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ORIGINAL ARTICLE

Manipulations to reduce simulator-related transient adverse health effects during simulated driving

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Abstract User comfort during simulated driving is of key importance, since reduced comfort can confound the experiment and increase dropout rates. A common comfort-affecting factor is simulator-related transient adverse health effect (SHE). In this study, we propose and evaluate methods to adapt a virtual driving scene to reduce SHEs. In contrast to the manufacturer-provided high-sensory conflict scene (high-SCS), we developed a low-sensory conflict scene (low-SCS). Twenty young, healthy participants drove in both the high-SCS and the low-SCS scene for 10 min on two different days (same time of day, randomized order). Before and after driving, participants rated SHEs by completing the Simulator Sickness Questionnaire (SSQ). During driving, several physiological parameters were recorded. After driving in the high-SCS, the SSQ score increased in average by 129.4 (122.9 %, $p = 0.002$) compared to an increase of 5.0 (3.4 %, $p = 0.878$) after driving in the low-SCS. In the low-SCS, skin conductance decreased by 13.8 % ($p < 0.01$) and saccade amplitudes increased by 16.1 % ($p < 0.01$). Results show that the investigated methods reduce SHEs in a younger population, and the low-SCS is well accepted by the users. We expect that these measures will improve user comfort.

Keywords Driving simulator · Physiological measures · Eye-tracking

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1 Introduction

One reason for the popularity of driving simulators (DS) is that laboratory-based DS are a safe way to test driving performance under standardized conditions [31]. Thereby, a person is immersed in a computer-generated virtual environment and interacts with the technical system [29]. The interaction happens via a sensor-controlled car model that provides input (i.e., steering wheel, pedals) and output modalities (i.e., vision, sound, vibration, motion).

Among many applications, DS are used to study driving behavior [32, 35], to train novice drivers [15], for fitness to drive assessments [6], and to test and validate new cockpit components [11].

User comfort during simulated driving is of key importance, since reduced comfort can alter the behavior of the user, confound data [33], limit the effectiveness of training [19], and increase dropout rates [9]. However, many users experience discomfort during and sometimes after a session in a DS [8, 9, 20, 25]. There are many factors that influence comfort in a DS (for review see [44]). One of the most important is simulator-related transient adverse health effect (SHE), also known as simulator sickness or simulation adaptation syndrome. Kolasinski [30] maintain that SHE depends on individual user factors (i.e., age, gender, experience), task-specific factors (i.e., driving circuit, optical flow), and simulator-related factors (i.e., field of view, contrast). In the review of Brooks et al. [5], five theories about the pathophysiology of SHE are described. The most accepted theory that explains SHE is Reason and Brand's sensory conflict theory [41]: It proposes that SHE is the result of a mismatch between the sensory information of the visual and the vestibular system. Hence, the optical flow of the virtual scene indicates motion via the visual system, while the vestibular system does not perceive acceleration, which indicates no motion. Optical flow is the distribution of apparent velocities of movement of brightness patterns in an image [21]. In a fixed-based DS, optical flow is caused by relative motion of virtual objects on the screens and by user head movements [47]. As studied by Gibson [18], the amount of optic flow depends on the environment and might be an important contributor to SHE in fixed-based DS.

Symptoms of SHE can range from mild discomfort to severe and prolonged nausea, dizziness, and disorientation [22, 42]. Symptoms can appear within minutes and can cause discomfort for up to several hours [45]. Estimates of SHE incidence vary widely. Bertin et al. [3] reported 30 %, while in another study Kennedy [28] reported 88 %. Furthermore, it has been reported that 80 % of all participants showed an increase of symptoms within 10 min after becoming immersed in a virtual environment and can arise from relative motion of objects and the viewer [9].

Several researchers [17, 26, 27] developed and adopted questionnaires as measures of SHE, and the Simulator Sickness Questionnaire (SSQ) became the most often used measure to quantify symptoms of SHE [43]. Others have combined the SSQ with a number of physiological measures and have found that simulator-induced symptoms are associated with increased heart [10] and respiratory rate [24], increased skin conductance [23], and decreased skin temperature [3]. Sweating is a common physiological manifestation of SHE and can be measured by an increased skin conductance. That is why besides SSQ, skin conductance is used in most studies on SHE as main outcome measure [2, 3, 24]. In addition, we measured fixation durations as well as saccade amplitudes using a head-mounted eye-tracking system. According to the sensory mismatch theory [5], SHE occurs when there is a mismatch between input to the visual system created by the optical flow and the vestibular system. Therefore, one might expect that participants would try to minimize retinal optical flow which could be achieved by less eye movements, more central fixations, and reduced saccade amplitudes. Hence, we expect to see a reduction in the saccade amplitudes as a compensatory mechanism to SHE. Therefore, it was hypothesized that fixation durations increase and saccade amplitudes decrease when SHE occur.

