Sick of Scents: Investigating Non-invasive Olfactory Motion Sickness Mitigation in Automated Driving

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ABSTRACT

While automated vehicles are supposed to become places for purposes beyond transportation, motion sickness is still a largely unsolved issue that may be critical for this transformation. Due to its previously shown positive impact on the gastric and central nervous system, we hypothesize that olfaction (in particular the scents of lavender and ginger) may be able to reduce motion sickness symptoms in a non-invasive manner. We investigate the effects of these scents on the driver-passenger in chauffeured drives in a test track study with a reading-span non-driving related task. Evaluation of self-rated (Simulator Sickness Questionnaire, UX Curves) and physiologically measured motion sickness (Electrogastrography, Electrocardiography), and observations are presented and discussed. Results indicate that the issued scents were detrimental to the well-being of participants in the comparisons between post-task (baseline, scented) and pre-test measurements, with symptoms in the lavender-scented group being perceived as slightly less harsh than in the ginger-scented group.

CCS CONCEPTS

• **Human-centered computing** → **Empirical studies in HCI**; • **Applied computing** → *Computers in other domains.*

KEYWORDS

automated driving, motion sickness, non-driving related tasks, olfaction, user interfaces

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1 INTRODUCTION

Motion sickness (also often referred to as kinetosis) is a prevalent problem in transport, with some claiming its origins date back to the time "shortly after man adopted forms of travel other than his own two legs" [16]. Even in ancient greek wars and, more recently, the second world war, the problem found its place in history books with, e.g., Ambrose who describes the second world war's D-Day invasion: "Eisenhower smelled victory in the air, but to the men of the Allied Expeditionary Forces, whose transports and landing craft had left harbor, the smell in the air was vomit" [2]. In the upcoming era of automated driving [3] resolving this issue will once more be of critical importance. The driver is increasingly being removed from actual driving, expected to more frequently and more intensively engage in so-called Non-Driving Related Tasks (NDRTs, [47]). However, with this shift of human attention away from the road to an unrelated task, a mismatch between visual and vestibular perception is fostered and thus motion sickness may increase, which has serious implications on the well-being of *driver-passengers* [10, 48]. Safety may also be impacted, as, with SAE level 3 [49], the user may engage in NDRTs but is still also required to be able to respond to a so-called request to intervene (or take-over request), i.e., a handback from automated to manual driving [17]. Hence, we consider motion sickness to be a crucial problem for the acceptance, utility and safety of establishing higher levels of automated driving (SAE levels 3-5). After all, automated vehicles will only safely and comfortably present us with opportunities to be productive or relax [33] during individual mobility if the problem of motion sickness and the numerous other human factors challenges [17] are successfully tackled.

In this work, we will investigate potential countermeasures to motion sickness in a user study conducted on a test track that simulates automated driving with a chauffeured driver, and an engaging/highly demanding productivity-oriented NDRT with a reading-span task. As potential mitigator of the induced motion sickness, we investigate constant olfactory stimulation in two variations: lavender as calming scent affecting the central-nervous system, and ginger as scent with potentially positive effects on the gastric system.

The contribution of this paper is: The setup, results and discussion of a user study evaluating the potential of (ginger and lavender) scented cars as potential remedy for motion sickness utilizing physiological, observational and self-rating measures.

