Electrodermal Responses to Driving Maneuvers in a Motion Sickness Inducing Real-World Driving Scenario

Elena N. Schneider, Benedikt Buchheit, Philipp Flotho, Mayur J. Bhamborae, Farah I. Corona-Strauss, Florian Dauth, Mohamad Alayan, and Daniel J. Strauss

***Abstract*—Motion sickness is a phenomenon attracting increasing attention with the ever-growing popularity of highly automated driving. Understanding motion sickness is of significant interest in the context of self-driven vehicles because, in this case, all occupants of the vehicle are passengers and, therefore, more susceptible to motion sickness. In this article, we report the findings of a study wherein motion sickness was induced in 40% of the participants while driving in real-world conditions. By recording various psychophysiological parameters continuously (electrodermal activity, skin temperature, heart rate, and heart rate variability), we investigate the feasibility of using these to objectively assess motion sickness. Furthermore, the instantaneous physiological reactions of participants to unpleasant driving maneuvers are examined. The changes in the electrodermal activity show a strong correlation with the subjective ratings of motion sickness levels as reported by the participants. The phasic component of the electrodermal activity suggests differences between participants that are susceptible to motion sickness and those who are not. Several driving maneuvers (accelerations, cornering, and driving over speed bumps) were identified as events triggering significant electrodermal responses. These responses could be the result of a mismatch between visual and vestibular perception acting as an aversive, arousing stimulus. While, in this work, the driving maneuvers were partially overlapping and nonuniform, our results pave the way for future investigation of physiological responses to single driving events and their relation to motion sickness with the potential to identify real-time markers of possibly unpleasant driving maneuvers.**

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***Index Terms*—Electrodermal activity (EDA), electrodermal response (EDR), motion sickness (MS), self-driving cars.**

I. Introduction

MOTION sickness (MS) is a long-known phenomenon describing an illness caused by various types of motion and motion perception, such as traveling by sea, automobile, airplane, or in space [1], [2], and in virtual reality scenarios [3]. Symptoms can be nausea, vomiting, pallor, cold sweating, and headache [4]. When self-driving vehicles become a common occurrence, the proportion of people susceptible to MS is significantly increased, as more people are passengers that would be involved in doing other activities in the vehicle such as reading or playing games, instead of being involved in driving the vehicle [5]. The severity of the experienced symptoms varies considerably among subjects. In fact, many individuals do not experience MS in any way [6]. Factors such as habituation, fatigue, or concentration can also affect the susceptibility to MS [1], [6], [7]. The precise neural mechanisms leading to MS are still unclear [8].

The "sensory conflict" theory tries to explain MS as a result of a mismatch within the central nervous system between expected motion and processed sensory information [9]. When gazing downwards at a smartphone while moving in a car, the visual system perceives a static scene (the smartphone), whereas the vestibular system reports motion. In the case of a nondynamic driving simulator, the visual system perceives motion, while the vestibular system reports no motion. This mismatch could likely be the cause of reported nausea and simulator sickness [10]. While there are several hypotheses attempting to explain the cause of MS [11], one of the most cited is the "toxic hypotheses" [12], which states that the vestibular organ acts as a toxin detector in addition to its involvement in orientation and balance [6]. Since the aforementioned sensory mismatch is similar to that caused by the ingestion of toxins, the body reacts to this by inducing vomiting, which could potentially be an explanation for the emesis that occurs in individuals experiencing MS [12]. However, there are also arguments against this theory as the sole cause of MS [11].

Thermoregulation is a factor that is greatly affected in the development of nausea, which leads to the fact that MS and thermoregulation are also closely related [13]. Core body temperature decreases while experiencing MS and nausea [14]–[16].

Additionally, the so-called "cold sweating" starts, leading to a decrease in skin temperature [16] and an increase in electrodermal activity (EDA). Besides the tonic, slow-changing part of the EDA, also its phasic, fast-changing component increases with higher MS ratings [17], [18]. Prior to those symptoms, the so-called "sopite syndrome" occurs, a preliminary stage of MS describing symptoms like yawning, drowsiness, mood changes, and physical or mental aversion to work [19], [20]. Sleepiness, headache, and discomfort are also among the symptoms of MS [1]. A lot of research on MS has been carried out using an optokinetic drum [21], exposure to a nauseogenic rotating chair test [22], [23], or similar paradigms. Although an increased number of studies are conducted in real cars [24]–[26], only few of these studies record physiological data in addition to subjective questionnaires to evaluate the subject's state [18], [27], [28]. In the future, self-driving cars might use the physiological data of a passenger to objectively detect the development of MS at an early stage. Physiological measures such as EDA, heart rate (HR), heart rate variability (HRV), electroencephalography, and electrogastrogram have been used for evaluating MS in prior works [29]. The advantages of some of these signals are the ease of sensor attachment and the ability to measure with minimally intrusive wearable systems, such as wristbands. Minimally intrusive sensors or contactless measurement systems can ease the monitoring of vehicle occupants and increase their acceptance of such systems.

So far, it is known that there are certain oscillations eliciting MS to a larger extent than others, e.g., very low frequency vertical oscillations around $0.2\,\mathrm{Hz}$ [30], which are more common in nautical travel. In terms of MS, driving at a constant speed is perceived to be the most comfortable [5]. However, the combined accelerations in a vehicle are exposed to changing environmental influences and, therefore, usually manifest themselves much more dynamically than on a ship. The vestibular system is very sensitive to these changes in acceleration. Therefore, for this study, we chose a route that reflects real-world driving and traffic conditions to confirm preliminary results of the authors showing associations between MS and the autonomic nervous system using strong lateral and longitudinal accelerations [31]. Mainly, we intended to assess different driving maneuvers that might elicit an observable response of the autonomic nervous system on a short time scale. These responses might be used for the instantaneous evaluation of comfort levels of driving maneuvers and their relationship to MS.

II. Materials and Methods

In order to gather data that reflect real-world situations, we carried out the measurements in a Volkswagen Touran (second generation) retrofitted to house all the measurement equipment in accordance with the safety regulations. The participants were seated in the rear seat of the vehicle, and during each recording session of approximately 1 h, they were asked to perform simple cognitive tasks (see Section II-B). The same pretrained driver drove the car to minimize the variance across the measurements. However, small deviations in driving dynamics due to different traffic conditions could not be ruled out. Physiological data from the participants, driving dynamics data from the vehicle, and subjective feedback from the participants were recorded during each measurement; the details of which are as follows.

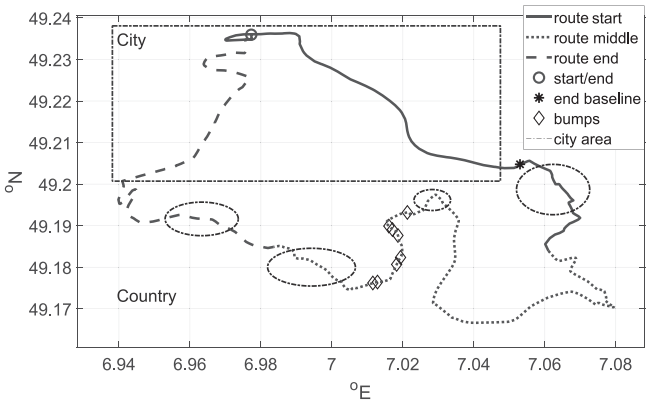

Fig. 1. Schematic representation of the driven route, with three sections (start, middle, and end), baseline ("start" until "end baseline"), and speed bumps. Sections were separated with respect to driving time. Start and end points of the sections can slightly change between subjects due to different traffic conditions.