Prothero et al. [40] has put forth a new hypothesis which addresses how a stable background reference—an "independent visual background" (IVB)—would be used to enhance the observer's perception of the stable inertial frame of reference. The hypothesis was tested in a virtual environment using a head-mounted display to present a moving scene with an IVB and another scene without IVB to test SHE in healthy subjects [39]. The introduction of the IVB resulted in lower SSQ scores and improved user comfort. These effects were also confirmed in other studies (e.g., [12–14]). Lin et al. [34] added several IVB types to a driving simulator and evaluated the resulting impact in SHE. They found that after 2 min of driving exposure, subjects reported lower SSQ scores. Mourant et al. [37] investigated SHE and driving in four environments (country, suburban, city, and curves) using a fixed-base driving simulator. When driving on straight roads, subjects reported less SHE than driving in a city environment and on curves. They concluded that the rapid optic flow experienced in the driving simulator makes a substantial contribution to SHE. Yin and Mourant [47] studied the perception of optical flow when driving straight ahead and driving on curves. Results revealed that the amount of optical flow was highest when driving in curves and lowest when driving straight ahead. Thereby, the amount of optical flow was represented as the mean value of the sum over the number of image frames.

The purpose of this study was to investigate a combination of three methods to reduce the sensory mismatch during simulated driving and evaluate whether this reduces SHE in a fixed-based driving simulator.

2 Methods

2.1 Participants

Twenty (10 woman, 10 men) healthy participants were included in the study. None of the participants were taking any medication, nor suffered from any vestibular dysfunction. The mean age was 27.7 years (SD = 2.9, aged 24–32 years). All participants had comparable computer skills and were active drivers; none of them had experienced an immersion in simulated driving before. All participants wore their daily vision aids. The experiment was conducted in accordance with the latest Declaration of Helsinki and approved by the local ethics committee. Prior to inclusion, all participants gave informed consent.

2.2 Procedure

Starting point was a manufacturer-provided scene characterized by a high optical flow that is associated with a high-sensory conflict (high-SCS). We applied three methods that lead to a new scene with reduced sensory conflict (low-SCS). The methods were (1) scene optimization aiming at a reduction in optical flow, (2) superimposing of an IVB to provide visual motion and orientation cues that match those from the vestibular receptors, and (3) decrease of brightness of lateral projection screen to further reduce optical flow. Both scenes and the three methods are described in the following section. In this study, we were investigating differences between the two different scenes (high-SCS and low-SCS), and therefore, the experiment took place on two different days but on the same time of day. Participants were advised to eat the same on both days. The order the participant was exposed to the high-SCS or low-SCS scene was randomized. Participants were given a verbal explanation and instructions on the electrode attachment, the eye-tracker, as well as the handling of the driving simulator. Prior to exposure to the virtual scene, participants completed a pre-immersion questionnaire and the SSQ [27]. To get baseline measures, participants were instructed to observe a frozen image of the virtual scene for 5 min. Then, participants were exposed for 10 min either to the original or the adapted virtual driving scene. After the virtual drive, participants were advised to observe again a frozen image of the scene for 1 min. Each participant filled out the SSQ again and completed a post-immersion questionnaire after detachment of sensors and eye-tracking system.

2.3 Description and adaptations of the scenes

The driving circuit is implemented in the virtual environment of the driving simulator. The virtual environment is composed of two elements:

- The scene that specifies the static characteristics of the simulation including the terrain, roadways, signage, buildings, and vegetation [16].
- The scenario that specifies the dynamic characteristics of a simulation. This includes what is to happen and where it is to happen. Thus, it binds together activities and places. A scenario is typically defined as a series of episodes with tightly controlled critical events interspersed with periods of free driving [16]. Thus, other traffic participants (i.e., cars, cyclists, pedestrians) are characterized by their position, velocity, behavior, and appearance.

Both scenes (low-SCS and high-SCS) incorporated a four-lane (two-lanes per direction) road with moderate traffic that included seven right and 11 left turns, three intersections, and three roundabouts. During the route, all participants encountered standardized driving conditions. Furthermore, participants had to react to standardized scenarios such as a deer jumping on the street from the right, an emergency braking of the car in front, a car abruptly leaving a parking place, and a child behind a pillar jumping in the street from the right border. The scenarios as well as the route of the low-SCS were exactly the same as in the high-SCS, but three methods were investigated to adapt the scene to reduce SHE:

1. First, the virtual scene was optimized aiming at a reduction in optical flow (Fig. 1). Optical flow depends on the virtual environment and objects such as building and trees close to the road generate more optical flow. Therefore, objects along roads (i.e., houses, street lamps) were removed and road side and surface were homogenized.
2. As a second modification, an IVB was implemented. The IVB is a component in the virtual scene that provides visual motion and orientation cues that match those from the vestibular receptors [14]. In our study, a static, thin (3 mm, 4 cycles per radian), black grid IVB was superimposed over the entire virtual scene (Fig. 2).
3. Third, brightness of the lateral projection screens was decreased by 48 % (Fig. 2) to further reduce optical flow. Thereby, the contrast of the lateral projection screens became decreased which leads to a decrease of optical flow [21].

2.4 Apparatus

2.4.1 Driving simulator

A fixed-based driving simulator (F12PI-3/A88, Foerst GmbH) setup was used to create the simulation environment. Three projectors (Ultra Short Focus LCD projector, Sanyo) with 1,024 × 768 pixel resolution project the image onto three canvases (1.80 × 1.39 m). The canvases form a 120° angle and are positioned in front of the participant, creating a 180° horizontal and 40° vertical field of view. Three computers with Microsoft Windows 7 operating system (Microsoft Corp.) are used to control the simulation. One computer calculates and controls the dynamic scenario, and the other two computers render the graphics at 35 Hz. To avoid interferences as well as distractions to the driver, the driving simulator is installed in a temperature-, light-, and noise-controlled room (Fig. 3).

