The Impact of Motion on Individual Simulator Sickness in a Moving Base VR Simulator with Head-Mounted Display (HMD)

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Abstract. Simulators are increasingly used for training applications. Therefore, it is essential to consider negative side effects like simulator sickness. Influencing factors of simulator sickness are related to the individual, to the system, or to the training design. Our empirical study investigates some of these factors in a 30-min virtual helicopter flight with HMD. 30 subjects (M_{age} = 19.3 years; SD = 4.02) completed the MSSQ (motion sickness susceptibility questionnaire) and the SSQ (simulator sickness questionnaire) before exposure and the SSQ after exposure. The participants received the same treatment on two consecutive days: One day without real motion and the other day with real motion realized utilizing a motion platform. Results show that symptoms of simulator sickness significantly increased directly after VR-exposure. One hour after exposure, the symptoms of simulator sickness are comparable to symptoms before exposure. A difference between the two conditions with real motion and without could not be observed after exposure. Individual motion sickness susceptibility has been identified as a predictor for experiencing simulator sickness. Implications of our findings for the training of helicopter crews and theoretical implications in terms of simulator sickness are discussed.

Keywords: Virtual reality · Virtual training · Helicopter · Simulator sickness · Motion cueing · Moving base simulator · Motion platform

1 Introduction

Advances in Virtual Reality (VR) provide new technical capabilities for advanced education and training. Particularly, costly and inaccessible contents can be trained more effectively and efficiently with VR-HMDs (Head-Mounted Displays). Training of helicopter crews is an example for this. The crew members need special skills to identify and evaluate critical situations especially for difficult rescue missions. This includes the identification of dangerous situations and special risks in the environment. In general, VR provides a natural immersion in a computer-generated environment and, thus, a close link to training content. VR is a promising technology, which has the ability to immerse users and, thus, creates a sense of presence. Nevertheless, negative side effects like simulator sickness are still present and limit practical applicability.

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2 Related Work

Simulator sickness is a special form of motion sickness. Both forms have in common that negative after-effects occur. However, after-effects are triggered through different components of the human sensory system. Motion sickness is evoked through the movement of a vehicle, ship, aircraft or any other moving object. The movement stimulates the human's vestibular system. In contrast to motion sickness, simulator sickness is not necessarily triggered by the movement of the body, but by a conflict between the vestibular system and the visual system. Unpleasant symptoms can also occur due to visual stimulation in a fixed base simulator [1]. Hence, the symptoms are rather induced visually.

2.1 Measuring and Predictors of Symptoms

Symptoms of motion sickness and simulator sickness are quite similar and implicate symptoms like eyestrain, headache, sweating, disorientation and nausea [2].

Kennedy et al. [3] analyzed the occurrence of simulator sickness symptoms in VR systems and found that symptoms can be split in three symptom groups: oculomotor stress, nausea, and disorientation. Based on their findings they developed a simulator sickness questionnaire (SSQ) [2], which has since then become the most popular instrument to gather data about symptoms experienced after simulator exposure. Several attempts to develop instruments that are capable to measure symptoms during exposure did not achieve satisfactory results. Changes in psychophysiological indicators such as heart rate, skin conductivity, stomach activity and blinking are also likely to occur with increased sickness [4, 5]. However, the direction of change for most physiological measures of simulator sickness differs among individuals [6]. A great need for research and development of cost-effective and objective physiological measures still persists [7].

Different factors contribute to adverse health effects of using virtual environments. Factors influencing simulator sickness include system factors, application design factors and individual user factors [6]. Examples for system factors are latency, calibration, field of view, refresh rate or the use of motion systems in simulators. Application design refers to the training design of virtual reality applications like the duration or frequency of training or the movement in VR, e.g. head movement, standing/walking vs. sitting. Individual user factors include for instance gender, age, mental models, and health. Another individual user factor is the prior history of motion sickness, which is known as the best predictor for experiencing simulator sickness in simulator-based training [8]. The motion sickness susceptibility questionnaire (MSSQ) predicts individual differences in motion sickness caused by a variety of stimuli in the user's past experiences [9].