A. Route Design

The route driven for each measurement was planned such that each session would last for about 1 h during similar times of the day assuming the traffic conditions would also be similar. A graphical overview of the route can be seen in Fig. 1. The measurement started at the university campus, with a $10\,\mathrm{min}$ drive on the highway $(8\,\mathrm{km})$ which serves as the baseline; meanwhile, subjects were told to look outside the window and the maximal velocity was around $110\,\frac{\mathrm{km}}{\mathrm{h}}$. After that, we passed an urban area followed by the countryside with maximal velocity reaching about $70\,\frac{\mathrm{km}}{\mathrm{h}}$. The next section was a short highway track followed by localities with narrow streets with several narrow curves as well as eight speed bumps. All bumps were driven at a speed of $20\,\frac{\mathrm{km}}{\mathrm{h}}$. The last part of the driving route contained a short interurban section and again a city drive with a speed limit of $30\,\frac{\mathrm{km}}{\mathrm{h}}$. In total, the track consisted of $10\,\mathrm{km}$ driven in cities and about $22\,\mathrm{km}$ in interurban areas. For the analysis, the route was split into three segments of equal length (start, middle, and end), with the first section including the baseline measurement. Longitudinal and lateral accelerations reached up to $4\,\frac{\mathrm{m}}{\mathrm{s}^2}$, and vertical accelerations reached $2\,\frac{\mathrm{m}}{\mathrm{s}^2}$. Driven maneuvers and exact accelerations are described in detail in Section II-E2. The euclidean norm of *x*-, *y*-, and *z*-acceleration for each individual subject can be found in the supplementary materials.

B. Behavioral Tasks

In order to evoke MS, subjects had to look down at a tablet PC, placed on the lap with the help of a padded tablet holder, to perform the following tasks: playing "Tic Tac Toe" and "Simon Says," read text, and watch a silent movie (this sequence was repeated in a loop). Each part had a duration of about $5\,\mathrm{min}$. After reading the text and watching the video, a few questions had to be answered to assess their attention to the task. In addition, there was a subjective nausea rating on a visual analog scale [subjective motion sickness level (SMSL)] visible on the tablet,

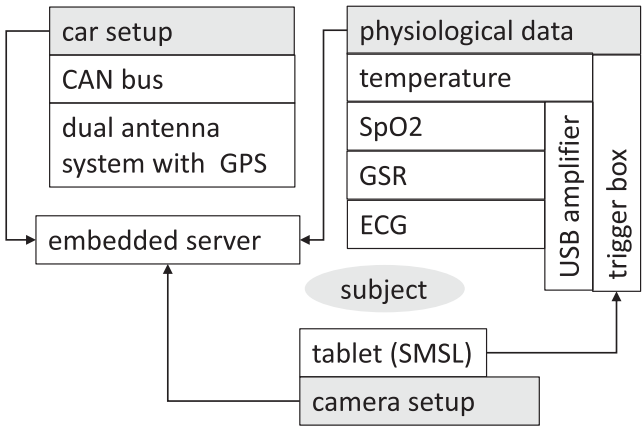

Fig. 2. Schematic setup of the car, with all sensors recording state of the car and the subject, and the camera setup with all used components.

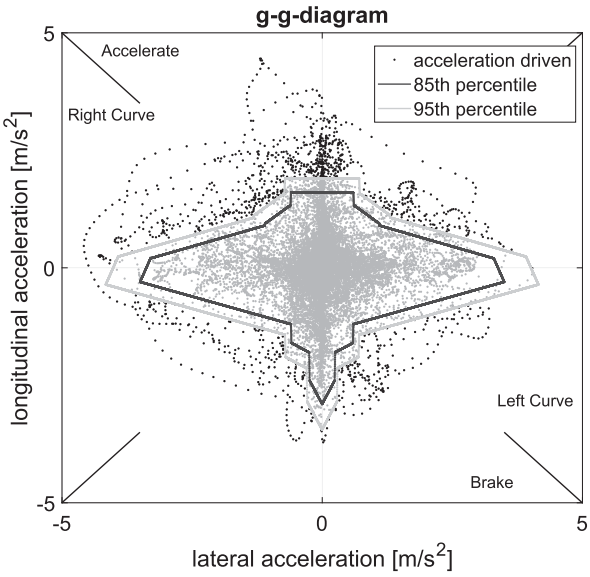

Fig. 3. g-g diagram of, 85th (gray), and 95th (black) percentiles of accelerations conducted during normal drives (model based). On the *y*-axis longitudinal accelerations can be seen (accelerating and braking) and on the *x*-axis, accelerations during cornering are depicted. The dots show the actual accelerations for one subject. The black dots were the maneuver used for the electrodermal response detection.

ranging from 0 (no symptoms at all) to 10 (vomiting or abortion of the measurement) comparable to the misery scale of MS, which ranges from 0 to 10 [32]. For a more intuitive evaluation, we replaced the descriptions of the stages in the misery scale (uneasiness, dizziness, headache, stomach awareness, nausea, etc.) with clip arts. Subjects were asked to rate their momentary SMSL in intervals of $5\,\mathrm{min}$. They were also able to rate their SMSL value at any time they experienced a change in their nausea level. Only a few subjects took advantage of this opportunity and the analysis of the SMSL was performed regardless of the number of evaluation points.

C. Data Acquisition

All measurement data was recorded using the same onboard computer ensuring proper time synchronization across different modalities. Fig. 2 illustrates the setup used for recording.

The physiological data was recorded with commercially available sensors and biosignal amplifier (g.tec USBamp, Guger Technologies OG, Austria) and a sampling frequency of $512\,\mathrm{Hz}$. The EDA measured was exosomatic with direct current (g.GSR, Guger Technologies OG, Austria) using two reusable dry Ag/AgCl electrodes attached to the second phalanx of the middle and ring finger of the left hand. Pulse (g.SPO2, Guger Technologies OG, Austria) was measured on the index finger and skin temperature (g.TEMPsens, Guger Technologies OG, Austria) on the little finger of the left hand. Three self-adhesive ECG electrodes were attached to the wrists and the left ankle.

The driving dynamics data was recorded from the vehicle's controller area network (CAN). This includes the GPS-based position, steering wheel angle, indicator flags, internally calculated velocities based on wheel speed, as well as the angle, angular velocity, and acceleration from the car's in-built sensors. Additionally, signals of the VBOX 3i (Racelogic Ltd, U.K.) were combined with the CAN. The VBOX 3i contained an external GPS/GLONASS dual antenna system and an inertial measurement unit to measure additional acceleration, angle, and GPS signals with a sampling frequency of $100\,\mathrm{Hz}$.

D. Participants

A total of 24 volunteers participated in the study. Four subjects had to be excluded from analysis, exhibiting steep increases in the tonic EDA (about $20\,\%$ in 1 s; see [33] and [34]) every time they interacted with the tablet. The resulting sample group for analysis included 13 male and 7 female subjects with a mean age of 23.85 ± 3.22 years ranging from 18 to 31 years. For the analysis of the responses to specific maneuvers (see Section III-D), we had to exclude another four subjects due to technical issues with the synchronization of physiological, behavioral, and/or CAN data. All subjects signed an information consent form and were again briefed about the experimental procedure during the measurement preparations while all remaining questions were answered.

