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Optical Correction Reduces Simulator Sickness in a Driving Environment

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Objective: We propose and test a method to reduce simulator sickness.

Background: Prolonged work in driving simulators often leads to nausea and other symptoms summarized as simulator sickness. Visual/vestibular mismatches are a frequently addressed cause; we investigate another possibility, mismatch between actual distance to a screen and depicted distances in the simulator's graphics.

Method: Drivers negotiated a figure-8 course in a photorealistic simulator. They reported discomfort and vection every 10 minutes up to 40 min. A correction group wore optometric test frames with +1.75 diopter lenses and prisms to converge parallel lines of sight on a screen 56 cm from the driver's eyes, preserving the normal accommodative convergence–to–accommodation (AC/A) ratio. A control group wore neutral lenses in the same test frames. In other experiments head tilt simulated vestibular experience on curves.

Results: The optical correction significantly reduced simulator sickness measured on a 10-point discomfort scale, where 1 is no problem and 10 is about to vomit. Vection ratings were similar for correction and control groups. Some drivers failed to complete the course because of high discomfort ratings, crashes, or other causes. Head tilt in the direction opposite each curve while wearing the correction did not affect discomfort, while tilt in the same direction as each curve made simulator sickness worse.

Conclusion: Optical corrections can significantly reduce simulator sickness, though they do not eliminate it. Head tilt while driving is not recommended.

Application: Simple optical corrections in spectacle frames, easily purchased at any optical facility, should be used in screen-based driving simulators. Strength of the correction depends on distance from the driver to the screen.

Keywords: simulator sickness, simulation and virtual reality, driver behavior, surface transportation, vision, sensory and perceptual processes, forces and moments, biomechanics, anthropometry, work physiology, interface evaluation, human-computer interaction, computer systems, simulation, methods and skills

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INTRODUCTION

Simulators and virtual reality environments have become essential tools to measure behavioral performance in real-world tasks, such as driving motor vehicles and piloting aircraft, finding applications in the military, aviation, and motor vehicle industries. Therefore it is critical that measurements made using simulators are accurate and valid. Various improvements to simulators have increased their perceived realism, including displays spanning larger areas of the visual field, head-mounted displays, stereoscopic displays, and motion cuing devices (de Winter et al., 2007). All simulators suffer the problem of simulator sickness regardless of the various additions, however, calling into question the validity of behavioral measurements made in simulated environments. De Winter et al. (2007) review evidence that better simulator fidelity does not alleviate simulator sickness and may make it worse, especially if stereo is added to the display. Human test subjects experiencing simulator sickness are less likely to perform a virtual task with the same attention and focus as they would the corresponding real-world task. Compensatory behaviors conducted by the subject to avoid inducing the discomfort of simulator sickness can obviously affect measurements of behavior. Moreover, simulator sickness can distract the subject from accurately responding to an experimental challenge.

Simulator sickness probably has several causes, depending on the type of display, driver condition, and simulation parameters. Simulators fall into two general classes, virtual reality and screen based. Both are susceptible to simulator sickness problems with prolonged use. Head-mounted virtual reality displays require very strong lenses to bring close displays into focus, which can introduce image distortion. There is always some update delay in these displays. Screen-based systems are less affected by those problems but have other disadvantages, including visual-vestibular mismatch and reduced field of view.

Another possible source of symptoms that has been less studied is a discrepancy between the accommodation and convergence of the eyes on a near screen and the depicted distances of near optical infinity in a driving environment. Most of the visual environment in a driving situation ranges from 5 m to 500 m (Evans, 2004). Stereoscopic vision is probably not important through most of this range; it is essential only up to 20 m (Sachsenweger & Sachsenweger, 1991) or less (Kemeny & Panerai, 2003). Rich monocular cues to depth in the simulated environment include texture gradients (Gibson, 1966), occlusion, motion parallax (Sachsenweger & Sachsenweger, 1991), and looming. A mismatch between the actual distance of the display and the depicted distance in the driving simulation might alert the brain that something is wrong in the body and initiate physiological defensive measures, such as generalized discomfort or nausea, motivating the driver to leave that environment and vomiting to expel any toxins that had caused the optical/visual mismatch.