2.2 Theories of Simulator Sickness

Three common theories exist in literature referring to the causes of simulator sickness: the poison theory, the postural instability theory, and the sensory conflict theory [10]. These three theories had originally been developed for motion sickness and later transferred to simulator sickness. The poison theory by Treisman [11] attempts to explain sickness symptoms from an evolutionary point of view. It holds that the adverse stimulation of vestibular and visual system triggers mechanism that evolved to prevent poisoning. Hence, unpleasant symptoms are caused by alleged poisoning. The postural instability theory developed by Riccio and Stoffregen [12] states that symptoms are caused by a loss of postural control. The duration of the postural instability influences the severity of symptoms. The sensory conflict theory is the most popular theory. Many authors agree that simulator sickness is caused by a mismatch of senses. The theory has been originally developed by Reason and Brand [10]. An example for a sensory conflict can be found in virtual reality applications in general: Wearing a VR-HMD - flying with a virtual helicopter - and sitting on a stationary chair at the same time, induces a sensory conflict. The user is moving in the virtual environment, but not in the real world.

Thus, the movement is induced visually and not vestibular. The optical flow patterns of the surrounding landscape passes by and creates a sense of self-motion. Visually induced illusory self-motion is known as vection, which is a precondition for simulator sickness [13]. To sum up, visual stimulation is present in virtual reality applications while vestibular stimulation might be absent. According to the sensory conflict theory the discrepancy between what is seen and what is felt triggers unpleasant symptoms.

2.3 Impact of True Motion on User's Simulator Sickness

Since the sensory conflict theory is the oldest and most influential theory, our work focuses on how to reduce simulator sickness within the framework of sensory conflicts. To reduce sensory conflicts the usage of motion simulators is a suitable option. A combined system of VR-HMDs and a motion platform is capable to provide corresponding visual and vestibular input.

Casali was the first researcher who introduced motion platforms to reduce simulator sickness [14]. However, he reported that in some cases real motion can be helpful to reduce the severity of symptoms and in other cases it is not. This is in line with other studies conducted in the last century that provides ambiguous findings. In past studies, users suffered from simulator sickness symptoms, although motion platforms were used [15, 16]. A possible explanation is that the motion platforms were not aligned correctly with the visual input. Another explanation is true motion sickness. This means that the sickness is motion-induced and not a result of sensory conflicts [10].

Nevertheless, anecdotal evidence from practice exists, that pilots and instructor operators agree that flying with the motion system turned off induced more sickness [17, 18]. In another study (Miller and Goodson, 1958) [cited by 19] the authors found that 75% of experienced pilots suffered from simulator sickness symptoms when the motion platform was turned off whereas 10% reported symptoms when the motion platform was turned on. The authors implicate that these effects might be only true for experienced pilots since they are used to motion.

More recent studies provided evidence that an activated motion system is able to reduce simulator sickness symptoms [20, 21]. These results are still discussed, since the same authors also found contradictory result [21]. Moreover, the validity of Curry's study is limited, because two simulators were compared that also differed in other features than motion [20].

Stein and Robinski compared different simulators and found that simulators with motion platforms are more likely to evoke simulator sickness symptoms [22].

McCauley draws the conclusion that there is no reliable evidence that using motion platforms prevent simulator sickness. Nonetheless, true motion contributes to the realism of the simulation and, therefore, positively influences the pilot's acceptance of simulators [23].

The scientific evidence for the sensory conflict theory is far from clear. Continuous research in this field is essential, since research results are ambiguous and the rapid technology progress limits a simple transfer of results from older studies. Furthermore, new investigations are crucial because above-mentioned studies did not analyze the impact of virtual reality HMDs as a COTS technology in combination with motion platforms.

2.4 Temporal Aspects of Simulator Sickness

Many studies explored the occurrence and the increase and decrease of simulator sickness symptoms over time. When studying the impact of motion on the severity of symptoms it is also important to examine the impact before and after exposure. It is important to check whether simulator sickness symptoms occur before analyzing if motion affected symptoms. Moreover, it is interesting to know when the symptoms will disappear. Examining the severity of symptoms over the time can also be beneficial for detecting interaction effects between motion and point of time.

An article by Dużmańska et al. reviews 39 different studies about temporal aspects of simulator sickness [24]. They found that severity of the simulator sickness increases with time of exposure. Likewise, the persistence of the symptoms varies between 10 min and even 4 h depending on the individual studies and the duration of VR exposure. Although there is a clear connection between duration of exposure and persistence of the symptoms, it is impossible to develop a single, universal pattern for this effect. Thus, the authors recommend to test time courses for each VR technology separately. For example, a study with a ship motion simulator, participants received a 30-min simulator exposure [25]. Within one hour, most participants fully recovered from the simulator sickness symptoms.