To assess their susceptibility to MS, participants filled out a custom designed psychometric questionnaire. Included were eight questions from the "Graybiel Malaise Score" [35] and the "Reason Brand Motion Sickness Susceptibility Questionnaire" including the modified versions of Golding [9], [33], [36] (see Appendix). For evaluation of the questionnaire, different scores (between 0 and 3) were assigned depending on the answer (high scores indicating MS susceptibility). Subjects with a score higher than or equal to 6 (maximum score: 12) were assumed to be susceptible to MS. According to their highest SMSL rating in the measurement, subjects were separated into the two categories Cat1 (SMSL < 7, robust subjects who did not develop MS) and Cat2 (SMSL ≥ 7, subjects with MS symptoms). All procedures were conducted in accordance with the Declaration of Helsinki and were approved by the local ethics committee (Identification number: 181/18 Ärztekammer des Saarlandes; Medical Council of the Saarland).

E. Data Analysis

1) Physiological Data: The physiological signals examined are the EDA with its tonic and phasic components including single electrodermal responses (EDRs), skin temperature, HR, and HRV. All analysis steps were conducted using software for scientific computing (MATLAB 2018b, MathWorks Inc., USA). The raw EDA signal was low pass filtered using a Butterworth Filter of order 2 and a cutoff frequency of $1\,0\,\mathrm{Hz}$. The data was visually examined to detect sections including large artifacts as described in [34]. Tonic and phasic parts of EDA were split with a convex programming procedure described in [37]. Subsequently, the tonic EDA was normalized according to [38], to enable better intersubject comparison. Amplitude (EDRamp) and frequency (EDRfreq) of spontaneous phasic EDA peaks and EDRs are the mean values of the peak parameters collected over a moving window of $5\,\mathrm{min}$. A minimum peak amplitude criterion for EDRs of $0.01\ \mu\mathrm{S}$ was used [39].

The ECG signal was detrended, an IIR notch filter of $5\,0\,\mathrm{Hz}$ was applied, and it was bandpass filtered with a zero-phase Butterworth filter of fourth order with cutoff frequencies of 5 and $5\,0\,\mathrm{Hz}$. A logistic sigmoid function was used for QRS-complex detection. Distances between R-spikes indicating HRs higher than 200 bpm were categorized as artifacts. For quantifying HRV, we calculated the standard deviation of the normal-to-normal intervals (SDNN) for segments of $5\,\mathrm{min}$.

Fig. 4 depicts the grand average of physiological data separated for Cat1 and Cat2. To check for close relations between the SMSL and physiological data, Pearson correlation coefficients (r) were calculated. To average the correlation coefficients, we used Fisher's z-score [40]. Since the SMSL is a stair-shaped signal and the physiological signal is not, the physiological data was segmented and approximated by the mean in each segment with constant SMSL to reduce the false correlations that can occur due to sudden sharp increases in the SMSL (see Fig. 5).

2) Maneuver Classification: To visualize an instantaneous response to motion as an evoked EDR, specific driving maneuvers were isolated. Large accelerations in every direction (longitudinal acceleration and braking (x-acceleration), cornering (y-acceleration), and speed bumps) were separated. We applied a one-way analysis of variance to examine whether mean phasic EDA was significantly different 10 s before and 10 s after the maneuver. We chose this time scale due to the latency of EDRs which can vary from 1 to 10 s after an event [41]. Additionally, we wanted to be sure that every event is included in the analysis, and also if it was marked shortly before or after the actual start. Wegschweider and Prokop [42] defined a reference driver model regarding accelerations in every direction. This model is visualized in a g-g-diagram of horizontal acceleration. The theoretical "normal" driver is defined by the 85th percentile (see Fig. 3, dark gray graph). To classify maneuvers in this study, the respective 95th percentile was estimated (see Fig. 3, light gray graph). For the analysis, only maneuvers with accelerations larger than the 95th percentile were used (see Fig. 3, black dots). The time point at which the horizontal acceleration exceeded the $9\,5\,\%$ limit was defined as the start point of a maneuver. The maneuver is finished when the value decreases below the limit again. The positions of the speed bumps in the individual measurements were detected based on the recorded GPS position of the car and the known GPS position of the speed bumps. The time point of the tire hitting the obstacle was approximated based on the vertical acceleration and defined as reference point.

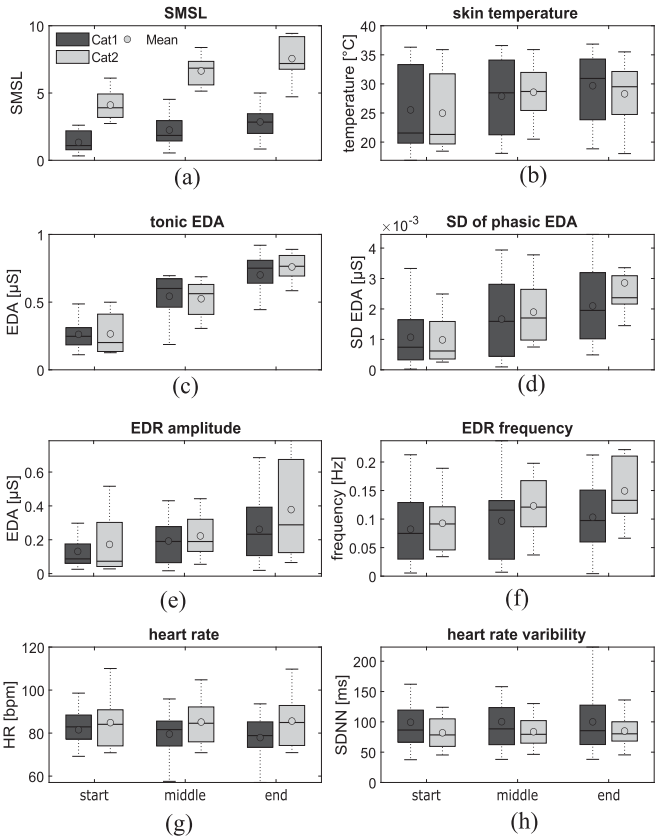

Fig. 4. Boxplots of the physiological data of all subjects separated into three measurement sections (start, middle, and end). The dark gray boxes show Cat1 and the light gray boxes Cat2. In addition to the median, the mean is also depicted (little circles). (a)–(h) SMSL and the different psychological measures.