2 RELATED WORK

In his 2014 review, Diels asked "Will Autonomous Vehicles Make Us Sick?" [9]. He (and others before) concisely summarizes the causes of motion sickness: a) a conflict between the movements of the travel vehicle perceived by the human organs of balance and the motion sensed by the eyes, and b) motion that humans are simply not used to from an evolutionary perspective, i.e., low frequency oscillating motions. Specifically in vehicles, these can stem from driving behavior (fore and aft, and lateral oscillations) and vehicle characteristics (particularly soft suspension < 1 Hz; high lateral sway amplitudes in the rear of long vehicles like buses) [9]. Sivak and Schoettle [48] subsequently published an estimation of how many people may suffer from motion sickness in automated vehicles, based on a previous international survey on types of NDRTs people would want to engage in automated vehicles [47]. Accordingly, they come to the conclusion that from 25.9% (Japan) up to 52.7% (India) will engage in NDRTs, which increase the frequency and severity of motion sickness, and conclude that *"self-driving cars cannot be thought of as living rooms, offices, or entertainment venues on wheels and require careful consideration of the impact of a moving environment"* [10]. Still, they and others suggest adaptions to vehicle design, in order to counter motion sickness, by (1) maximizing the *passenger-drivers'* visual field of view (with large windows and windshield displays), (2) directing the gaze straight ahead, (3) restricting posture by not having swivel seats and/or restricting head motion [9, 48]. Other strategies could include (4) adding visual stimuli increasing the user's ability to anticipate vehicle motion, and (5) even medications [10, 48]. Many of these concepts have been investigated accordingly. For example: (ad 1) Griffin and Newman show that increasing the external view effectively reduces motion sickness of car passengers [21]. (ad 2) Wada and Yoshida [52] report that head tilt towards the centripetal direction with eyes open greatly reduced the severity of motion sickness. (ad 3) Salter et al. [44] recently investigated seating directions and come to the conclusion that driving with rearward seating sickness levels were low but still significantly higher than with traditional forward-directed seats. (ad 4) Karjanto et al. [26] confirmed that peripheral visual light stripes can indeed help in mitigating motion sickness during fully automated driving, while at the same time reducing mental workload and increasing situation awareness. (ad 5) In a review of clinical literature, Murdin et al. [39] found that Hyoscine is an effective drug to prevent motion sickness that can be applied using nasal spray.

Besides these suggested, and directly to the sensory conflict related strategies, researchers have also investigated completely different paths that seem to have no apparent direct impact on the visual-vestibular mismatch or evolutionary aetiology of motion sickness. Keshavarz and Hecht [28] found that pleasant music has significant positive effects on self-rated experienced motion sickness symptoms on visually-induced motion sickness. Perrin et al. [41] similarly state that rally co-drivers reported increasing motion sickness with stress (63.0% of co-drivers), on-board temperature (43.0%), and on-board smells (e.g., gas and exhaust smells: 46.5%). Salter et al. [44] successfully utilized bone conduction vibration to reduce motion sickness experienced in automated driving while engaging in a "gaze-down" NDRT.

In this work, we intend to investigate the effects of scents further. Specifically, the potential of olfactory stimulation as a motion sickness mitigator for *passenger-drivers* in automated vehicles, who engage in a productivity-oriented office work NDRTs. Various scents have previously been applied in the automotive domain. They were found to be able to increase alertness / reduce drowsiness (e.g., [22]), improve mood and well-being [11], lower the amount of driving mistakes made [12, 37], reduce average driving speed [13], and act as reminder or notification modality [14, 54]. For example, Wintersberger & Dmitrenko et al. [54] successfully augmented a visual automation reliability display with a lemon scent in case of a change to low reliability, and lavender for a change to high reliability. In helping with motion sickness, industry predicts a commercialization of aromas in cars by 2030, stating that "if I can encapsulate those (authors' note: fragrances such as ginseng, herbal oils and lavenders) in plastics, I can prevent motion sickness" [25]. In other previous research, medical trials have shown that lemon scent can effectively treat pregnancy-related nausea and prevent vomiting [30]. Lin Lua and Zakaria [36] reviewed articles investigating essential oils and aromatherapy for nausea and vomiting, finding that they suggest inhaling vapor of peppermint and ginger essential oils reduced both incidence and severity of nausea and vomiting. Still, the reviewed articles appeared to suffer from methodological flaws and "an acute lack of additional research in this area" [36]. Holtman et al. [24] report that the observed positive effects of ginger intake on motion sickness do not stem from a direct stimulation of the central nervous system (i.e., the origin of the sensory mismatch causing motion sickness) but rather from ginger's influence on the gastric system. The relaxing odor of lavender, on the other hand, was shown to have increased beta power, improved mood, and better performance (faster, more accurate) in a computation task in a EEG study by Diego et al. [8], while the stimulating odor of rosemary only improved task completion speed [8]. The arousing smell of lemone was found to not have any significant effect on motion sickness [40]. The are only few studies on olfactory motion sickness mitigation in a somewhat driving-related setting we found but some exist in simulation or XR settings (such as [7]). In one somewhat driving-related study, Keshavaraz et al. [29] show a bicycling video to 62 participants with either rose or leather odor, and find that pleasant scents (rose, in this case) are able to reduce visually induced motion sickness.