EXPERIMENT 1

To evaluate the influence of this mismatch, we corrected the vision of half of our subjects to be consistent with the perceived distances in the driving environment by correcting their lines of sight to parallel and their focus to infinity. We corrected both convergence and accommodation because correcting only one or the other would disturb the normal accommodative convergence–to–accommodation (AC/A) ratio. Accommodating the focus of the eye's lens to near targets reflexively induces a convergence of the two lines of sight, even in open-loop conditions, two components of the near triad (Myers & Stark, 1990). The third component of the triad, pupillary constriction, is transient and would not affect our long-term conditions. Correcting only accommodation or only convergence would disturb the AC/A ratio and might induce a simulator sickness of its own.

Because demand characteristics might loom large in measures of motion sickness, we compared our optically corrected participants with a control condition in which participants wore the same test frames as the corrected participants, with lenses that summed to no correction. The control is important because participants in the corrected condition might expect different results than normal, biasing our measures (Michael, Garry, & Kirsch, 2012).

Method

Participants. Participants were 56 students from University of California, Santa Cruz, who received course credit in an undergraduate introductory psychology class for participation, 27 in the correction condition and 29 in the control condition. To be eligible to participate in the study, participants had to have a driver's license and self-reported 20/20 vision without spectacles or 20/20 vision corrected with contact lenses. All were between the ages of 18 and 23 in this and subsequent experiments. Participants were tested individually and did not know whether they were in the correction or control group or indeed that there were two groups. They were assigned pseudorandomly to either the correction or the control condition.

Apparatus. Driving was performed on a HyperDrive and Vection Beta Version 1.9.35 driving simulator controlled by three PCs, one for development, one for operation, and one for display. The driver's interface consisted of a fixed display screen in the participant's frontal plane and Logitech controls: a steering wheel with force feedback, accelerator and brake pedals, and push button transmission. Physiological optics defines a unique station point at which all simulated motions and shapes of objects are geometrically accurate. Display software was calibrated by the manufacturer to a screen 50° in width. To achieve this angle, we mounted the LCD flat screen 56 cm in front of the participant's corneas. With this display size, the screen projects to more than 90% of the primary visual cortex. Vertical adjustment of the station point was accomplished with an adjustable-height chair that placed the eyes at the height of the center of the screen. Thus drivers' corneas were located at the unique station point at which the programmed geometry matches the geometry of the real world. A simulated rearview mirror was located at the top of the screen about where it would be in a typical vehicle.

The display was a photorealistic driving environment with landscape, sky and road details, and a context that changed about every 5 min during driving, including urban, suburban, country, and wilderness formats, all with paved roads. Driving was in the daytime with clear weather.

The driving course consisted of a figure-8 configuration so that the number of left and right curves would be equal, 27 in each direction, with hills and light traffic (33 vehicles encountered during each traverse of the course). The figure 8 consisted of two rectangular patterns joined at 1 corner, where the roads crossed at a traffic light. Hills, and curves in addition to those needed to negotiate the figure 8, were included to increase the possibility of simulator sickness (Mourant, Rengarajan, Cox, Lin, & Jaeger, 2007), driving the participants above a floor of no effects. In some parts of the course, hills and curves occurred together in a mountain environment.

Total length of the driving course was 30 simulated kilometers, so that driving the whole course required about 25 to 30 min. All participants started at the same start point and were asked to drive for 40 min, so part of the course was repeated. They started with a long straight stretch to accustom themselves to the environment. This segment was driven in about 4 min, followed by a 90° turn to the left. Drivers were instructed to drive in a normal way and to go straight ahead at each intersection. The rectangular pattern requires six right-angle turns. Turns 1, 2, 4, 5, and 6 from the starting point were highway curves with a radius of 100 m, and Turn 3 was a right-angle turn in an urban environment. Other curves were less than 90°. The software tolerated minor driving errors but terminated the session for a significant crash.

While driving, participants wore test spectacles in one of two configurations, corrected or control. In the corrected condition, two test lenses were mounted in front of each eye: prisms to bend the lines of sight inward by a binocular total of 3° and spherical lenses of +1.75 diopters in each eye. Correction of both vergence and accommodation preserved the normal AC/A ratio.

The lenses slightly undercorrected vision to infinity in both accommodation and convergence at the center of the display. These optics were chosen to maximize the well-corrected area projecting to and near the foveas. On the tangent screen, peripheral areas are of course more distant from the eyes, so that complete correction occurred in a ring around the point where the lines of sight met the screen center. The precise diameter of the ring depended on the exact optics of the driver, slightly different for each one. Thus sharp focus with relaxed accommodation occurred within the diameter of the ring and for a variable region beyond it, depending on the current pupil diameter and corresponding depth of field for each driver. More peripherally, the drivers were slightly overcorrected, but visual acuity declines rapidly with eccentricity in any case.

