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The best way to assess visually induced motion sickness in a fixed-base driving simulator

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A B S T R A C T

Objective: Driving simulator usage is becoming more widespread, yet many users still experience substantial motion sickness-like symptoms induced by optical flow, called visually induced motion sickness (VIMS). The Fast Motion sickness Scale (FMS) allows for continuous on-line assessment of VIMS. Using mixed models for ordinal data, this study investigated how to optimally analyze FMS data, and then used the resulting models to examine the development of symptoms over time in detail. Additionally, the study explored the impact of specific VIMS-inducing road elements.
Methods: Twenty-eight healthy young adults without prior simulator experience completed six courses on two days in a fixed-base driving simulator. VIMS severity was reported every minute using the FMS. Each course included two road elements designed to induce VIMS. The data was analyzed using cumulative link mixed models.
Results: The FMS data deviated clearly from a normal distribution. Treating FMS data as ordinal led to preferable models compared to models assuming interval scale. VIMS increased within each drive and over consecutive courses, but decreased between two days separated by a week (adaptation). Adaptation was attributable to less pronounced symptom increases on the second day, both within each course and between consecutive drives. VIMS increases within each drive were less pronounced during later courses of each day (habituation). Participants differed both in general symptom levels and in their progressions of VIMS over time. Additionally, VIMS-inducing road segments could be identified as leading to higher probabilities of symptom increases.
Conclusion: Mixed models analyses of FMS data from repeated VIMS measurements can benefit from taking deviations from normal distribution and interval scale into account. The gained insights into habituation and adaptation processes, as well as into the impact of specific road elements, can help in planning and conducting future driving simulator experiments.

Abbreviations: VIMS, visually induced motion sickness; FMS, fast motion sickness scale; ANOVA, analysis of variance; AIC, Akaike information criterion.

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1. Introduction

Simulators become increasingly important in industrial and scientific research, because they can provide a safe environment for complex test scenarios with high situational control and reproducibility. They enable us to gain experience with situations that are too dangerous or too infrequent outside the simulator, e.g., driving under the influence of alcohol, medication, or sleep deprivation (Muttray et al., 2013). On the other hand, the usage of simulators can adversely affect the operator's well-being, causing motion sickness-like symptoms, referred to as simulator sickness. Understanding what factors influence simulator sickness and how it develops over time can help simulator operators develop strategies that can reduce the occurrence of such undesirable side effects.

1.1. Simulator sickness and related concepts

Both moving and fixed-base simulators can cause simulator sickness in susceptible individuals. Typical symptoms include nausea, dizziness, eye strain or, in severe cases, even vomiting. When motion sickness-like symptoms are due to optic flow and without requiring physical motion, they are called visually induced motion sickness (VIMS; Keshavarz, Hecht, & Lawson, 2015). These adverse effects can last from minutes to several hours after exposure depending on the subject and the severity of the symptoms (for an overview of VIMS, see Keshavarz et al., 2015). As we conducted our experiment in a fixed-base driving simulator, we refer to the symptoms participants reported in our experiment as VIMS.

Reports about intensity and type of simulator sickness symptoms show influences of individual susceptibility including transient changes of fitness, the kind of simulation (simulator setup and simulation design), but also by the experimenter's measurement criteria (Kolasinski, 1995; Lawson, 2015). The symptoms of motion and simulator sickness worsen with increasing duration of exposure (Keshavarz & Hecht, 2011; Kolasinski, 1995; Lawther & Griffin, 1986). Both relatively constant and very rapid increases have been reported, the latter also after a certain level of discomfort had been reached (Bock & Oman, 1982; Davis, Nesbitt, & Nalivaiko, 2015; Reason & Graybiel, 1970b). Consequently, the incidence of simulator sickness differs considerably between studies, ranging from 10 to 90% (Kolasinski, 1995; Lawson, 2015).

Two mechanisms influence the development of simulator sickness over time, habituation, understood as a short-term reduction of symptoms following exposure without lasting effects, and adaptation, here seen as a long-lasting decrease of participants' susceptibility (for an overview see Keshavarz et al., 2015). Both habituation and adaptation to a nauseating environment including moving and fixed-base driving simulators have been shown to reduce symptoms of motion sickness (Golding & Stott, 1995; Howarth & Hodder, 2008; Kennedy, Stanney, & Dunlap, 2000; Mackrous, Lavallière, & Teasdale, 2014; Reason & Graybiel, 1970a; Watson, 2000). There is considerable variability between subjects (McCauley, Royal, Wylie, O'Hanlon, & Mackie, 1976). Some sensitive participants are not capable of adapting to inertial motion (Tyler & Bard, 1949). Even increased sensitivity due to repeated exposures to visual stimuli applied with a head mounted display has been reported (Howarth & Hodder, 2008).

Another influence on simulator sickness severity relates to the design of the driving scenario. The literature indicates that design decisions, such as the inclusion of sharp turns, may lead to an increase in symptoms (Stoner, Fisher, & Mollenhauer, 2011). In their review, Classen, Bewernitz, and Shechtman (2011) evaluated the impact of "Context and Environment Factors" to be "probably predictive" (p.181) of simulator sickness. However, attempting to evaluate the impact of particular road characteristics in a naturalistic driving context is difficult and previous studies often included confounded design choices, such as simultaneous variation of road curvature and visual complexity of the scene (Mourant, Rengarajan, Cox, Lin, & Jaeger, 2007; Park, Allen, Fiorentino, Rosenthal, & Cook, 2006). More importantly, the standard tool to assess VIMS and simulator sickness, the Simulator Sickness Questionnaire (SSQ; Kennedy, Lane, Berbaum, & Lilienthal, 1993), comprises 16 items. As it takes too long to administer repeatedly during a drive, it has a very low temporal resolution. Alternative approaches to motion sickness assessment have been explored in various studies both during exposure to nauseating stimuli and afterwards (Bagshaw & Stott, 1985; Bles, de Graaf, Bos, Groen, & Krol, 1997; Bock & Oman, 1982; Diels & Howarth, 2013; Garrick-Bethell, Jarchow, Hecht, & Young, 2008; Golding, Mueller, & Gresty, 2001). Out of these self-assessment scales, only the Fast Motion Sickness Scale (FMS; Garrick-Bethell et al., 2008) has been validated against the SSQ (Keshavarz & Hecht, 2011). As it consists of only a single question concerning the user's symptom level with responses ranging from 0 to 20, the FMS offers the great advantage of frequent, repeated symptom assessments. This could in principle be used to closely monitor the development of symptoms during any given test run, and allows for a cut-off criterion (e.g. a score of 15) to prevent frank sickness (Keshavarz & Hecht, 2011).

Besides monitoring the driver's status during simulator usage, this study investigates whether quick repeated assessment can also be useful in studying VIMS and simulator sickness in greater detail. The FMS' fine-grained ratings could reveal both habituation and adaptation processes, which this study investigated by monitoring the development of VIMS over the course of several days of simulator usage, with several simulated drives on each day. Additionally, the study used the FMS to evaluate the impact of specific road segments on VIMS. For these purposes, it needs an analysis strategy that can efficiently make use of dense information contained in the FMS data. Here, we propose a mixed-effects regression model based analysis strategy to address the temporal progression of VIMS in detail. This approach is explored in the next section.