To the best of our knowledge, a study evaluating the effects of odors specifically targeting motion sickness in automated vehicles does not yet exist. In detail, we aim to tackle the issue from two angles: (1) the gastric system with the potentially beneficial impacts of ginger (cf. [24]), and (2) overall performance and relaxation with lavender, thereby also potentially reducing motion sickness symptoms (cf. [8]).

3 RESEARCH QUESTION & USER STUDY

What are the psycho-physiological effects of ginger and lavender scents on motion sickness in fully automated driving with passengers, who are engaged in a non-driving related task?

For the study investigating this question, we applied a split-plot design with *Scent* as between- and *Treatment* as within-subjects

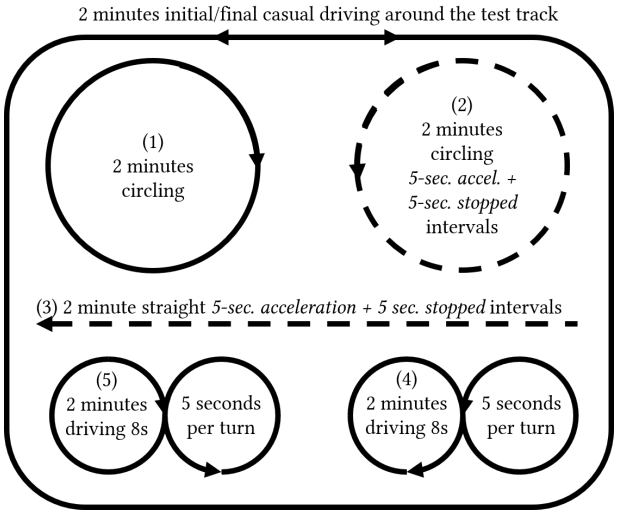


Figure 1: Maneuvers executed on the test track.

variables. Scents consisted of ginger (group *GG*) and lavender (group *LV*) fragrance. Treatments included baseline drive in a regular, not scented car (baseline, *BL*) and the drive in an artificially scented car (scented, *SC*). Participants were quasi-randomly assigned to a group and each underwent two drives on a test track in quasi-randomized order: the baseline drive (*BL*) and a drive with a scented car (*SC*), whereas the fragrance was corresponding to the assigned group (*GG*/*LV*). Evaluated measurements were taken before the whole test run (pre-test), during, and after each drive (post-BL, post-SC).

3.1 Scents & Cars

In order to prevent carry-over / scent mixing effects, three separate vehicles (Audi A1, VW Golf, BMW 1) were used for the three conditions (all are similarly sized and motorized). GG and LV vehicles were scented by applying 10 ml of the respective essential oil on a 25 cm^2 piece of felt and attaching it to the center mirror. The scent-pad was renewed regularly to achieve comparable scent intensity. Participants were seated on the front passenger and the experimenter on the back seat. The car was driven by a chauffeur.

3.2 Test Track

To induce motion sickness with a realistic feeling of driving (such as on a rural or city road), we decided against a single, constant motion (e.g, circling, driving big eights, ...) but for a variety of maneuvers that were executed by the chauffeur driver. These maneuvers are sketched in the following description, as well as in Figure 1.

Each drive was 15 minutes long, and started and ended with 2 minutes casually driving around the whole test track (slight curves on the corners of the track) at 20 km/h. After / before that maneuver, five other two minute long maneuvers were scattered randomly into the test drive: (1) driving a circle in one direction for two minutes without counter-steering, (2) driving the same circle with accelerating for 5 seconds, followed by a abrupt braking maneuver and remaining stopped for 5 seconds, repeatedly, (3) same as maneuver two but driving straight ahead, (4) alternating 5 second left and 5 second right steering ("driving eights"), and lastly, (5) the same as maneuver four but in the opposite direction. The frequently selected interval of 5 seconds was chosen as 0.2 Hz were previously shown to be effective in inducing motion sickness [46, 47]. The sequence of these maneuver was consistent amongst all drives and automatically issued to the chauffeur's headphones via audio recordings.