2.4.2 Sensory systems

While the participant was immersed to the virtual world, eye movements, heart rate, respiratory rate, skin temperature, and skin conductance were measured. Eye movements were recorded by using a head-free eye-tracker with video-based/corneal reflection tracking (SMI iView X HED, 50 Hz). Two cameras were used—one to capture the pupil and the corneal reflection and one to film the scene. The outcome variables of the eye-tracking measurements were

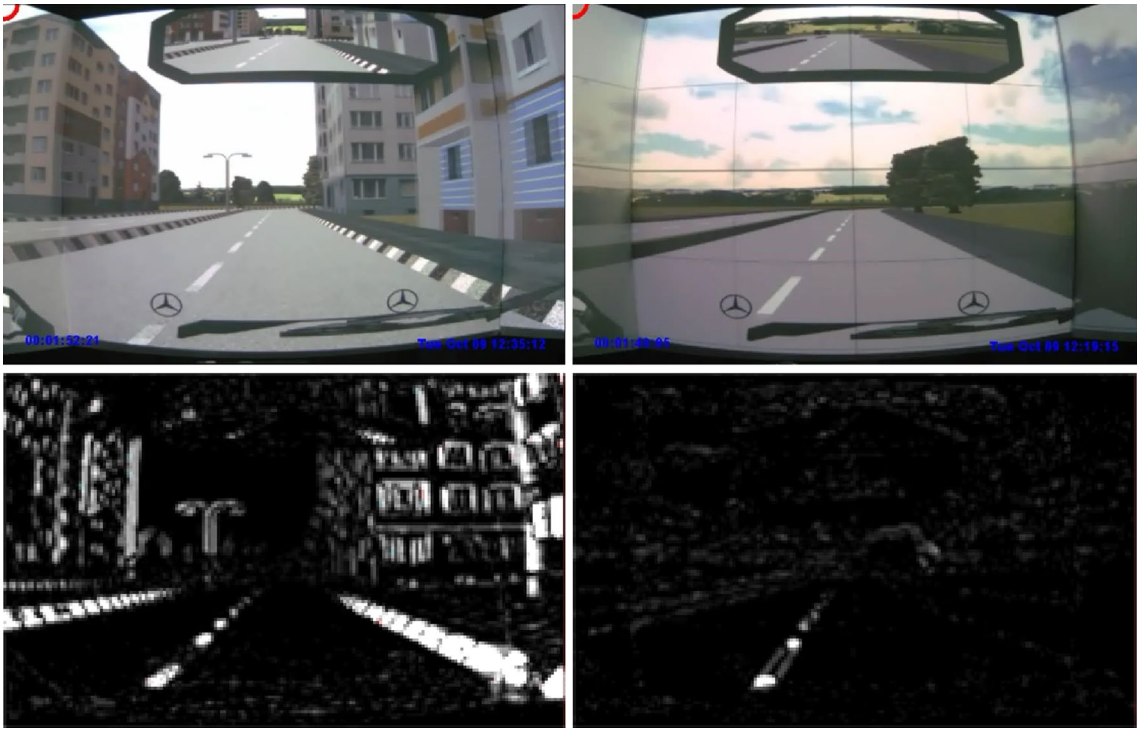


Fig. 1 *Upper images* show screenshots of the high-SCS (*left*) and low-SCS as participants are seeing them recoded with the scene camera from the head-mounted eye-tracker. In the *lower images*, the optical flow during 0.04 s (25 frames per second) of the two scenes is shown in *gray scale*. Optical flow was calculated using Horn and Schunck's algorithm [21]