Participants in the control condition wore the same test spectacles with a +0.12 diopter and a –0.12 diopter lens in front of each eye, summing to no correction but giving the appearance and weight of two nonplanar lenses as in the correction condition. There was no prism correction in the control condition. Drivers were not told which condition they were in or even that there were two conditions.

Procedure. All procedures were approved by the University of California, Santa Cruz, Institutional Review Board (IRB). After signing an informed consent form, participants were tested for distance visual acuity with a Snellen E-chart. All but one had 20/20 or better acuity at a distance of 20 ft. (6.45 m), reading the 20/20 line of the chart without error. The remaining participant was slightly myopic and was refracted by the first author to 20/20 vision with negative spherical lenses in the test frame. He fell in the control condition and was corrected with –1.5 diopters spherical correction in each eye for the driving test.

The test spectacles were adjusted for height, interpupillary distance, and tine length to be held snugly by the ears, so that participants were looking through the center of each lens when they fixated the center of the driving display. Lenses were premounted and participants were not told about the nature of the optical correction.

Following adjustment, the participant was shown into an experimental room with black walls and ceiling to control stray light, the chair was adjusted in height and position to ensure proper distance from the screen and ideal eye level, and the controls were explained. The experiment was executed with all room lights off. Drivers were cautioned to take curves and crests of hills slowly to avoid driving off the road. They were informed that every 10 min, the experimenter would interrupt their driving to ask two questions, first about vection, explained as the feeling of self-motion, and then about discomfort. Each was judged on a 10-alternative double-anchored Likert scale.

The vection scale was described in the following words:

> Vection is the feeling of self-motion. While you are driving, every 10 minutes we'll ask you whether you have a feeling of self-motion on a 1-to-10 scale, where 1 is you're certain that you're standing still and 10 is a feeling of motion as vivid as real motion in a car.

This measure was included to disguise the fact that we were primarily interested in the discomfort scale, which assessed simulator sickness. That scale was described with the words, "We also want to know how comfortable you are, on a 1-to-10 scale: 1 is no problem, 10 is about to vomit." In practice, we kept a plastic-lined wastebasket next to the driver's chair, and the simulation was stopped if a participant reported an 8 or more on the discomfort scale. No vomiting occurred for any participant. This precaution resulted in a reduction in the number of participants at the longer driving durations.

Following the driving period, each participant filled out a questionnaire asking what they thought the experiment was about and whether they had these ideas during or after the experiment. They were then debriefed, thanked, and dismissed.

Because successive vection and discomfort estimates could not be considered statistically independent at the four sampling times, the number of observations was different at each sampling time, and the data are ordinal rather than ratio scales, we used a mixed effects model to compare control and correction conditions at each sampling time.

Results

Descriptive statistics. Figure 1 shows the means and standard errors for the discomfort scale at each of our sampling intervals, with a least-squares quadratic fit to each condition. The sample means,

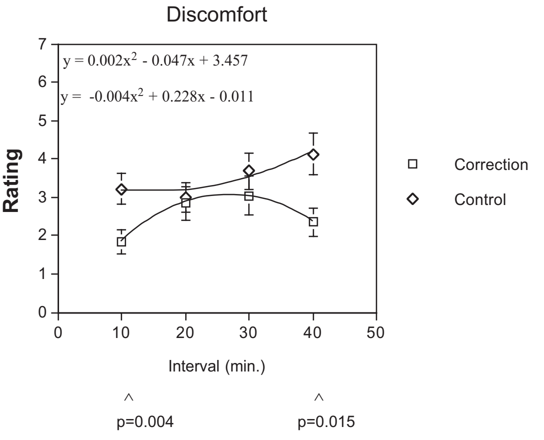

Figure 1. Discomfort ratings during 40 min of simulated driving, with unweighted least-squares quadratic fits. In the correction condition, both accommodation and vergence are adjusted to optical infinity. The *p* values are Mann-Whitney *U* tests performed separately for each time interval.

standard deviations, and sample sizes for the corrected and control conditions are given in Table 1 for the 10-, 20-, 30-, and 40-min time periods.