3.3 Non-Driving Related Task

We chose the reading-span task by Daneman and Carpeter [6] as NDRT. It is a frequently utilized tool for cognitive processing and reading comprehension experiments [53], and was used in various automotive HCI studies (e.g., to employ different levels of workload [4], or simulate typical office tasks [45]). The task requires significant amounts of visual attention and cognitive resources by displaying single sentences that have to be rated on their semantic correctness (binary). Additionally, after every sentence, a keyword is shown, which has to be remembered over the span of multiple issued sentences as an instrument to require working memory. The open source software package by von der Malsburg [51] allowed to easily deploy and use the task on a Microsoft Surface Pro Notebook PC, as well as calibrate its difficulty based on the users' individual capabilities. Utilized configuration parameters were: `allow_sloppy_spelling=true, target/response_display_time: 1000m, tested_memory_levels=3, time_out_factor=2.5s`. Due to the nature of the task and device, participants had to engage in the NDRT in a gaze-down fashion, with the device on their lap. Participants were instructed to engage in the task the entire drive in both drives (BL and SC) but allowed to stop if experienced motion sickness symptoms required them to do so.

3.4 Measurements

We follow a triangulation approach of measurements including self-ratings, observations and physiological measurements in order to provide a comprehensive view on the independent variables' effects. Dependent variables were collected at different points in time (*Treatments*): *Pre-test*, i.e. before executing any of the experiments' drives; *post-task*, i.e. after each drive (which includes both post-BL and post-SC measurements); or *during* the drive (denoted by the condition or independent variable abbreviation).

Observations were performed by an experimenter sitting on the back seat utilizing the center mirror, which was intentionally directed at the passenger, and included a) behavioral mitigation strategies like stopping a task, opening windows, fixating the horizon, or similar, b) exposure times to stimuli (duration/abortion of drive/NDRT engagement), and c) user behavior like excessive yawning, sighing, hyperventilation and flatulence [46].

Post-task self-ratings consisted of the Simulator Sickness Questionnaire (SSQ) by Kennedy et al. [27] and User Experience (UX) Curves by Kujala et al. [32]. The SSQ is a widely used multi-item scale on experienced motion sickness symptoms like head pressure or sweating, where each symptom has to be rated from "none", "slight", "moderate" to "severe" (quantified as 0 to 3). These ratings are then weighted and summed into 4 weighted category scores: Nausea (N), Oculomotor (O), Disorientation (D) and Total Score (TS). UX Curves, on the other hand, are generally used as a retrospective tool for users' subjective user experience over time in longitudinal

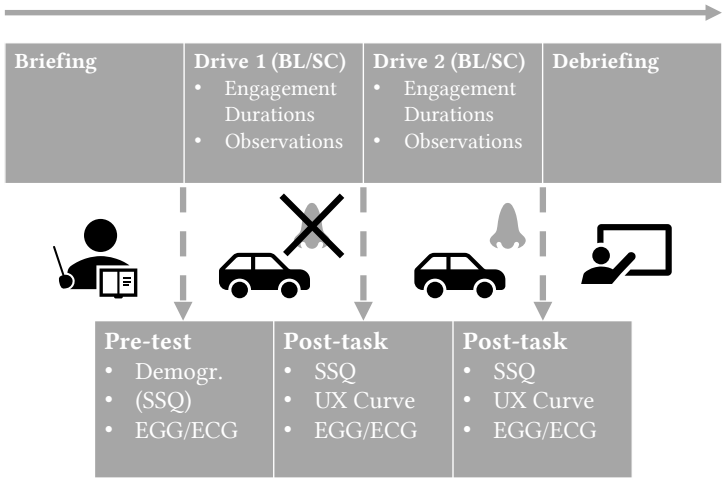


Figure 2: Procedure overview. Conditions (groups and whether the SC-drive was with lavender or ginger scent) were counterbalanced.

studies. Others, however, have utilized it for UX as post-task evaluation tool for shorter tasks (e.g., 6 minutes per drive in [18]) and more specific concepts too, such as trust [55] or drowsiness [34]. We utilize this method to qualitatively evaluate the development of motion sickness over time for each drive (~15 minutes per drive).