III. Results

From the 20 included subjects, 12 were categorized into Cat1 (female: 4, male: 8, and age: 23.83 ± 3.54 years) and 8 into Cat2 (female: 3, male: 5, and age: 23.88 ± 2.9 years). Two participants from Cat2 had to abort the measurement due to severe nausea. $4\,3\,\%$ of the women and $3\,8\,\%$ of the men got motion sick, resulting in a total of $4\,0\,\%$ of all subjects. Fig. 4(a) shows the SMSL of the subjects of Cat1 and Cat2, separated into three measurement sections. Furthermore, the completed questionnaires were used for an additional method of categorizing participants into susceptible and not susceptible to MS. Comparing this categorization with the SMSL rated in the measurement, $7\,7\,\%$ of the subjects were separated correctly into the two classes. The results of the behavioral tasks (gaming scores and answered questions) show that the subjects were very focused on their given tasks, indicated by very high scores, which did not vary throughout the measurement or in relation to the rated SMSL. A statistical overview of the physiological data from all subjects during the various stages of the recording

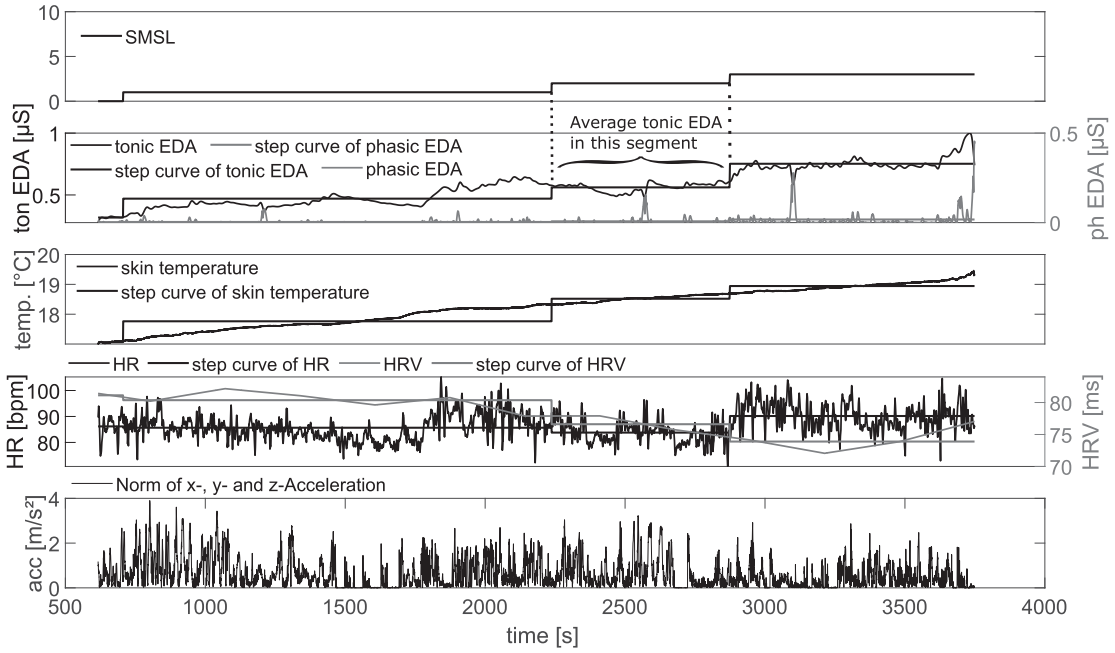

Fig. 5. SMSL, EDA [tonic EDA (ton), and phasic EDA (ph)], temperature (temp.), heart rate (HR), and heart rate variability (HRV) of one subject after the baseline measurement until the end of the measurement can be seen. Similar plots for all subjects can be found in the supplementary material.

session, separated into Cat1 and Cat2, can be seen in Fig. 4. Fig. 5 illustrates the data for one specific subject (male, 24 years).

A. Heart Rate and Heart Rate Variability

Over the course of the measurement, mean HR slightly decreased for Cat1 (from 81 to 78 bpm) and remained constant for Cat2 (85 bpm) [see Fig. 4(g)]. The changes within the categories are small, but deviations between the categories of 5–7 bpm might suggest a general difference between the categories ($p = 0.06$). Large standard deviations (12 bpm for Cat1 and 6 bpm for Cat2) indicate high intersubject differences in HR. The mean HRV (SDNN) shows a similar trend. It remained relatively constant for Cat1 [see Fig. 4(h)] and increased slightly by 4 ms for Cat2 throughout the experiment. The smallest difference between the mean of the two categories is around 15 ms at the end of the measurement. There is only a slight negative correlation between HR and SMSL ($r = –0.22$, $p < 0.001$) and no correlation between SDNN and the SMSL ($r = 0.09$, $p < 0.001$).

B. Temperature

The skin temperature of the little finger and the SMSL show a positive average correlation ($r = 0.66$, $p < 0.001$). A small difference is visible between the temperature of susceptible and nonsusceptible subjects. Whereas the mean temperature rose by $2\,^{\circ}\mathrm{C}$ for Cat1 from the middle to the end section, it slightly decreased for Cat2 [see Fig. 4(b)]. In general, the skin temperature is seen to be increasing from the start to the end of the measurement

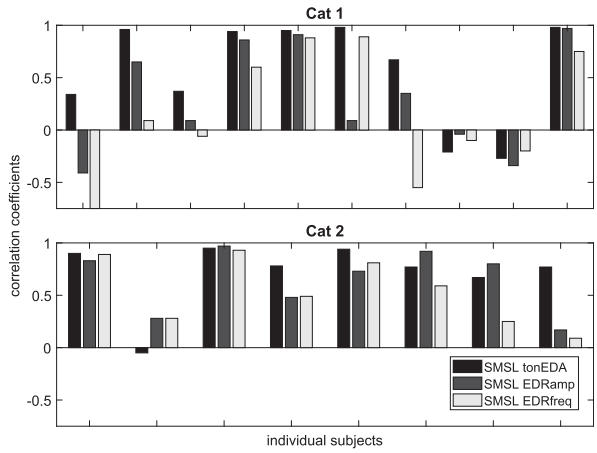

Fig. 6. Correlation coefficients of SMSL with tonic EDA, EDR amplitude, and EDR frequency for the included individual subjects.

C. Electrodermal Activity

Fig. 6 presents the individual correlation coefficients for all subjects between SMSL and tonic EDA, EDRamp, and EDRfreq. In the top graph, subjects from Cat1 can be seen, and on the bottom graph Cat2. The tonic EDA shows a positive average correlation with the SMSL ($r = 0.81$, $p < 0.001$). $40\,\%$ of the subjects showed a very high correlation of over 0.9 (see Fig. 6). Correlation between tonic EDA and measurement time shows an r-value of 0.86 ($p < 0.01$) during the measurement and $r = 0.03$ ($p < 0.001$) during the baseline drive. In Fig. 5, the tonic part of the EDA closely follows the SMSL, especially in the middle and at the end of the measurement. To analyze the relation between the phasic component of the EDA and the SMSL, the moving

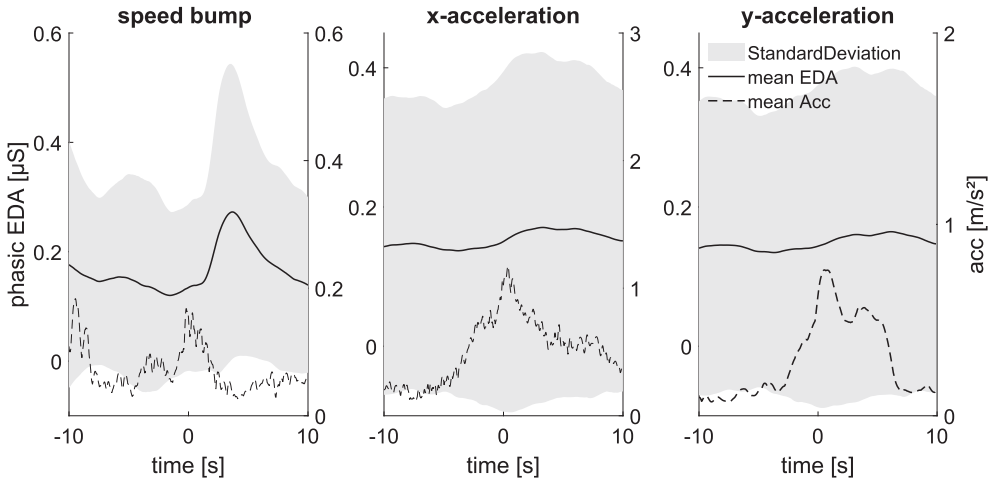

Fig. 7. Mean electrodermal responses of 16 subjects to different driving maneuvers. Mean phasic EDA 10 s prior until 10 s post an event (solid line) and the corresponding accelerations (dotted line).