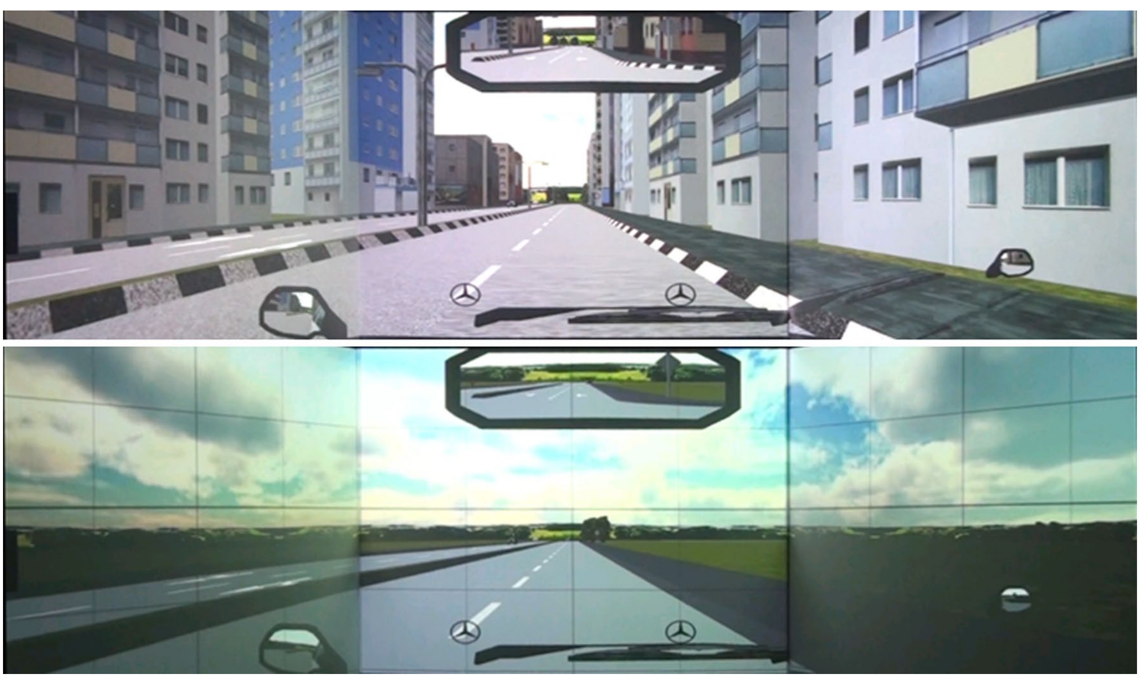


Fig. 2 Screenshots of high-SCS (*upper image*) and low-SCS scene. Low-SCS scene was optimized with respect to reduce optical flow and contains an independent visual background. Furthermore, brightness of the two lateral projection screens was decreased

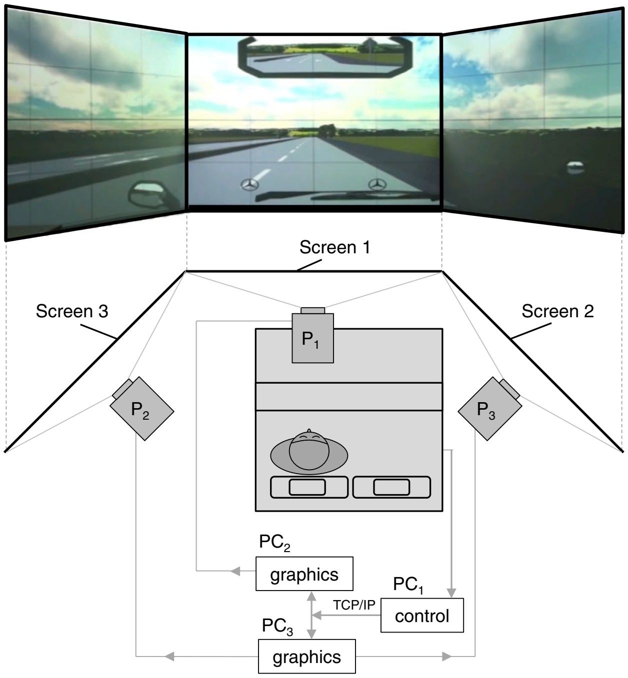


Fig. 3 Top-down view (schematic) of the experimental setup (P_{1-3}: projectors). PC_1 controls the dynamic scenario, while PC_2 and PC_3 render the graphics at 35 Hz. The participant was sitting in the driving simulator's chassis, which is based on authentic original design

fixation durations and saccade amplitudes, which were stored on a separate computer.

Heart rate was measured using a photoelectric pulse sensor for pulsatile blood flow (g.PULSEsensor, g.tec medical engineering GmbH). The sensor was positioned at the volar surface of the distal phalanx of the index finger. Skin conductance was recorded with a galvanic skin response sensor (g.GSRsensor, g.tec medical engineering GmbH) at the volar surfaces of the distal phalanxes of the third and fourth fingers of the left hand. A thermistor flow sensor (g.SLEEPsensor, g.tec medical engineering GmbH) was used to get respiratory rate (nose and mouth). Skin temperature was measured using a thermistor YSI 400 (g.TEMPsensor, g.tec medical engineering GmbH), which was attached at the volar surface of the distal phalanx of the fifth finger. Heart rate, respiratory rate, skin temperature as well as skin conductance were amplified with a DataLink amplifier (Biometrics Ltd.) and sampled with 1,000 Hz. Signals were not filtered before data analysis.

2.5 Data analysis

All data were calculated as mean values for time frames of 60 s for the experimental period of 10 min as well as 5 min before and 1 min after immersion. Matlab R2011a (The MathWorks, Inc.) was used to conduct the data analysis.

Mean duration of saccades and fixations as well as saccade amplitudes were calculated directly from the eye-tracking system using the corresponding event marker (SMI). Minimal fixation duration was defined as 80 ms. To quantify heart rate and respiratory rate, a low-pass filter was applied and a peak detection algorithm was used to count peaks per minute. Signal amplitudes were not taken into account. Skin conductance and temperature were continuous signals where mean values of every minute (amplitude) were calculated. Nonparametric Wilcoxon rank-sum test was used to test significance of the differences between the measures in the high-SCS and the low-SCS. Furthermore, linear regression was calculated to show dependency of the change in SSQ score and the change in saccade amplitudes.