Pre-test and post-task physiological measurements utilized a 500 Hz physiological measurement system by g.tec with 3 electrodes and a recording duration of 15 minutes per *Treatment*. The measures include Electrogastrography (EGG) and Electrocardiography (ECG), whereas analysis can be performed on the same input signal [42]. In general, EGG is a tool to analyze myoelectrical stomach (i.e., gastric) activity and has been utilized as a tool to physiologically evaluate motion sickness [5] since its introduction as such in 1985 by Stern et al. [50]. *Tachygastric activity* (4-9 contractions per minute, cpm) was found to correlate with subjective motion sickness. In comparison, the so-called "basic electrical rhythm" (BER) of 2 - 4 cpm (0.05 Hz) describes regular activity, and 0.5 - 2 cpm "badygastria" too low activity. For a detailed discussion and its correlations to EGG, we refer to Cheung and Vaitkus [5] and, more recently, Yin et al. [56]. The latter further also served as an application-guide to EGG for this study. It has to be mentioned, however, that there is controversial evidence on the correlation of EGG measures and motion sickness [5].

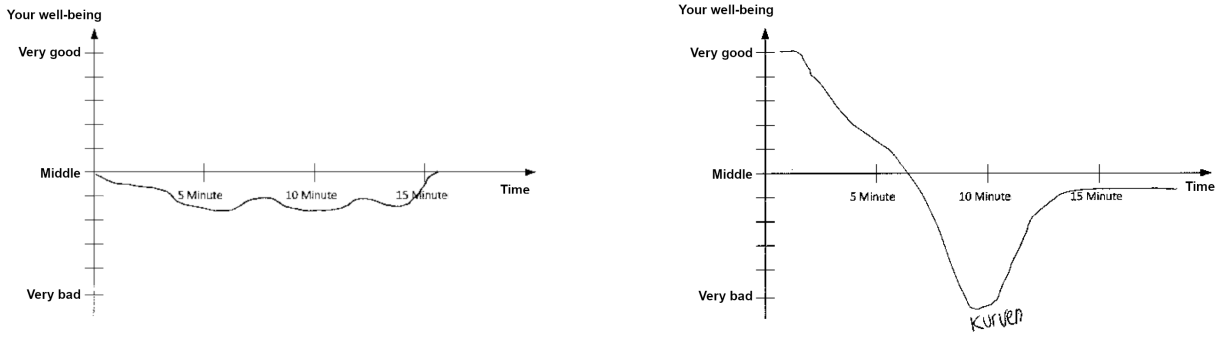
Electrocardiography, in particular Heart Rate Variability (HRV) analysis, was used previously in the HCI domain, e.g., as indicator for the valence of an experience and mental workload [19], or as features for drowsiness detection algorithms [35], but also motion sickness effects on the time between consecutive heartbeats (so called RR-intervals) and the Low-Frequency/High-Frequency ratio (the autonomic balance) have been found [57]. Specifically, we analyzed the following EGG indicators to indicate motion sickness: percentage of tachygastric activity (Tachygastria), percentage of arrhythmic gastric activity (Arrhythmia), dominant frequency in contractions per minute (DF cpm), and the maximum power spectrum density in decibels (MPSD dB). For ECG results, we analyzed the mean of RR-intervals in milliseconds (RR ms), the root mean of successive squared differences in milliseconds (RMSSD ms), and the mean low-frequency high-frequency ratio (LF/HF) based on the Welch method.

