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Comparing simulator sickness in younger and older adults during simulated driving under different multisensory conditions

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Driving simulators are valuable tools for traffic safety research as they allow for systematic reproductions of challenging situations that cannot be easily tested during real-world driving. Unfortunately, simulator sickness (i.e., nausea, dizziness, etc.) is common in many driving simulators and may limit their utility. The experience of simulator sickness is thought to be related to the sensory feedback provided to the user and is also thought to be greater in older compared to younger users. Therefore, the present study investigated whether adding auditory and/or motion cues to visual inputs in a driving simulator affected simulator sickness in younger and older adults. Fifty-eight healthy younger adults (age 18–39) and 63 healthy older adults (age 65+) performed a series of simulated drives under one of four sensory conditions: (1) visual cues alone, (2) combined visual + auditory cues (engine, tire, wind sounds), (3) combined visual + motion cues (via hydraulic hexapod motion platform), or (4) a combination of all three sensory cues (visual, auditory, motion). Simulator sickness was continuously recorded while driving and up to 15 min after driving session termination. Results indicated that older adults experienced more simulator sickness than younger adults overall and that females were more likely to drop out and drove for less time compared to males. No differences between sensory conditions were observed. However, older adults needed significantly longer time to fully recover from the driving session than younger adults, particularly in the visual-only condition. Participants reported that driving in the simulator was least realistic in the visual-only condition compared to the other conditions. Our results indicate that adding auditory and/or motion cues to the visual stimulus does not guarantee a reduction of simulator sickness per se, but might accelerate the recovery process, particularly in older adults.

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1. Introduction

Driving simulators are used for driver assessment and training as well as for automobile design and research. Arguably, the biggest advantage of driving simulators compared to on-road driving is their ability to reliably reproduce challenging or dangerous driving conditions that might be more likely to result in collisions (e.g., poor weather conditions, medication use, drowsiness, etc.), but with no risk of physical injury (Evans, 1991; Kearney & Grechkin, 2011) and to be able to maintain control over the experimental conditions. A major limitation associated with the use of driving simulators is the risk of causing simulator sickness, a specific type of motion sickness. The symptomatology of simulator sickness is similar to traditional motion sickness and can include pallor, cold sweat, fatigue, dizziness, nausea, and/or vomiting (see Kennedy, Drexler, & Kennedy, 2010; Keshavarz, Hecht, & Lawson, 2014a). The incidence of simulator sickness varies widely (Brooks et al., 2010; Classen, Bewernitz, & Shechtman, 2011) and reported rates range from less than 1% (e.g., Klüver, Herrigel, Heinrich, Schöner, & Hecht, 2016) to 60% (Stanney, Kennedy, Drexler, & Harm, 1999) depending on various factors such as the simulation task, the features of the simulator, and the characteristics of the individual users (Roe, Brown, & Watson, 2007; Stoner, Fisher, & Mollenhauer, 2011). Importantly, the extent to which these technologies can be successfully used across their many potential applications depends significantly on the extent to which adverse side effects can be avoided. In the context of driving simulation research, for instance, simulator sickness can have a financial impact (e.g., due to high drop-out rates resulting in extra costs for lab time and additional participant recruitment), but can also affect driving performance outcome measures (e.g., Mullen, Weaver, Riendeau, Morrison, & Bedard, 2010). In addition, simulator sickness may cause aftereffects, lasting for hours or even days, which can impair participants' daily life activities (e.g., Muth, 2009; Stanney et al., 1998; Stanney et al., 1999). In other words, the prevalence and severity of simulator sickness creates a major barrier to the adoption of simulators for the purposes of research, training, and assessment where they could otherwise be highly beneficial.

To date, the underlying mechanisms associated with simulator sickness are still not well characterized (for a discussion of different theoretical approaches see Keshavarz et al., 2014a). One of the most common theoretical frameworks is the sensory conflict theory (Oman, 1990; Reason, 1978; Reason & Brand, 1975), which proposes that simulator sickness is caused by a novel mismatch between or within the visual, vestibular, and somatosensory senses. Visual–vestibular conflicts, for instance, are common in fixed-base driving simulators, for which the visual system is indicating self-motion and the vestibular/somatosensory senses are signaling stasis. However, although sensory conflict can potentially lead to motion sickness under some conditions, there are many instances in which it does not. For instance, the majority of participants who experience illusory self-motion in the absence of physical movement (i.e. vection; Brandt, Dichgans, & Koenig, 1972; Hettinger, Schmidt, Jones, & Keshavarz, 2014) do not become sick, despite the arguable presence of a sensory conflict (see Keshavarz, Riecke, Hettinger, and Campos (2015), for a discussion). According to the sensory conflict theory, eliminating multisensory conflicts should reduce the risk of simulator sickness. Thus, in the context of driving simulation, a motion-base simulator that generates somatosensory and vestibular inputs that are similar to those experienced during real-world driving (e.g., otolith stimulation during acceleration or braking and/or semicircular canal stimulation during turning) and that are congruent with the associated visual inputs should lead to less simulator sickness compared to a fixed-base simulator that does not include motion cues. However, empirical evaluations of this assumption have provided mixed evidence (e.g., Hettinger, Berbaum, Kennedy, Dunlap, & Nolan, 1990; McCauley & Sharkey, 1992). In support of the sensory conflict theory, Curry, Artz, Cathey, Grant, and Greenberg (2002) asked a total of 151 participants to drive either a fixed-base or a motion-base driving simulator and found significantly reduced simulator sickness when the simulator contained motion cues. In contrast, Klüver, Herrigel, Preuss, and Hecht (2015) tested more than 200 participants on five different driving simulators, including two motion-base driving simulators and three fixed-base driving simulators, and reported no differences in simulator sickness across the five simulators. However, providing motion cues was not the only difference between the fixed-base and motion-base simulators in these studies and potentially confounding variables were present. For instance, the horizontal field-of-view (FOV; 180° vs. 140°) and the amount of motion delay (i.e., delay between steering input and motion response) varied between the fixed-base and motion-base simulator in Curry et al. (2002), and the FOV and picture resolution were different between the simulators used in Klüver et al. (2015). Because FOV and motion delays are also known to affect simulator sickness (Keshavarz, Hecht, & Zschutschke, 2011; Moss & Muth, 2011), it is not entirely clear whether the results found in these earlier studies can be attributable to the presence or absence of motion cues per se. One goal of the present study was to fill this gap by evaluating participants' simulator sickness ratings when the exact same driving simulator and the exact same driving scenarios were used to test conditions under which (a) the motion system was activated and (b) the motion system was deactivated (stationary position).

In contrast to the effects of combining visual and physical motion cues on the experience of simulator sickness, research assessing the effects of combining visual and auditory cues is comparatively sparse. The few studies that have investigated the role of background sounds (e.g., ambient cues) on simulator sickness did not find differences in sickness severity when background sounds were present versus absent (e.g., Keshavarz & Hecht, 2012a; Nichols, Haldane, & Wilson, 2000). However, the sounds used in these studies were rather simple (e.g., street traffic noise, background chatter, in-game sounds) and did not provide information specifically related to changes associated with self-motion per se. Keshavarz, Hettinger, Kennedy, and Campos (2014b) demonstrated that auditory cues alone can also generate feelings of motion sickness in some participants under certain circumstances. Specifically, they showed that when participants were blindfolded and exposed to auditory cues that rotated along the yaw axis, when asked to tilt their head to their right or left shoulder, some participants