standard deviation with a sliding window of 10 s was used as a general measure of the phasic EDA alteration ($r = 0.65$, $p < 0.001$). Additionally, amplitude (EDRamp, $r = 0.6$, $p < 0.001$) and frequency (EDRfreq, $r = 0.43$, $p < 0.001$) of EDRs were calculated over a moving window of $5\,\mathrm{min}$. Fig. 4(c) depicts the course of the normalized tonic EDA for all subjects, split into Cat1 and Cat2. Cat2 shows slightly higher mean levels of tonic EDA in the last section of the measurement ($0.76\ \mu\mathrm{S}$) than Cat1 ($0.71\ \mu\mathrm{S}$). In the first and second sections, Cat1 showed slightly higher mean values than Cat2, indicating a faster increase for Cat2 than for Cat1. Note that the phasic EDA in Fig. 4(d)–(f), the standard deviation of the phasic EDA, and the mean amplitude and frequency of the EDRs show also differences between the categories along the end of the measurement. EDRfreq increased from the middle section to the end section for Cat2 by $25\,\%$ (from 0.12 to $0.15\,\mathrm{Hz}$) and for Cat1 only by $11\,\%$ (from 0.09 to $0.1\,\mathrm{Hz}$). EDRamp increased by $72\,\%$ for Cat2 (from 0.22 to $0.38\ \mu\mathrm{S}$) and by $36\,\%$ for Cat1 (from 0.19 to $0.26\ \mu\mathrm{S}$). This tends to suggest differences between Cat1 and Cat2, especially during the end of the measurement, even though *p*-values show no significant differences between categories ($p > 0.05$).

D. Electrodermal Responses to Motion

Specific driving maneuvers which are known to be uncomfortable during driving have been identified (see Section II-E2). For every subject, we could separate eight speed bumps, around 100 longitudinal, and around 100 lateral events. Some events are counted in both lateral and longitudinal categories, e.g., braking while driving a curve. We compared the mean phasic EDA of 10 s prior to the event onset and 10 s after the event onset. The mean of all EDRs shows a response to all three types of events (Fig. 7 acceleration, cornering, and speed bumps). Especially the speed bumps elicited a clear EDR. Mean EDR amplitude (onset to maximum) is $0.13\ \mu\mathrm{S}$ and the latency (start of the event to maximum of the EDR) is about 1.2 s on average. For cornering and accelerations, a response in the phasic EDA is visible as well, showing only a small increase after the event. However, there is a significant difference between the mean phasic EDA before and after the event ($p < 0.05$). Fig. 7 (dotted lines) shows the acceleration during the analyzed 20 s for every maneuver.

IV. Discussion

In our preliminary work (see [31] and supplementary material), we observed large correlations between EDA, HRV, and MS under strong accelerations. For this study, we designed the paradigm to reflect commuting in a self-driven car in real-world traffic conditions. Our results confirm a close connection between EDA and MS. Additionally, we could observe EDRs after certain driving maneuvers. The tonic EDA shows the strongest correlations with subjective MS ($r = 0.81$, $p < 0.01$). EDA is commonly used to study mental arousal, emotions, and stress [41]. Cold sweating being a symptom of MS does result in an increased EDA. Smyth *et al.* [27] indicate that EDA cannot be used for real-time evaluation of MS because it is affected by emotions and environmental factors. But since an onset of MS can also result in an increase in the perception of stress, we assume that increased EDA can also be attributed to increased stress due to MS. Besides the correlation to MS, EDA and the time on task are also strongly correlated ($r = 0.86$, $p < 0.01$). This close relation can be explained by the strong correlation between SMSL and time on task ($r = 0.87$, $p < 0.01$). However, especially the time course of the tonic EDA with increasing measurement duration looks very similar in both subject groups Cat1 and Cat2, indicating that time on task might have the highest impact. Comparing the correlations between tonic EDA and time during the baseline drive, it can be seen that, without the sensory mismatch (subjects had to look to the road ahead), there is no correlation between EDA and time ($r = 0.03$). This suggests that EDA is mainly affected by MS. Irmak *et al.* [18] explain the correlation between EDA and time with the persistent stabilizing muscle action due to the motion of the vehicle. However, we cannot exclude the possibility that temporal effects, and with this, occurring discomfort or annoyance can have impact on EDA. In contrast to the tonic EDA, the phasic component has been shown to correlate more strongly with MS, while being also less affected by temporal aspects [18], [43], [44]. Our

data suggests similar behavior, showing differences between susceptible and nonsusceptible subjects. Particularly, EDRamp and EDRfreq show a larger increase in Cat2 subjects than in Cat1 subjects as the measurement progresses, whereas the increase in tonic EDA does not show such differences. Phasic EDA consisting of EDRs can be separated into nonspecific, also called spontaneous EDRs, and evoked EDRs. Because of the similar dynamics distributed over the driving route, indicating a constant number of events potentially evoking EDRs, all EDRs were analyzed as spontaneous ones in the first step. The frequency and amplitude of the spontaneous EDRs are therefore not distorted. It has been shown that the spectral content of phasic EDA is better suited for interindividual comparability of EDA [45]–[47]. However, optimizing spontaneous EDR parameters was not the scope of this article.