3 Results

3.1 Simulator Sickness Questionnaire

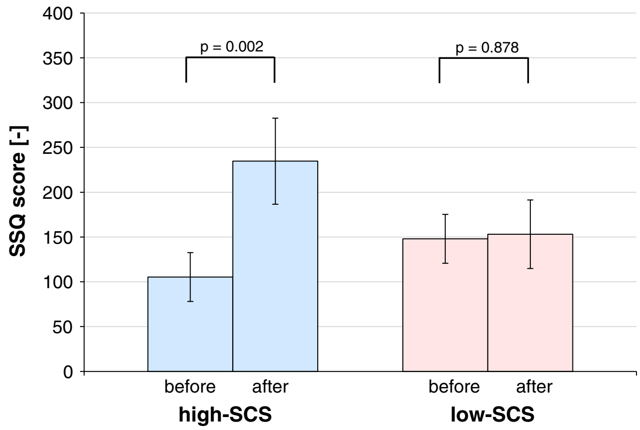
All participants rated the SSQ before and after both the high-SCS and low-SCS scene. Figure 4 shows the mean values of the SSQ. Before driving in the high-SCS, mean SSQ score was 105.25 (SE 27.8), while the score was 148.01 (SE 26.8) before the low-SCS scene. After 10-min driving in the high-SCS, the SSQ score increased by 122.9 % ($p = 0.002$) compared to an increase of 3.4 % ($p = 0.878$) after driving in the low-SCS. The difference of the change in SSQ between the high-SCS and the low-SCS was statistically significant with $p = 0.005$.

Note that the results trend to differ among genders (Fig. 4, right). In the high-SCS, female subjects ($N = 10$) reported a mean increase of SHE by 160.98 points ($p = 0.038$), while males ($N = 10$) rated SHE 97.81 points higher ($p = 0.019$). This difference showed a trend with $p = 0.073$. In the low-SCS, female subjects rated SHE 24.98 points higher ($p = 0.620$), while in the male group, a decrease of 14.91 points ($p = 0.748$) was measured.

3.2 Physiological measures

In Table 1, mean values of different physiological measures are summarized for both scenes. While differences in heart rate, respiratory rate, and skin temperature were less noticeable, skin conductance was significantly lower and saccade amplitudes were higher in the low-SCS.

The mean saccade amplitudes during driving are in the low-SCS 16.1 % ($p < 0.01$) higher compared to the high-SCS (Fig. 5). Also, in the low-SCS scene, the mean fixation duration is 6.3 % ($p = 0.081$) smaller than in the high-SCS scene. In both scenes, the difference between before and during driving is not significant ($p_{high} = 0.320$,



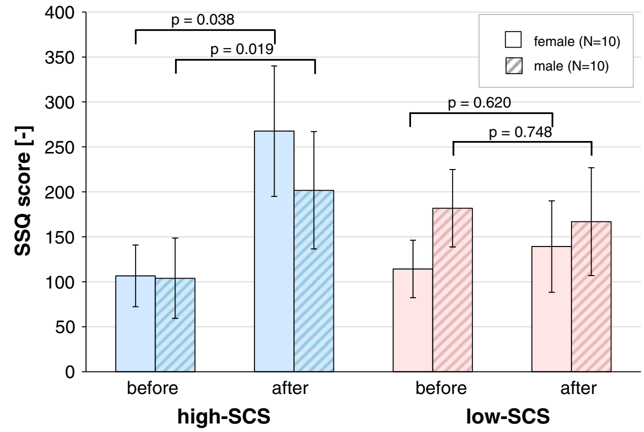


Fig. 4 *Bar plots* of mean values of the Simulator Sickness Questionnaire before and after both the high-SCS and low-SCS scene. *Left plot* represents scores of both genders ($N = 20$); *right plot* shows results female ($N = 10$) and male ($N = 10$) separately. *Error bars* represent the standard error

Table 1 Summary of the mean values and standard errors (SE) of the physiological measures recorded during simulated driving in the high-SCS and the low-SCS

	High-SCS			Low-SCS			p[a]
	5 min prior	During driving	1 min after	5 min prior	During driving	1 min after	
Fixation duration (ms)	523.02 (32.02)	617.52 (71.49)	531.12 (58.72)	522.28 (31.01)	580.82 (51.96)	568.16 (62.07)	0.081
Saccade amplitude (deg)	2.09 (0.19)	1.82 (0.13)	1.91 (0.18)	2.12 (0.25)	2.17 (0.15)	2.02 (0.21)	**<0.01**
Heart rate (number/min)	75.40 (1.90)	80.36 (3.31)	76.67 (3.06)	76.00 (2.51)	81.99 (2.56)	76.75 (2.67)	0.154
Respiratory rate (number/min)	19.15 (0.83)	20.83 (1.33)	18.71 (0.85)	19.86 (0.69)	20.95 (1.46)	18.21 (0.74)	0.365
Skin conductance (μS)	3.29 (0.03)	3.40 (0.04)	3.40 (0.05)	3.28 (0.03)	3.36 (0.03)	3.36 (0.04)	**<0.01**
Skin temperature (°C)	31.09 (0.05)	31.29 (0.08)	30.92 (0.06)	31.11 (0.04)	31.09 (0.05)	31.00 (0.05)	0.459

Significant p-values are in bold

[a] p value computed between high-SCS and low-SCS during driving

$p_{low} = 0.671$). Furthermore, the cumulated fixation time in the center of the image (<10° eccentricity) versus the periphery (>10° eccentricity) were calculated. In the low-SCS, the mean value and standard deviation of the time spent in the center are 58.3 ± 6.6 % versus the high-SCS 63.5 ± 8.7 % of the total cumulated fixation time. The difference of 5.2 % is statistically significant with $p = 0.006$.