2.5 Study Objectives

The current study examines the impact of motion on individual simulator sickness in a moving base VR simulator. We use modern virtual reality HMDs for a novel investigation of the sensory conflict theory. Furthermore, we analyze the time course of the simulator sickness decline and the prediction of simulator sickness through motion susceptibility history.

3 Method

We conducted an empirical study to examine the impacts of different variables on simulator sickness. This section describes sample, procedure and design as well as materials and measures.

3.1 Sample Description

30 subjects, 28 men and 2 women, volunteered in our study with a mean age of 19.3 years (SD = 4.02). Most of the subjects were particularly interested in video games (28). 18 subjects stated that they play video games several times a week. They had no experience in helicopter flying and little VR experience. Analyzing the motion sickness susceptibility by the MSSQ revealed that participants had an average score of 4.74, which is a relatively low score compared to the norms Golding [9] reported (M = 12.9, SD = 9.9). A necessary precondition was a normal or a corrected to normal vision, which was tested beforehand. All subjects participated in both conditions (motion, no motion).

3.2 Procedure

Prescreening took place on the first day and consisted of eyesight testing, ratings of the SSQ and the MSSQ. After prescreening subjects received a 5 min VR-training followed by the 30-min exposure. The SSQ was used to collect data on simulator sickness symptoms before and directly after and one hour after VR-exposure. The interval of one hour was chosen because based on the findings of [25] it was likely that the symptoms would have disappeared one hour after VR-exposure. The Motion Sickness Susceptibility Questionnaire (MSSQ) was administered to detect individual vulnerabilities. During VR-exposure, the participant is in the right rear part of the virtual helicopter. While looking out from the helicopter's side door, participants completed visual search- and working memory tasks. In the real world the subject knelt on a motion platform and pressed buttons on an input device (see Fig. 2). The participants received the same treatment on two consecutive days: One day without real motion and the other day with real motion realized using a motion platform. We named these conditions: motion vs. no motion. Conditions were counterbalanced for the two days. On the second day, the subjects were asked after exposure which condition they preferred either motion or no motion. The entire procedure is illustrated in Fig. 1.

3.3 Experimental Design

Two independent variables were defined for a 2 $\times$ 3 repeated measures ANOVA. The first independent variable was motion with two levels (motion/no motion). The second was point of time (before, after, and 1 h after). Besides analyzing the focal independent variables, we also examined the effect of motion sickness susceptibility (MSSQ) as a predictor for simulator sickness. Altogether, we analyzed how motion, point of time, and motion sickness susceptibility influences the dependent variable simulator sickness.

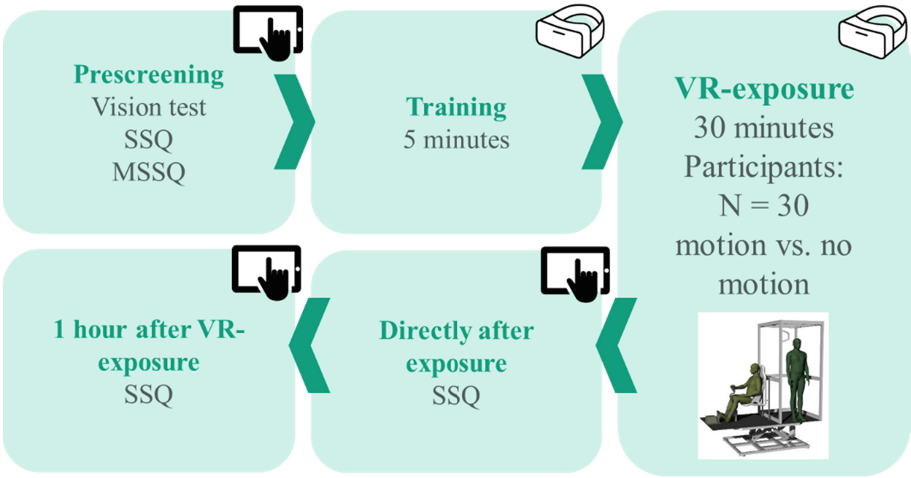

Fig. 1. Illustration of the experimental procedure.