Inferential statistics. About half the participants withdrew due to extreme discomfort, crashes, or other reasons before the 40-min testing period. Although a larger proportion of participants dropped out in the control than the corrected condition, the difference in proportion of drivers completing the course in the two conditions was not statistically significant ($z = 0.85$, $p = .4$). Therefore dropout rates will not be considered further.

The standard repeated-measures ANOVA is not ideal for these data because it would require listwise deletion with a corresponding loss of power and generalizability. The data were instead analyzed using a mixed effects linear model that uses all available data at each time point. The model included the effects of condition and time as well as a quadratic time effect, a Condition × Time interaction, and a Condition × Quadratic Time interaction. Time was centered to remove nonessential multicollinearity (Cohen, Cohen, West, & Aiken, 2003, p. 202).

A variety of covariance structures can be specified in mixed effects models. With repeated-measures data that appear to be heteroscedastic over time, as suggested by the standard deviations in Table 1, the most appropriate covariance

TABLE 1: Sample Means and Standard Deviations

	10 min	20 min	30 min	40 min
Control	3.2 (2.13)	3.0 (1.98)	3.7 (2.41)	4.1 (2.13)
Corrected	1.9 (1.63)	2.9 (1.63)	3.0 (2.38)	2.4 (1.54)

Note. Standard deviations are in parentheses. The control sample sizes are 29, 27, 26, and 15, and the corrected sample sizes are 27, 27, 23, and 17 for the 10-, 20-, 30-, and 40-min periods, respectively.

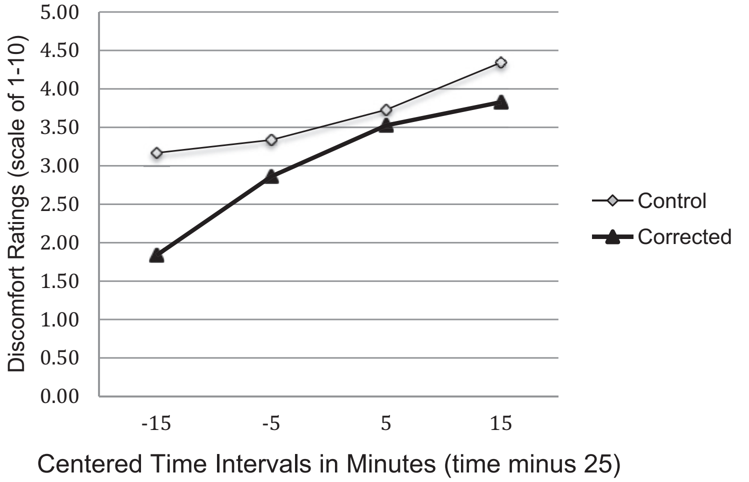

Figure 2. Predicted means from the mixed effects model.

structures are the heterogeneous Toeplitz (HT) and unstructured (UN) forms. The Akaike Information Criterion (AIK) and Bayesian Information Criterion (BIK) model fit criteria (smaller is better) suggest that the HT covariance structure (AIK = 743, BIK = 765) is slightly superior to the UN covariance structure (AIK = 741, BIK = 773).

The results of the mixed effects model analysis revealed a statistically significant Condition × Quadratic Time interaction under both covariance structures: HT, $t(40, 9) = -2.104$, $p = .042$; UN, $t(33, 2) = -2.296$, $p = .028$. The nature of this interaction effect is clearly seen in Figure 2, which displays the predicted mean discomfort scores for each condition and time period. Given the Condition × Quadratic Time interaction effect, the main effect of condition will be misleading and instead the simple main effects of condition at each of the four time periods were examined. The simple main effect of condition was statistically significant at the 10-min period, $t(45, 4) = -2.488$, $p = .017$, 95% confidence interval [–2.41, –0.25], and the tests of simple main effects of condition at the three other time periods were inconclusive though in the predicted direction.

Vection. Vection ratings were generally higher than discomfort ratings but were not significantly affected by the optical correction (Figure 3). The differences between corrected and control groups did not reach statistical significance by Mann-Whitney U tests, $p > .067$ at every sampling time. Median vection ratings were identical in corrected and control conditions at 20 and 30 min. Because none of these initial results showed statistically significant differences between conditions, a mixed model was not run.

When asked about the purpose of the experiment, only three drivers guessed our research question correctly. Most of those who had any opinion thought that we were testing their driving skill.