3.5 Procedure

An overview of the procedure is given in Figure 2. Before the experiment, each participant received a briefing and consent form, the Motion History Questionnaire [20], and a brief survey on demographics. Additionally, participants had to confirm to not suffer from olfactory dysfunctions, adverse reactions to strong cents, respiratory problems or the flu. Female participants were further included only if they declared to not be pregnant. Test conditions were counterbalanced, took approximately 15 minutes each and included constant engagement in the reading-comprehension task on a tablet-PC. The participant was seated on the front passenger and an observing experimenter on the back seat during each drive. The chauffeur, simulating the fully automated driving mode (but visible to the passenger), utilized a speech recording over a Bluetooth ear plug for accurate timings of driving maneuvers, in order to improve reproducibility. Participants were able to cancel the NDRT and drive at any point in time. Natural motion sickness coping mechanisms, like conscious breathing, opening the windows or chewing gum were also allowed and recorded by the observer. Before the first drive (either BL or SC), pre-test measurements were recorded (SSQ, EGG/ECG) and an introduction to the NDRT given, as well as its difficulty level calibrated to each participant. After each drive, first the SSQ was filled and then the EGG/ECG measurement recorded – even if the drive was aborted prematurely (on a voluntary basis). After the experiment, participants were debriefed and reminded to not drive on their own for at least two hours.

3.6 Participants

Participants were recruited via mailing lists and included students and volunteers, as well as personal contacts. In total, 16 female and 8 male in the age range of 18 to 35 (mean, $M = 22.83$ years; standard deviation, $SD = 4.43$ years). Their self-reported mileage per year



(a) Stable **(b) Deteriorating**

Figure 3: Exemplary UX Curves that were utilized to self-rate well-being over time and labelled in German (fluent language of all participants). Vertical axis "Your well-being": very bad (bottom), middle (middle horizontal axis), to very good (top); Horizontal axis: time from start (0 minutes) to end (15 minutes) with labels in 5 minute intervals. The left UX Curve (Figure 3a) shows a stable but negative trend over time after a GG SC-drive. The right UX Curve (Figure 3b) shows a deteriorating trend with a negative peak annotated by the participant with "curves".

as driver was $M = 9204$ km, $SD = 9113$ km, and $M = 3375$ km, $SD = 3148$ km as a passenger. They further reported to be driving $M = 35.82\%$ of their driving time on rural roads ($SD = 25.87\%$), $M = 31.40\%$ on highways ($SD = 28.11\%$), and $M = 28.40\%$ in cities ($SD = 23.04\%$).

4 RESULTS

For statistical analyses, we utilized IBM SPSS v24. Results are reported as significant with $p < 0.05$. For the sake of brevity and readability, we concentrate mostly on statistically significant results but report all results and list all descriptive statistics in the respective figures and tables.

4.1 Self-rated Motion Sickness

Self-reported symptoms and UX Curves: In addition to their ratings in the SSQ, participants were instructed to verbally report specific experienced symptoms of motion sickness to the experimenter during the entire experiment. As another tool of self-reflecting their well-being in regards to their experience over time, they were also required to draw a UX Curve post-task, which we report here in quantified form according to the original method paper's analysis recommendations (cf. [32]).

Symptoms verbally mentioned by the participants: 8 times participants mentioned a special decrease in their well-being during the 5 seconds long small-curves intervals (4x BL, 2x GG, 2x LV; e.g., as seen in Figure 3b), whereas the two minutes long constant-diameter circle driving was noted to be the worst part in 1 BL drive and 3 LV drives; in 7 drives participants noticed increasing headaches (3x BL, 4x LV); one participant mentioned the stop-and-go phases as most detrimental to his/her well-being; only three participants specifically reported that they noticed the car's scent in the SC condition, whereas two (1x GG, 1x LV) also mentioned to dislike them.

Considering UX Curves, the vast majority show a clear picture: deteriorating well-being over time. In 21 of 24 BL drives UX Curves were deteriorating (1x improving, 2x stable). All (12 of 12) post-LV and 9 of 12 post-GG drive UX Curves also report a deteriorating trend. Three post-GG drive UX Curves were stable. Exemplary UX curves randomly selected from the results pool are shown in Figure 3.