3.4 Apparatus and Measures

Technical Specifications of the Apparatus

For our experiment, we set up an experimental demonstrator including a motion platform, a VR-HMD and the virtual simulation itself. The construction on the motion platform was self-built (see Fig. 2). The virtual simulation was developed using the software VBS3 from Bohemia Interactive Simulations [26]. For displaying the simulation, the Oculus Rift CV1 was used as a popular low-cost VR-HMD [27]. The motion base *6 DoF Electrical Motion System* by Brunner [28] was used to provide real motion analog to the virtual simulation.

The motion system provides heave, pitch, roll, yaw, surge, and sway movement, as well as a combination of all of them. Movement information were transferred from simulation framework to the motion base with a transfer rate of 60 Hz. Scientific experience indicates that, in practice, it is not necessary to update faster than 60 Hz [29]. Testing our experimental demonstrator for any physical thresholds in terms of velocity and acceleration shows that the motion system is able to perform 97 to 99.5% of all the movements timely and correctly. In pretests subjects stated that they did not recognize any mismatches between visual and vestibular input.

Questionnaires

SSQ scores were calculated according to Kennedy et al. [2]. 16 different somatic symptoms were rated from *none* to *severe*, which corresponds to values from 0 to 4. The single symptoms and their severity ratings (0, 1, 2, 3) were sorted into subscales: nausea, oculomotor distress, and disorientation. Values for each subscale were summed up and weighted. The total score was calculated by multiplying the summed subscale values by 3.74.

The short form of the MSSQ, which was applied, asks for the previous sickness occurrences in cars, buses, trains, aircrafts, small boats, large ships, swings,

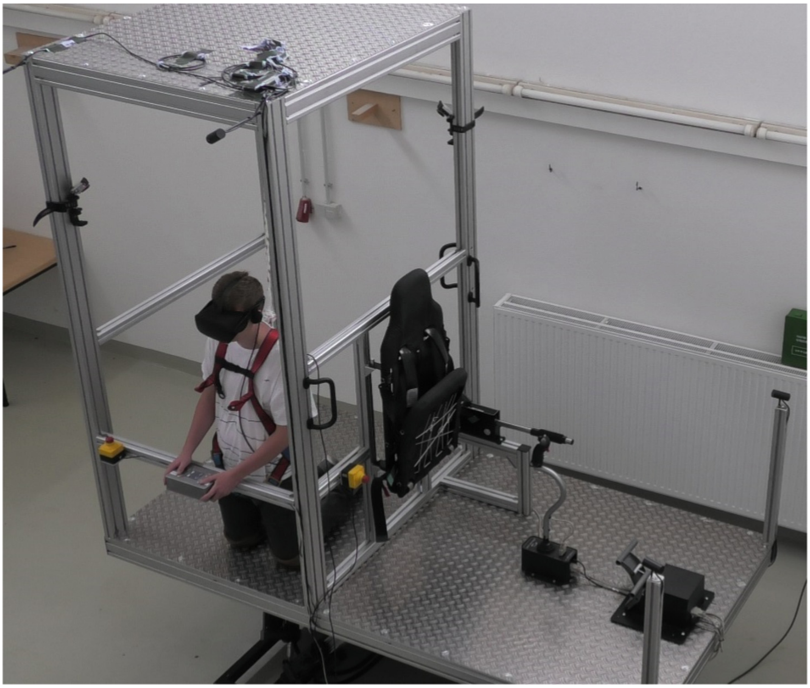

Fig. 2. Picture of the experimental demonstrator with subject.

roundabouts in playgrounds, and leisure park attractions. Subjects can rate their experiences by ticking one of these options: not applicable/never travelled, never felt sick, rarely felt sick, sometimes felt sick, and frequently felt sick. It asks separately for childhood experiences before age 12 and the experiences over the last 10 years. Calculation of the total scores followed the instructions of Golding [9]. In his initial sample the median score was 11.3, 25th percentile was 5.5, and 75th percentile was 19.0.

4 Results

In the following sections statistically significant results are marked with * for $p < .05$, ** for $p < .01$, and *** for $p < .001$. SSQ scores were found not to be normally distributed due to a broad range of individual symptom severity. Nonetheless, parametric analyzing methods were applied since ANOVAs are relatively robust to violations of normality [30]. The reported degrees of freedom were corrected according to the Greenhouse-Geisser procedure.