EXPERIMENT 2

Having found a reduction in simulator sickness with optical correction of focus and convergence, preserving the normal AC/A ratio, we

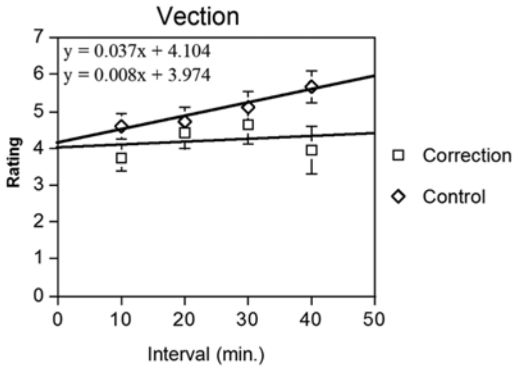

Figure 3. Vection ratings during 40 min of simulated driving. Ratings were sampled at the same time as the comfort ratings in Figure 1. Error bars are between-subjects standard error. None of the differences between ratings at any interval are statistically significant. Straight lines are unweighted linear fits.

investigated additional interventions; we next asked whether a vestibular intervention could reduce symptoms further. We introduced a vestibular intervention by asking drivers to tilt their heads toward the shoulder opposite the direction of turn of the steering wheel (the roll axis). While turning the wheel to the left, for instance, the driver would tilt the head toward the right shoulder. During turns to the right they would tilt the head to the left. Although the vestibular stimulation would not be the same as that in a real vehicle, we reasoned that the intervention might create a pedestal to reduce sensitivity to vestibular errors by Weber's law. Though the maneuver feels unnatural, tilting the head in the direction opposite the turn reproduces at least qualitatively the deviation of the otolith gravity vector for that turn (Figure 4).

Method

Participants. Participants were 31 students from University of California, Santa Cruz, who received course credit in an undergraduate introductory psychology class for participation. Criteria for inclusion were the same as in Experiment 1, and participants were from the same subject pool.

Apparatus. Participants performed simulated driving on the simulator and the driving course used in Experiment 1. To monitor head tilt, we had them wear a custom-built inclinometer mounted on the apex of a lightweight soft plastic frame consisting of a band arching over the head from ear to ear connected to a padded band that was adjusted on an axis from the forehead to the inion to be tight but comfortable. Thin wires connected the sensor to the electronics in the base, which was out of sight of the drivers. In addition, they wore the corrective lenses in test frames as in Experiment 1.

Procedure. All procedures were approved by the University of California, Santa Cruz, IRB. After signing an informed consent form, participants were tested for distance visual acuity with a Snellen E-chart. All had 20/20 or better acuity. The test frames were adjusted and the inclinometer tightened on the head frame. Drivers first practiced left and right head tilts, read out on the digital display of the inclinometer base to be at least 10° in each direction. The required degree of tilt was above the relatively high threshold for otolith afferents (Yu, Dickman, & Angelaki, 2012). During driving, the experimenter continuously monitored the readout to assure adequate tilt; achieving adequate minimum tilt was not problematic for the drivers.

Before testing, the drivers negotiated a separately programmed practice course consisting of a one-block detour away from a main road to accustom them to the head tilt required at each turn. They made a left turn, then two rights, and finally a left back to the main road at a traffic signal. They were reminded of the head tilt at each turn. During the experimental run, they were reminded only if they failed to tilt, which occurred very infrequently. Vection and discomfort were recorded every 10 min as in Experiment 1. Participants drove for 40 min unless they crashed or responded with an 8 or 9 on the comfort scale.

Data were analyzed with Mann-Whitney *U* tests. Since drivers in the vestibular manipulation condition drove with both the inclinometer and the optical correction, data were compared to the data for the optical correction–alone condition of Experiment 1.

Results

Comfort. Comfort ratings were not significantly different from those obtained in the correction