We were able to identify single driving maneuvers eliciting strong EDRs. Passing speed bumps, accelerations, and cornering lead to a significant increase in mean EDA on a short time scale of about 10 s. The isolated maneuvers are known to increase discomfort and lead to MS [5], [48]. Urban driving conditions, where such events are clustered, also favor the onset of MS symptoms the most [24]. Usually, EDRs are triggered by aversive stimuli like loud noises, arousing images, or startling events. Such stimuli increase arousal, leading to an increased tonic EDA and to EDRs. Even without MS symptoms, the mismatch between visual and vestibular perception, described by the "sensory conflict" theory, is an aversive stimulus, perceived as uncomfortable and unpredictable and therefore increasing arousal. This might be a contributing factor to trigger EDRs. The presented EDRs show no direct relation to MS as assessed by the SMSL here. In real-world driving conditions, not every event detected by vestibular receptors can be identified and separated from other events. Speed bumps were rare events on the driven route, with only eight bumps per subject. Therefore, we can see a clear mean EDR with all parameters in the standard range of amplitudes higher than $0.01\ \mu$S and latencies around 1–3 s [39], [41], [47]. While the presence of motion artifacts can never fully be ruled out, tests with the electrodes in the car could not produce motion artifacts during intentionally executed movements that resemble the motion during the experiment. Care was also taken to ensure that the electrodes were always attached tightly enough to avoid slipping on the skin. The speed bumps were always driven at the same speed, but the visible responses and parameters changed between subjects and trials, also suggesting that no motion artifacts were measured. The phasic EDA during acceleration and cornering also shows an increase but no clearly shaped responses, which can be attributed to the onsets of the events, which could not be triggered exactly. Also, no event elicits the same response, e.g., acceleration to different velocities and length of the curves, can also affect the shape of the responses. Additionally, several different accelerations can operate at the same time, leading to overlapping EDRs. Mühlbacher *et al.* [28] state that driving maneuvers or unexpected events (like accelerations) only negatively affect the EDA and complicate the evaluation. Here, we suggest an isolated examination of EDRs to those events, to detect changes related to SMSL. Such driving maneuvers also increase discomfort and arousal, which are known to alter the parameters of EDRs. However, whether an increased level of MS has an impact on EDRs has to be investigated in future. Here, the speed bumps were all concentrated in one section of the driving route (see Fig. 1), and other driving maneuvers were not driven completely isolated. This avoids the possibility to recognize differences in the EDRs with increasing MS. To investigate this aspect in more detail, attention should be paid to the separation of driving maneuvers to see EDR development over time. If there are alterations with increasing MS, subjective ratings on a short time scale, like in [18], can be extended with an objective measure. We already know that latencies of EDRs change with cognitive effort [47], which suggests that MS or discomfort could also have effects on EDRs. Considering both the spontaneous and the evoked EDRs, the amplitude increases over time, as mentioned above [see Fig. 4(e)]. This increases the confidence to find changes in event-related EDRs with different MS states in future measurements. One main problem using the EDA as an objective MS evaluation factor is the high deviation between individuals. $40\,\%$ of the subjects showed strong positive correlations with $r \geq 0.9$, while others exhibited only poor correlations ($r < 0.3$, $p < 0.001$). Fig. 6 demonstrates that some subjects of Cat1 show no correlation between SMSL and EDA features at all. Similar results by Irmak *et al.* [18] indicate that phasic EDA shows significant changes with subjective sickness level, but only at the group level with a high spread across individuals. Our results show that most subjects with weak correlation between EDA and SMSL belong to Cat1 (not susceptible to MS). We also see that phasic EDA is closely related to the SMSL for these cases. With the use of other electrode placements, an objective evaluation of MS might be more feasible. EDA recordings from the face, especially phasic EDA parameters, provide stronger correlations to MS than the recording sites we used [43], [49], [50]. Variances in EDA triggered by environmental influences can thus be reduced, and, importantly, the start of cold sweating in the face, triggered by nausea, can be detected. However, long-term EDA measurements can lead to degrading signals, followed by polarization of electrodes [39]. In the future, some of those limitations might be overcome by contactless methods. Besides imaging and analysis of skin surface temperature in the face, preliminary studies could show that the contactless approximation of EDA signal from RGB sensors on the hand is possible in a static lab setting [51]. The multimodal camera recordings of the face collected in this study can help to investigate whether noncontact monitoring methods are able to reliably approximate the temperature and EDA dynamics in the face to realize contactless real-time evaluation of MS.

Core temperature is also affected by the onset of MS. With increasing nausea, body temperature is downregulated. One of the involved mechanisms in thermoregulation is vasodilation which releases heat to the environment. For this purpose, blood flow is increased in skin surface [15], [52], [53]. This is also reflected in our data with a positive correlation between finger skin temperature and SMSL ($r = 0.66$, $p < 0.01$). Latest studies conducted in real-world driving situations reported positive correlations between MS and skin temperature in some subjects as well [27], [28]. Despite that, the skin temperature shows a slight decrease for Cat2 subjects during the last part of the measurement. High SMSL toward the end, resulting in cold

sweating, could lead to this decrease. To verify this assumption and to draw clear conclusions, there needs to be a comparison of the core temperature with the body surface temperature on the skin, because of a lack of data of skin surface temperature in MS studies under controlled conditions. Preliminary analysis of the facial thermal imaging data shows a noticeable increase in the temperature followed by a sudden drop in subjects that experienced severe nausea. Such drops have only been observed in experiments monitoring the tail temperature of rats during rotation, related to the "toxic hypothesis" [15]. Cold sweating shortly before vomiting or abortion of the experiment can lead to such a sudden decrease of skin temperature. The reliability of facial thermal data is relatively poor because it can easily be influenced by environmental factors such as air flow within the vehicle itself. In our case, the standard air condition system of the vehicle was set to $20\,^{\circ}\mathrm{C}$, but this cannot guarantee a constant ambient temperature within the vehicle which was not monitored.

HR and HRV show almost no correlation to the SMSL in our setting. Many studies indicated that the HR increases, whereas the HRV decreases, with rising MS [3], [50], [54], [55], while other studies report no effects related to MS [49]. Preliminary results of the authors, presented in the supplementary material, indicate increased HRV for susceptible subjects compared to not susceptible ones. In this experiment, the HR data suggests a difference between susceptible and nonsusceptible subjects [see Fig. 4(g), $p = 0.06$]. For Cat1, a small decrease in HR is visible, which could be related to excitement or nervousness at the beginning of the measurement, which leads to a high HR. With increasing duration and no signs of MS, the subjects relaxed and got used to the environment, causing the HR to decrease. Similar results have been discussed in [18]. Gavgani *et al.* [49] argued that cardiac symptoms can be explained by stress due to a new experience, but they have no relation to MS because cardiac changes have no evolutionary benefit as per the "toxic hypothesis" theory presented in [12]. There are subjects with increasing HR and decreasing HRV (see Fig. 5), although no severe MS was experienced (SMSL ≤ 3). This indicates, besides high standard deviations, a high variability between individuals.

Combining physiological signals, especially the EDA, with the preclassification by the questionnaire, an assessment of a person's current MS stage might be possible in the future. Using this questionnaire, we were able to correctly classify the subjects into "not susceptible" and "susceptible" with respect to the actual SMSL. This allows the planning of routes tailored to an individual minimizing the probability of MS occurrence. SMSL was collected every $5\,\mathrm{min}$, which we identified as an ideal compromise between high-frequent self-assessment and distraction-free focus on the tasks. We could not find any disadvantages regarding the choice of the evaluation interval, such as large increases in SMSL from one interval to the next. If the subjects felt a sudden change, they always had the possibility to adjust the SMSL at any time. However, only few subjects made use of this option, which confirms that, on average, they were focused on their tasks instead of their symptoms, which was our intention for choosing the assessment interval. Another indication of the subjects' high level of concentration on their tasks is their consistently good performance which changed neither with respect to time nor SMSL. Those results are backed by Smyth *et al.* [56] who observed an independence of task performance and MS. Additionally, the tasks were designed to distract the participants from the route without being too challenging to avoid frustration.

We designed the traveled route to represent daily commute. Compared to other studies investigating MS under real driving conditions, the perceived accelerations are similar in terms of intensity. However, large accelerations occur less frequently than in [18] where slalom maneuvers were performed. We compensated the lower density of accelerations with a longer duration of the route of about $40\,\mathrm{km}$ with an average duration of $50\,\mathrm{min}$. A known trigger for MS is an acceleration frequency of $0.2\,\mathrm{Hz}$. Although, our paradigm did not contain explicit maneuvers to evoke these situations, we observed the MS symptom onset in the susceptible subjects after 10–$20\,\mathrm{min}$, comparable to studies with artificially created routes [18], [57].