Figure 6 shows the progress of skin conductance. At the beginning, skin conductance starts increasing significantly ($p < 0.001$) in both scenes and reaches a plateau. Compared to the high-SCS, in the low-SCS skin, conductance is 13.8 % smaller ($p < 0.01$) during driving. No significant differences prior the experiment and during experiment were found for the other physiological measures.

3.3 Correlation SSQ: physiological measures

Linear regression was calculated between the change of SSQ score and saccade amplitudes as well as skin conductance. Strong correlation of $r = 0.80$ was found for saccade amplitudes (Fig. 7) and weak correlation for skin conductance ($r = 0.34$). Positive SSQ scores (x axis) mean that symptoms of SHE increased during driving in the simulator, while scores <0 mean a decrease of symptoms. Since not the difference between the two scenes are of interest, the values of both the high-SCS and the low-SCS were taken into account ($N = 40$).

4 Discussion

The primary aim of this study was to describe and investigate a combination of three methods to evaluate whether they reduce SHE. The methods were (1) scene optimization aiming at a reduction in optical flow, (2) superimposing of an IVB, and (3) decrease of brightness of lateral projection screen to further reduce optical flow.

When comparing the SSQ score before and after driving in the simulator, in the high-SCS, the SSQ score increased by 122.9 % while in the low-SCS, only a minor increase

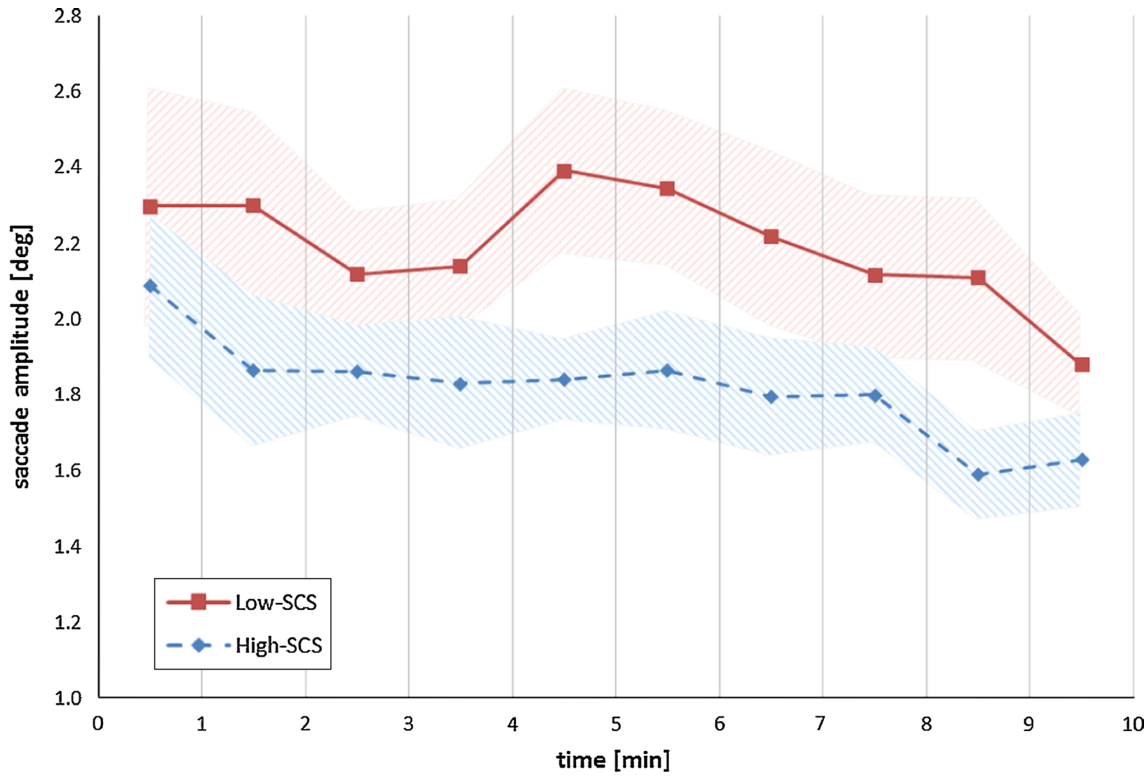


Fig. 5 Progress of saccade amplitudes during 10-min driving in the simulator. Mean values of each minute was calculated. *Shaded area* represents the standard error