4.1 Impacts of Motion and Point of Time

Results of a repeated measures ANOVA revealed a significant main effect of point of time for the SSQ total score, $F(1.41, 39.33) = 19.00$, $p < .001$, $\eta^2 = .40$, for the subscale nausea, $F(1.59, 44.36) = 11.91$, $p < .001$, $\eta^2 = .30$, for the subscale oculomotor, $F(1.41, 39.55) = 16.06$, $p < .001$, $\eta^2 = .36$ as well as for disorientation, $F(1.65, 46.05) = 11.61$, $p < .001$, $\eta^2 = .29$. Follow-up pairwise comparisons are depicted in Fig. 3.

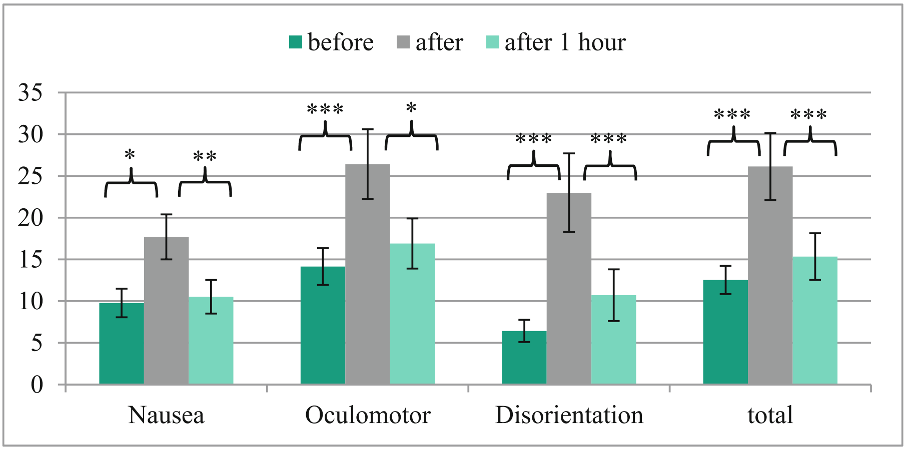

Fig. 3. Means and standard errors of simulator sickness symptoms before, after and 1 h after VR-exposure.

Neither a main effect of motion nor an interaction effect of motion and point of time was found to be significant. Hence, we could not detect any significant differences between motion and no motion in any of the SSQ scales (see Fig. 4).

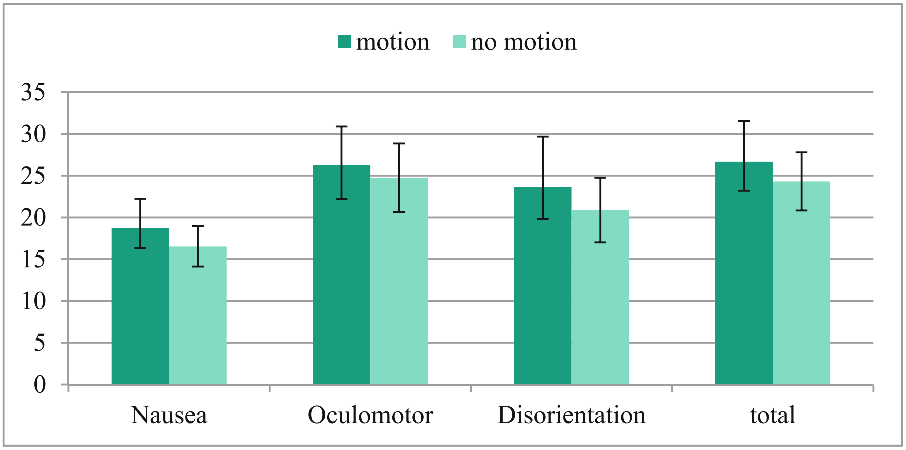

Fig. 4. Means and standard errors of simulator sickness symptoms for motion and no motion.

The evaluation of the subject's preference showed that 26 subjects (87%) favored the condition which included real motion generated by the motion system. According to most subjects the simulation felt more realistic when the motion system was applied.