V. Conclusion

The development of self-driving cars will be closely linked with the methods for monitoring the state of the passengers. In this context, the objective assessment of MS has earlier been identified as an important problem that needs to be addressed to ensure the acceptance of self-driving cars. Our work brings MS research one step closer to out-of-lab scenarios. We could reproduce established measures in real-world traffic. We tried to find correlates of the autonomic nervous system to map the SMSL objectively and to enrich the still limited amount of available data in real-world traffic. We found strong correlations between MS and EDA parameters for a subset of the participants. Phasic EDA suggests differences between participants susceptible to MS and participants not susceptible. These results match with previous findings presented in literature. Moreover, single EDRs to different driving maneuvers, strong vertical, lateral, and horizontal accelerations were reported for the first time. Future measurements and evaluations need to investigate to what extent MS or discomfort alters the appearance of EDRs evoked by driving maneuvers.

Appendix

TABLE I
Motion Sickness Questionnaire

Do you see yourself as prone to motion sickness?	Not at all 0	Little 1	Moderate 2	Extreme 3
Can you read or watch videos during a car trip without getting sick?	No 0		Yes 1	
How severe are your symptoms when they occur?	0–1 0	2–5 1	6–8 2	9–10 3
Have you ever taken medication for motion sickness symptoms?	No 0		Yes 1	
Do you have any tricks to avoid the occurrence of motion sickness?	No 0		Yes 1	
Does sitting in the front or back seat affect motion sickness?	No 0		Yes 1	
Does the way of sitting affect motion sickness?	No 0		Yes 1	
Do factors such as attention or fatigue influence motion sickness?	No 0		Yes 1	

Sum of scores < 6 not susceptible (Cat1).
Sum of scores ≥ 6 susceptible (Cat2).

REFERENCES

[1] K. E. Money, "Motion sickness," *Physiol. Rev.*, vol. 50, no. 1, pp. 1–39, 1970.

[2] F. Schmäl, "Neuronal mechanisms and the treatment of motion sickness," *Pharmacology*, vol. 91, pp. 229–241, 2013.

[3] L. L. Zhang, J. Q. Wang, R. R. Qi, L. L. Pan, M. Li, and Y. L. Cai, "Motion sickness: Current knowledge and recent advance," *CNS Neurosci. Therapeutics*, vol. 22, pp. 15–24, 2016.

[4] J. R. Lackner, "Motion sickness: More than nausea and vomiting," *Exp. Brain Res.*, vol. 232, no. 8, pp. 2493–2510, 2014.

[5] C. Diels and J. E. Bos, "Self-driving carsickness," *Appl. Ergonom.*, vol. 53, no. Part B, pp. 374–382, 2015.

[6] J. F. Golding, "Motion sickness susceptibility," *Autonomic Neurosci.: Basic Clin.*, vol. 129, pp. 67–76, 2006.

[7] D. Huppert, E. Grill, and T. Brandt, "Survey of motion sickness susceptibility in children and adolescents aged 3 months to 18 years," *J. Neurol.*, vol. 266, no. s1, pp. 65–73, 2019.

[8] Y. Wei, Y. O. Okazaki, R. H. So, W. C. Chu, and K. Kitajo, "Motion sickness-susceptible participants exposed to coherent rotating dot patterns show excessive N2 amplitudes and impaired theta-band phase synchronization," *NeuroImage*, vol. 202, 2019, Art. no. 116028.

[9] J. T. Reason and J. J. Brand, *Motion Sickness*. New York, NY, USA: Academic Press, 1975.

[10] J. E. Bos, W. Bles, and E. L. Groen, "A theory on visually induced motion sickness," *Displays*, vol. 29, no. 2, pp. 47–57, 2008.

[11] C. M. Oman, "Are evolutionary hypotheses for motion sickness "Just-So" stories?," *J. Vestibular Res.: Equilibrium Orientation*, vol. 22, no. 2–3, pp. 117–127, 2012.

[12] M. Treisman, "Motion sickness: An evolutionary hypothesis," *Science*, vol. 197, no. 4302, pp. 493–495, 1977.

[13] G. Nobel, A. Tribukait, I. B. Mekjavic, and O. Eiken, "Effects of motion sickness on thermoregulatory responses in a thermoneutral air environment," *Eur. J. Appl. Physiol.*, vol. 112, no. 5, pp. 1717–1723, 2012.

[14] K. P. Ossenkopp, Y. J. Rabi, L. A. Eckel, and E. L. Hargreaves, "Reductions in body temperature and spontaneous activity in rats exposed to horizontal rotation: Abolition following chemical labyrinthectomy," *Physiol. Behav.*, vol. 56, no. 2, pp. 319–324, 1994.

[15] E. Nalivaiko, J. A. Rudd, and R. H. So, "Motion sickness, nausea and thermoregulation: The "toxic" hypothesis," *Temperature*, vol. 1, no. 3, pp. 164–171, 2014.

[16] A. Hemingway, "Cold sweating in motion sickness," *Amer. J. Physiol.-Legacy Content*, vol. 141, no. 2, pp. 172–175, 1944.

[17] H. Wan, S. Hu, and J. Wang, "Correlation of phasic and tonic skin-conductance responses with severity of motion sickness induced by viewing an optokinetic rotating drum," *Perceptual Motor Skills*, vol. 97, no. 3 II, pp. 1051–1057, Dec. 2003.

[18] T. Irmak, D. M. Pool, and R. Happee, "Objective and subjective responses to motion sickness: The group and the individual," *Exp. Brain Res.*, vol. 239, no. 2, pp. 515–531, 2021.

[19] A. Graybiel and J. Knepton, "Sopite syndrome: A sometimes sole manifestation of motion sickness," *Aviation, space, Environ. Med.*, vol. 47, no. 8, pp. 873–882, 1976.

[20] B. Lawson and A. Mead, "The sopite syndrome revisited: Drowsiness and mood changes," *Aerospace*, vol. 43, pp. 181–192, 1998.

[21] J. Dahlman, A. Sjörs, J. Lindström, T. Ledin, and T. Falkmer, "Performance and autonomic responses during motion sickness," *Hum. Factors*, vol. 51, no. 1, pp. 56–66, 2009.

[22] P. S. Cowings, S. Suter, W. B. Toscano, J. Kamiya, and K. Naifeh, "General autonomic components of motion sickness," *Psychophysiology*, vol. 23, no. 5, pp. 542–551, 1986.

[23] A. Rolnick and R. E. Lubow, "Why is the driver rarely motion sick? The role of controllability in motion sickness," *Ergonomics*, vol. 34, no. 7, pp. 867–879, 1991.

[24] S. Salter, C. Diels, P. Herriotts, S. Kanarachos, and D. Thake, "Motion sickness in automated vehicles with forward and rearward facing seating orientations," *Appl. Ergonom.*, vol. 78, pp. 54–61, 2019.

[25] O. X. Kuiper, J. E. Bos, and C. Diels, "Looking forward: In-vehicle auxiliary display positioning affects carsickness," *Appl. Ergonom.*, vol. 68, pp. 169–175, 2018.

[26] J. Smyth, P. Jennings, P. Bennett, and S. Birrell, "A novel method for reducing motion sickness susceptibility through training visuospatial ability - A two-part study," *Appl. Ergonom.*, vol. 90, 2021, Art. no. 103264.

[27] J. Smyth, S. Birrell, R. Woodman, and P. Jennings, "Exploring the utility of EDA and skin temperature as individual physiological correlates of motion sickness," *Appl. Ergonom.*, vol. 92, 2021, Art. no. 103315.