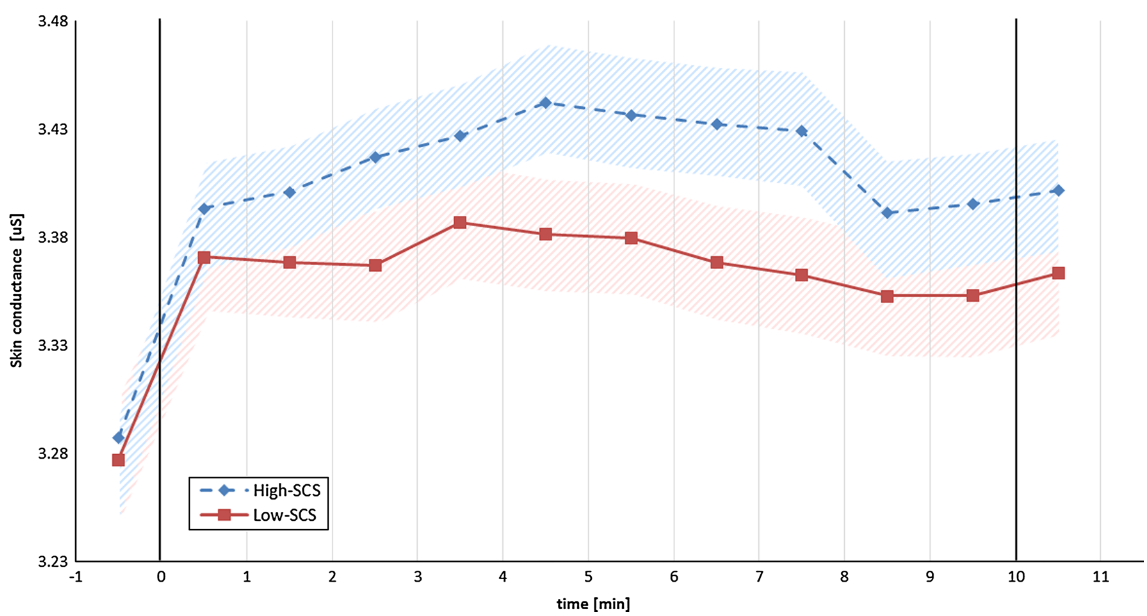


Fig. 6 Progress of skin conductance during 10-min driving in the simulator, and 1 min before and after immersion. Mean values of each minute was calculated. *Shaded area* represents the standard error

of 3.4 % was observed. This result supports strongly the hypothesis that the combination of the three methods significantly reduces SHE. This is true for both genders, but the effects are more pronounced in female participants, who seems to be more susceptible to SHE and would benefit the most from the proposed methods to reduce SHE.

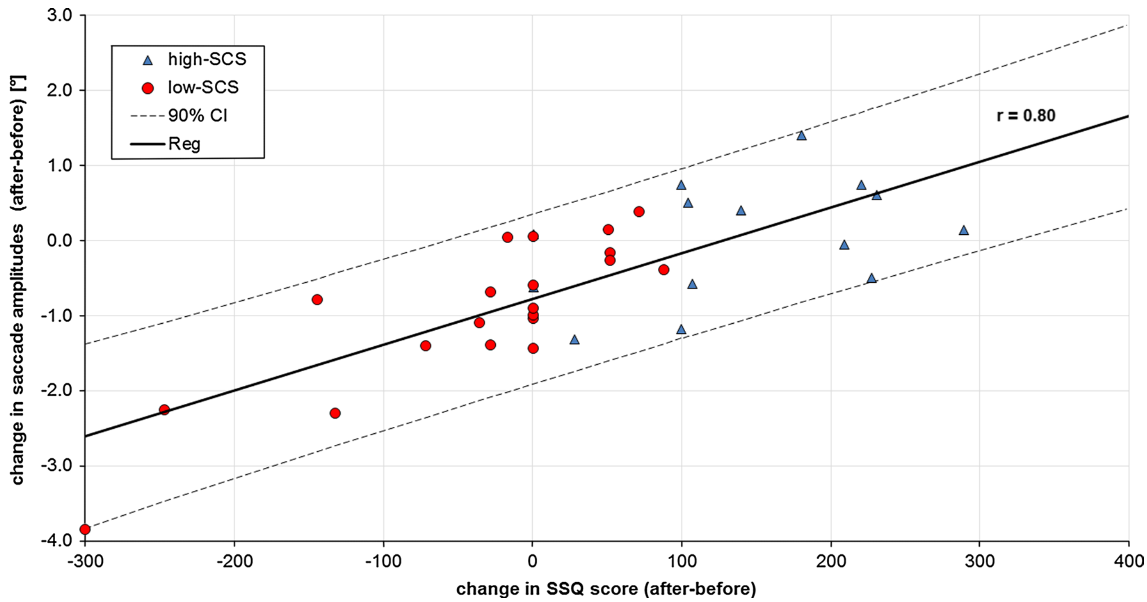


Fig. 7 Linear correlation between the change in SSQ score and the change in saccade amplitudes

The gender differences have also been noticed by others [1, 30, 38]. Note that the SSQ score before driving depends on participant's actual condition and was, therefore, not the same at the 2 days. In this study, the change in SSQ score caused by the immersion into a virtual driving scene was relevant.