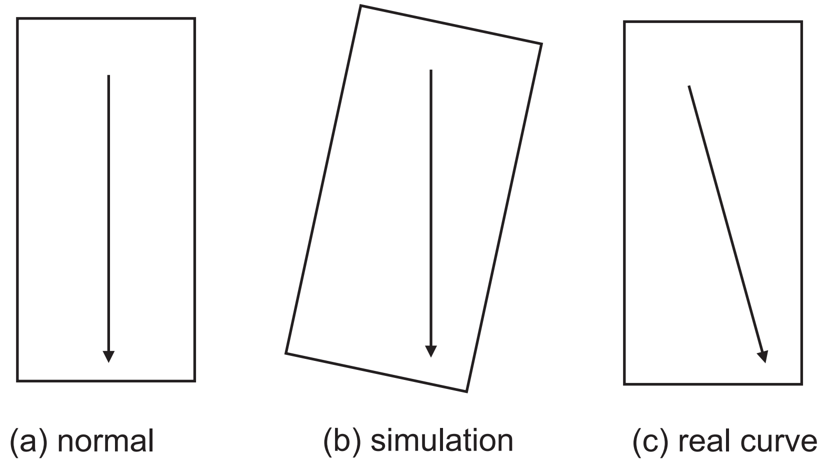

Figure 4. Head positions (rectangles) and otolith gravity vectors (arrows) in three conditions. (a) Upright head, gravity vector vertical, as in Experiment 1. (b) Head tilted to the right in the simulator during a leftward curve, as in Experiment 2. The gravity vector remains vertical because there is no real motion, but the relationship of the vector to the head position is the same as in a real curve. (c) In a curve during driving of a real vehicle, the gravity vector deviates in the direction opposite the curve, a leftward curve in the example, while the head remains upright.

condition of Experiment 1, Mann-Whitney *U* test, $p = .075$ at the 10-min sample and $p > .28$ at the longer sampling intervals. All mean differences were less than 1 Likert scale unit. Because none of these initial results showed statistically significant differences between conditions, a mixed model was not run. Thus adding a vestibular intervention did not reduce symptoms of simulator sickness beyond the benefit already obtained from the optical correction of Experiment 1.

Vection. The vection measure showed similar results. Ratings of vection were not statistically significantly different from those of the correction-alone condition at any of the sample times, Mann-Whitney *U* test, $p = .074$ at 40 min, $p > .22$ at the other sample times. All mean differences were less than 1 Likert scale unit.

Discussion

The slightly higher ratings of discomfort with the vestibular intervention compared to the visual correction–only conditions at the first sampling interval, 0.62 Likert scale units, may have been due to drivers being disturbed by the head tilt maneuver. This difference apparently dissipated as the head-tilt task became automatized with practice.

The rationale for head tilt in the direction opposite each curve was to reproduce at least qualitatively the change in the otolith gravity vector during steering. In a left turn, for instance, the gravity vector will swing to the right as momentum carries the otolith to the right of the turn. Tilting the head to the right deviates the gravity vector in the same direction. The tilt feels unnatural to the drivers, but they soon master it.

EXPERIMENT 3

Normally, if drivers tilt at all during turns, they tend to tilt their heads in the direction of the turn. Head tilt in the same direction as the turn feels more natural than the opposite tilt of Experiment 2 but deviates the gravity vector in the direction opposite its change in real driving. This condition has greater face validity because it mimics the tendency of drivers to tilt into a turn in order to reduce strain on the neck muscles but deviates further from the changes of the gravity vector in normal driving.

Method

Participants. Participants were 34 students from University of California, Santa Cruz, who received course credit in an undergraduate introductory psychology class for participation. Criteria for inclusion were the same as in Experiment 1, and participants were from the same subject pool.

Apparatus. Driving was performed on the simulator and the driving course used in Experiment 1. To monitor head tilt, we had them wear the inclinometer as described in Experiment 2 in addition to the test frames with optical correction.

Procedure. All procedures were approved by the University of California, Santa Cruz, IRB. Procedures followed those of Experiment 2, except that the drivers were instructed to tilt their heads in the same direction as the steering wheel.

Results

Discomfort. At all sampling intervals, discomfort ratings were higher in the tilt condition than in the optical correction–only condition of Experiment 1. Ratings were significantly higher at 10 min, Mann-Whitney U test, $U = 643$, $p = .007$, and at 40 min, Mann-Whitney U test, $U = 413$, $p = .006$. The intermediate samples, though in the same direction, were not significantly different, $p > .10$. Thus in general, tilting the head in the direction of each curve made the symptoms of simulator sickness worse.

Vection. The vection measures showed a significant increase in vection of 2.09 Likert scale units at the 40-min sample, Mann-Whitney $U = 401$, $p = .013$. Other ratings of vection were not statistically significantly different from those of the correction-alone condition, $p > .12$.