[28] D. Mühlbacher, M. Tomzig, K. Reinmüller, and L. Rittger, "Methodological considerations concerning motion sickness investigations during automated driving," *Information*, vol. 11, no. 5, 2020, Art. no. 265.

[29] A. Koohestani et al., "A knowledge discovery in motion sickness: A comprehensive literature review," *IEEE Access*, vol. 7, pp. 85755–85770, 2019.

[30] J. F. O'Hanlon and M. E. McCauley, "Motion sickness incidence as a function of the frequency and acceleration of vertical sinusoidal motion," *Aerosp. Med.*, vol. 45, no. 4, pp. 366–369, 1974.

[31] B. Buchheit, E. N. Schneider, M. Alayan, F. Dauth, and D. J. Strauss, "Motion sickness prediction in self-driving cars using the 6DOF-SVC model," *IEEE Trans. Intell. Transp. Syst.*, to be published, doi: 10.1109/TITS.2021.3125802.

[32] J. E. Bos, S. N. Mackinnon, and A. Patterson, "Motion sickness symptoms in a ship motion simulator: Effects of inside, outside, and no view," *Aviation Space Environ. Med.*, vol. 76, no. 12, pp. 1111–1118, 2005.

[33] J. F. Golding, "Predicting individual differences in motion sickness susceptibility by questionnaire," *Pers. Individual Differences*, vol. 41, no. 2, pp. 237–248, Jul. 2006.

[34] R. Kocielnik, N. Sidorova, F. M. Maggi, M. Ouwerkerk, and J. H. Westerink, "Smart technologies for long term stress management at work," in *Proc. 26th IEEE Int. Symp. Comput.-Based Med. Syst.*, 2013, pp. 53–58.

[35] A. Graybiel et al., "Diagnostic criteria for grading the severity of acute motion sickness. naval aerospace medical institute," *Nav. Aerosp. Med. Center*, vol. 39, no. 5, pp. 453–455, May 1968.

[36] J. F. Golding, "Motion sickness susceptibility questionnaire revised and its relationship to other forms of sickness," *Brain Res. Bull.*, vol. 47, no. 5, pp. 507–516, 1998.

[37] A. Greco, G. Valenza, A. Lanata, E. P. Scilingo, and L. Citi, "cvxEDA: A convex optimization approach to electrodermal activity processing," *IEEE Trans. Biomed. Eng.*, vol. 63, no. 4, pp. 797–804, Apr. 2016.

[38] D. Lykken, R. Rose, B. Luther, and M. Maley, "Correcting psychophysiological measures for individual differences in range," *Psychol. Bull.*, vol. 66, no. 6, 1966, Art. no. 481.

[39] W. Boucsein et al., "Publication recommendations for electrodermal measurements," *Psychophysiology*, vol. 49, no. 8, pp. 1017–1034, 2012.

[40] R. A. Alexander, "A note on averaging correlations," *Bull. Psychon. Soc.*, vol. 28, no. 4, pp. 335–336, 1990.

[41] M. E. Dawson, A. M. Schell, and D. L. Filion, "The electrodermal system," in *The Handbook of Psychophysiology*, J. L. Cacioppo, G. Tassinary, and G. G. Berntson, Eds. Cambridge, U.K.: Cambridge Univ. Press, 2007, ch. 7, pp. 159–181.

[42] M. Wegscheider and G. Prokop, "Modellbasierte komfortbewertung von fahrerassistenzsystemen," *VDI Berichte*, vol. 1900, no. 1900, pp. 17–36, 2005.

[43] J. F. Golding, "Phasic skin conductance activity and motion sickness," *Aviation, Space, Environ. Med.*, vol. 63, no. 3, pp. 165–171, 1992.

[44] E. Nalivaiko, "Thermoregulation and nausea," in *Handbook of Clinical Neurology, Thermoregulation: From Basic Neuroscience to Clinical Neurology, Part 1*, vol. 156, A. A. Romanovsky, Ed. Amsterdam, The Netherlands: Elsevier B.V., ch. 27, 2018.

[45] H. F. Posada-Quintero et al., "Time-varying analysis of electrodermal activity during exercise," *PLoS One*, vol. 13, no. 6, 2018, Art. no. e0198328.

[46] H. F. Posada-Quintero, T. Dimitrov, A. Moutran, S. Park, and K. H. Chon, "Analysis of reproducibility of noninvasive measures of sympathetic autonomic control based on electrodermal activity and heart rate variability," *IEEE Access*, vol. 7, pp. 22523–22531, 2019.

[47] H. F. Posada-Quintero and K. H. Chon, "Innovations in electrodermal activity data collection and signal processing: A systematic review," *Sensors*, vol. 20, no. 2, 2020, Art. no. 479.

[48] M. Turner and M. J. Griffin, "Motion sickness in public road transport: The relative importance of motion, vision and individual differences," *Brit. J. Psychol.*, vol. 90, no. 4, pp. 519–530, 1999.

[49] A. M. Gavgani, K. V. Nesbitt, K. L. Blackmore, and E. Nalivaiko, "Profiling subjective symptoms and autonomic changes associated with cybersickness," *Autonomic Neurosci.: Basic Clin.*, vol. 203, pp. 41–50, 2017.

[50] A. Mazloumi Gavgani, D. M. Hodgson, and E. Nalivaiko, "Effects of visual flow direction on signs and symptoms of cybersickness," *PLoS One*, vol. 12, no. 8, 2017, Art. no. e0182790.

[51] M. J. Bhamborae, P. Flotho, A. Mai, E. N. Schneider, A. L. Francis, and D. J. Strauss, "Towards contactless estimation of electrodermal activity correlates," in *Proc. 42nd Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, Montreal, QC, Canada, 2020, pp. 1799–1802.

[52] N. Charkoudian, "Skin blood flow in adult human thermoregulation: How it works, when it does not, and why," *Mayo Clinic Proc.*, vol. 78, no. 5, pp. 603–612, 2003.

[53] A. Javaid, H. Chouhna, B. Varghese, E. Hammam, and V. G. Macefield, "Changes in skin blood flow, respiration and blood pressure in participants reporting motion sickness during sinusoidal galvanic vestibular stimulation," *Exp. Physiol.*, vol. 104, no. 11, pp. 1622–1629, 2019.
[54] M. S. Dennison, A. Z. Wisti, and M. D'Zmura, "Use of physiological signals to predict cybersickness," *Displays*, vol. 44, pp. 42–52, 2016.
[55] A. Sjörs, J. Dahlman, T. Ledin, B. Gerdle, and T. Falkmer, "Effects of motion sickness on encoding and retrieval performance and on psychophysiological responses," *J. Ergonom.*, vol. 4, no. 1, 2014, Art. no. 124.
[56] J. Smyth, P. Jennings, A. Mouzakitis, and S. Birrell, "Too sick to drive: How motion sickness severity impacts human performance," in *Proc. IEEE Conf. Intell. Transp. Syst.*, 2018, pp. 1787–1793.
[57] M. L. Jones, V. C. Le, S. M. Ebert, K. H. Sienko, M. P. Reed, and J. R. Sayer, "Motion sickness in passenger vehicles during test track operations," *Ergonomics*, vol. 62, no. 10, pp. 1357–1371, 2019.

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