Besides lower SSQ scores, all subjects also showed lower skin conduction when driving the low-SCS compared to driving the high-SCS (Fig. 7). The difference is significant and the correlation between SHE, SSQ, and skin conduction was also observed by others, who concluded that skin conduction is an important indicator for SHE [3, 29, 36]. The differences in heart rate, respiratory rate, and skin temperature between the two scenes are less noticeable than the difference in skin conductance. Also this has been observed by others, and Bertin et al. [3] concluded that skin conductance is probably the most reliable physiological SHE indicator.

In addition to these measures, we recorded fixation durations and saccade amplitudes. Saccade amplitudes showed significant differences between the high-SCS and the low-SCS, while fixation durations showed a trend. In the low-SCS, fixation duration is on average 6.3 % shorter compared to the fixations duration when driving in the high-SCS. Furthermore, the saccade amplitudes are 16.1 % higher in the low-SCS. Strong correlation between the change of saccade amplitudes and SSQ scores was found ($r = 0.80$). Compared to a correlation between skin conductance and SSQ, saccade amplitudes seem to be a reliable measure for SHE. No previous study has related saccade amplitudes to SSQ-assessed SHE. There are several explanations why SHE goes together with decreased saccade amplitudes. It could be that reducing eye movements is a compensation strategy of the visual system to reduce the amount of optical flow. Against this assumption speaks the saccadic omission that refers to a lack of awareness of the motion across the retina that is generated during a saccade [7, 46]. This is the result of a visual saccadic suppression, which is the selective blocking of the visual processing during eye movements [46]. Another explanation for the reduced saccade amplitudes in the high-SCS is that under the influence of SHE, the subject tries to minimize the difference of the optical flow that is perceived via the left and the right hemifield of vision. This difference is smallest when looking at the center of the scene. That would also explain the reduced saccade amplitudes in the high-SCS. This assumption is in favor with our finding, that the cumulated fixation time spent in the center of the image (<10° eccentricity) is 5.2 % ($p = 0.006$) smaller in the low-SCS compared to the high-SCS.

During the 10-min drive, the participants had to react to different scenarios: For example (1) react to a deer jumping on the street, including an emergency brake or (2) driving on a narrow road because of road works. While the former example (1) causes the skin conductance to increase, the second one (2) leads to a decrease of skin conductance and let the subject calm down. Between minute two and four of the simulated drive, there are more scenarios where the participant has to react to, which leads to an increase in skin conductance and a decrease in saccade amplitudes. This explains the drop of saccade amplitudes in the first minutes (see Fig. 5) in the low-SCS and the drop of skin conductance in high-SCS after 7 min.

We asked the test subjects whether they were disturbed by the IVB, but none of them even noticed the IVB. We observed the same for the decreased luminosity of the two lateral projection screens. Also, we observed that the low-SCS was much better accepted by the test persons than the high-SCS.

The reduction of scene complexity might have an influence on the driving performance. Therefore, we compared in post-analysis the driving performance in both scenes, and total number of errors, speed variability, lateral acceleration, time on brake pedal, and time to collision were evaluated. None of these parameters differed significantly in both scenes.

The strength of this study is that the measurements were conducted on two different days, with at least 1 day in between, at the same time of day. Also, the participants were instructed to eat the same on the 2 days. Furthermore, the test population is homogenous in age, gender, computer skills, and driving experience. The combination of SSQ and physiological measures is an additional advantage.

A limitation of the study is that we applied a combination of three methods, and we cannot determine how much each individual method contributes to the observed reduction of SHE. In this paper, we combine three modifications to reduce SHE during simulated driving. While others have studied single modifications (i.e., IVB [39]), no study has measured the effects of a combination of the three modifications. In this work, we show that the combination of the three modifications has significant effects on SHE, and these modifications can be recommended to other researchers as well. For future studies, it would be interesting to study the effects of the individual modifications in single conditions. Prothero et al. [39] used an IVB only and reduced SSQ score by 19.8 %. When we calculate the delta of SSQ score in the low-SCS and high-SCS and compare them, we found a reduction of 96.1 % which is statistically significant with $p = 0.005$. With this in mind and based on our observations, we believe that the reduction of scene content has the greatest influence to reduce SHE. Furthermore, the decrease of brightness is in favor to avoid flicker perception, which has been linked to SHE [30]. Due to the fact that the peripheral visual system is more sensitive to flicker than the fovea [4], the decrease of brightness in the two lateral projection screens is beneficial to avoid SHE. However, for future research, the influence of each method should be analyzed. While the influence of the IVB was already shown by others [12, 14, 34, 39], the contribution of the decrease of brightness should be further investigated (particularly with regard to the influence on optical flow and flicker). In addition, the impact on training efficiency due to degraded virtual reality by superimposing an IVB and simplifying urban scenarios needs to be investigated. Furthermore, the medium-sized number ($N = 20$) could be a limiting factor of the validity of our study.

Susceptibility to SHE differs among age groups [30]. Therefore, for future work, it would be interesting to conduct a similar study in other age groups (i.e., with older participants). Moreover, the critical optical flow when subjects start to feel symptoms of SHE could be interesting and could contribute to optimizing our adaptations.

In summary, the results indicate that the combination of the three methods will reduce SHE in fixed-based DS, which may improve the user comfort and may reduce dropout rates. Therefore, we can recommend these methods to other researchers as well.

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