Discussion

By tilting the head in the same direction as a curve, our drivers created a motion that felt natural but increased the discrepancy in the vestibular gravity vector between what is experienced in the simulator and what would occur in a real vehicle. This motion resulted in an increase in simulator sickness symptoms, in contrast to the result of Experiment 2 where there was no significant change in symptoms. The greater face validity of tilting the head in the direction of the curves was defeated by the large discrepancy in the vestibular gravity vector.

Vection remained the same as that experienced under similar conditions but without head tilt except at the longest interval. Here drivers experienced a long-term immersion with a head tilt that felt natural, resulting in a mean vection rating of 6.03, the highest of any condition in the three experiments.

GENERAL DISCUSSION

We have found that correcting the optics of participants to near infinity in simulated driving significantly reduces the discomfort of simulator sickness while not affecting vection. This finding suggests that future studies in simulators could benefit from inexpensive spectacles with prism and spherical corrections appropriate to the distance of the participants from the simulator's display screen.

Our results may underestimate the amount of simulator sickness experienced by the general population at the longer driving durations, because the participants who felt nausea or withdrew because of other symptoms were selectively removed from the sample. This attrition occurred in both the control condition and the correction condition. Thus the effectiveness of the optical correction in an unbiased sample would be larger than what we found at the longer driving durations. Those who dropped out were the most susceptible, leaving only a biased sample of the less susceptible drivers at the longer durations. Further, there is evidence that simulator sickness becomes more severe with age (Brooks et al., 2010; Kawano et al., 2012), so that interventions would be even more important in the general population than in our young, healthy sample. It is safe to assume that our subjects experienced neither nausea nor vection before the experiment started, with young, healthy drivers sitting before a fixed screen. This assumption implies a nonlinear jump in ratings in the first 10 min for most drivers in all conditions.

The difference between the discomfort or simulator sickness ratings on one hand and vection ratings on the other means that differences in vection did not cause differences in discomfort. Rather, the two phenomena appear to be independent, the experience of vection not being influenced by optical correction.

The benefit of increased fidelity in simulators has been questioned. One would hope that the greater expense of more realistic simulations (Roza, 2004) would decrease simulator sickness, but in fact, increased quality of simulation has been found to increase sickness (Lee, 2004). The reason for this seeming paradox may be that a greater sense of immersion in the environment makes it more difficult for the brain to dismiss mismatches between visual and vestibular stimulation. A possible result is that a greater sense of presence can interfere with performance (Nash, Edwards, Thompson, & Barfield, 2000) or learning (Whitelock, Romano, Jelfs, & Bourna, 2000) in the simulated environment. Our technique reduces at least the visual range mismatch without incurring the expense of more elaborate simulations.

The head-tilt manipulations of Experiment 2 did not result in any additional reduction in symptoms of simulator sickness, despite changes of the vestibular gravity vector in the direction of real changes with curves in the opposite-tilt condition. The difference between simulated and normal vestibular stimulation is that the drivers engaged in active head tilt to change the gravity vector, rather than the vehicle changing it in a real curve. The nervous system thus attributes the change in the vector to the driver's own action rather than to the driving situation, with an efference copy (Bridgeman, 2007) from the neck muscles compensating the vestibular signal and the obtained tilt of the visual world.

Head tilt in the same direction as the curve in Experiment 3, however, increasing rather than decreasing the discrepancy between expected and actual vestibular stimulation, had a deleterious effect. The tilting actions might have provided a pedestal to reduce the salience of visual-vestibular discrepancies in the simulator, but they did not. Thus we cannot recommend active head tilt in simulators, at least when there is no real tilt of the driver and the display.

Optical correction reduces simulator sickness but does not eliminate it, a result expected because we have corrected only one of the many possible causes of discomfort in simulators (Brooks et al., 2010). Visual-vestibular mismatch is another important influence on simulator sickness. Any amelioration of simulator sickness is useful for the many applications of driving simulators, however. Our result provides a simple and inexpensive way to reduce simulator sickness without sacrificing the perception of self-motion.

ACKNOWLEDGMENT

Driving simulator hardware and software were funded by the Volkswagen Electronics Research Laboratory, Belmont, California. We thank professor Frank Durgin for providing the inclinometer.

KEY POINTS

- Optical correction to near infinity reduced simulator sickness in a screen-based driving simulator.
- Head tilt to imitate vestibular stimulation in curves had no additional effect.
- Head tilt in the direction of each curve made simulator sickness worse.
- Vection was not affected by optical or vestibular interventions.

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