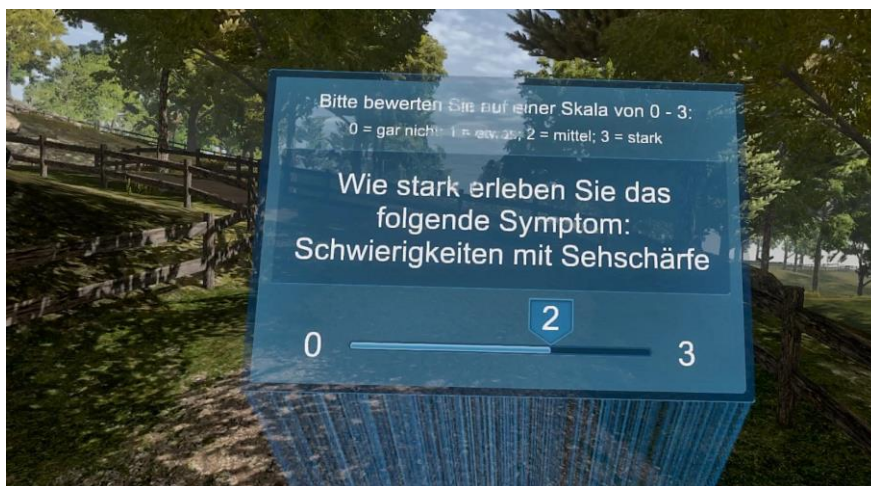


Figure 11. Answering questions within immersion.



Erklärung gemäß (bitte Zutreffendes ankreuzen)

§ 4 (1c) der Promotionsordnung

des Instituts für Bewegungswissenschaft der Universität Hamburg vom 18.08.2010

§ 5 (4d) der Promotionsordnung

des Instituts für Psychologie der Universität Hamburg vom 20.08.2003

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- § 7 (4) der Promotionsordnung des Instituts für Bewegungswissenschaft der Universität Hamburg vom 18.08.2010**
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