4.2 Motion Sickness Susceptibility

A moderated regression was conducted to examine whether the predictors motion susceptibility and motion, or their interaction influence total SSQ scores. Predictors were mean-centered to reduce multicollinearity and z-transformed. The assumption of homoscedasticity was graphically checked. The overall model revealed to be significant, $F(3, 56) = 6.52$, $p > .001$, $R^2 = .26$. MSSQ scores were found as a significant predictor of simulator sickness scores, $\beta = .48$, $p < .001$ (see Fig. 5).

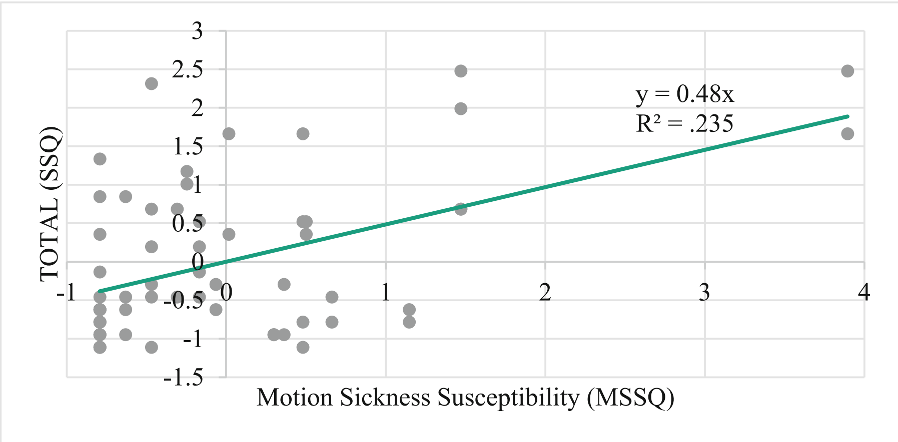

Fig. 5. Predicted simulator sickness symptoms as a function of motion sickness susceptibility.

Regarding the contribution of each individual predictor, motion revealed to be a non-significant predictor, $\beta = -.10$, $p = .653$. The interaction of both predictors does not explain a significant portion of the variance over and above the criterion, $\beta = -.29$, $p = .209$.

To sum up, individual motion sickness susceptibility was found as a predictor for experiencing simulator sickness. We could not find any evidence for a moderating function of motion on simulator sickness.

5 Discussion and Conclusions

The objective of the current study was to investigate the impact of motion on individual simulator sickness in a moving base VR simulator. We could not find any differences in simulator sickness for applying or not applying a motion platform. Thus, we cannot provide evidence for the sensory conflict theory. Past studies provided ambiguous results for using a motion platform to reduce simulator sickness as described in Sect. 2.3. Most of these studies are only partially comparable to our approach due to the age of the studies and other technical specifications of the simulator systems. That is why we discuss our results in a theoretical framework. Assuming the sensory conflict theory holds there are some possible explanations why we did not find differences between motion and no motion. One reason might be that our motion platform was not aligned correctly with the visual input. This should not apply to our simulation as explained in Sect. 3.4. Another explanation for the occurring sickness could be *true motion sickness [10]*. To test this explanation we intend to include real helicopter crews for our future research. They are familiar with real helicopter movements and may suffer less from motion sickness. Nonetheless, it should be emphasized that the real movement through the motion platform did not show any negative effects on simulator sickness. Moreover, the subject's preference clearly indicates advantages for the use of motion platforms in training. Since our results did not provide any evidence that real motion leads to increased severity of sickness the application of the used system is recommended with an activated motion system.

Furthermore, we detected that one hour after exposure the simulator sickness symptoms decreased to normal. It is pointed out that these results only apply to our simulation and thus are not transferable to other simulators. Further research can analyze the exact course of time for the sickness decrease by asking for the symptoms at shorter intervals. In general, it is highly recommended to measure the duration of simulator sickness decline for every new simulator in order to adapt the training design.

Motion sickness history is known to be one of the best predictors for simulator sickness [8, 9]. This is in line with our findings that motion sickness susceptibility is a predictor for simulator sickness symptoms right after VR-exposure. We could not detect any moderating function of motion for the relation between motion sickness susceptibility and simulator sickness. Thus, in our study an individual factor explains most of the variance in simulator sickness.

We conclude that interindividual variability seems to outweigh the effect of motion as system factor. Since interindividual factors are not adaptable, further research is needed in areas of system and training factors. It would be especially interesting to learn under which circumstances real motion is beneficial for the prevention of simulator sickness.

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