Simulator Sickness Questionnaire (SSQ): To assess perceived motion sickness, we utilized the SSQ pre-test and post-task. However, as the SSQ is originally intended and validated only for post-stimulus use [27], we only analyze statistical differences between post-task results and between participant groups. Pre-test results thus merely serve as descriptive re-confirmation of low experienced sickness before the actual experiment drives. Validation of required assumption by established reliability tests with Cronbach's α resulted in acceptable scores (Cronbach's $\alpha > 0.8$), and Shapiro Wilk's tests for normality indicated normally distributed results for all symptom categories (N, O, D, TS). To analyze the differences between independent variables, we utilized a Mixed Analysis of Variance (ANOVA), as the required assumptions for normality, as well as Levene's test for the homogeneity of error variances hold. Descriptive and test statistics are listed in Tables 1, and 2 respectively – except for interaction effects for the sake of brevity, since no statistical significance for these were found ($p_N = .089, p_O = .149, p_D = .165$, $p_{TS} = .070$). When assessing the influence of independent variable *Scent*, however, we found a significant main effect for symptom category O, indicating that the lavender-scented car induced stronger self-rated oculomotor symptoms than the ginger-scented car. Considering differences between baseline and scented drives, analyses revealed significant effects for symptom category D and the overall severity score TS, with both showing that the scented drive was experienced as worse in regards to perceived motion sickness.

In summary of the self-rated symptoms, participants consistently reported deteriorating well-being over time. Statistical evaluation of the SSQ has further shown that (1) the lavender group suffered from worse oculomotor symptoms than the ginger group and (2) that the overall severity of symptoms and specifically the disorientation category was, in fact, experienced as worse in the scented drives in comparison to the baseline (not-scented) ones.

Table 1: Descriptive statistics of Simulator Sickness Questionnaire weighted sum scores with mean (M) and standard deviation (SD) in brackets: N (Nausea, x9.54), O (Oculomotor, x7.58), D (Disorientation, x13.92), TS (Total Score, x3.74).

Treatment	Pre-Test		Post-BL		Post-SC	
Scent	**GG**	**LV**	**GG**	**LV**	**GG**	**LV**
N	3.98 (11.11)	8.75 (11.11)	74.73 (44.90)	75.53 (30.83)	68.37 (39.40)	89.84 (43.71)
O	10.74 (11.86)	15.16 (13.71)	41.06 (26.74)	56.22 (17.84)	38.53 (29.53)	62.54 (19.69)
D	1.16 (4.02)	3.48 (6.30)	68.44 (67.78)	71.92 (39.74)	92.80 (67.76)	124.12 (77.95)
TS	2.15 (3.42)	3.85 (3.96)	34.06 (25.55)	35.16 (15.89)	37.18 (24.96)	51.02 (27.08)

Table 2: Mixed ANOVA results of the SSQ analysis with (a) between-subjects factor *Scent* and within-subjects factor *Treatment* comparison results. Listed are: mean (M), standard error (SE), test statistics (F-value, significance value p, and effect size η_p^2) of corresponding comparisons. Significant effects are marked with asterisks: * if $p < 0.05$ and ** if $p < 0.001$.

(a) Between-subjects comparison

Scent	GG	LV	
Treatment	**Post-BL & -SC**	**Post-BL & -SC**	Test statistic
N	71.55 (10.82)	82.68 (10.82)	$F = 0.53, p = .475, \eta_p^2 = 0.02$
O*	39.80 (6.59)	59.38 (6.59)	$F = 4.42, p = .047, \eta_p^2 = 0.17$
D	80.62 (17.11)	98.02 (17.11)	$F = 0.52, p = .48, \eta_p^2 = 0.02$
TS	35.62 (6.44)	43.09 (6.44)	$F = 0.67, p = .42, \eta_p^2 = 0.03$

(b) Within-subjects comparison

Treatment	Post-BL	Post-SC	
Scent	***GG & LV***	***GG & LV***	Test statistic
N	75.13 (7.86)	79.10 (8.49)	$F = 0.47, p = .501, \eta_p^2 = 0.02$
O	48.64 (4.64)	50.53 (5.12)	$F = 0.41, p = .528, \eta_p^2 = 0.19$
D**	70.18 (10.85)	108.46 (14.91)	$F = 15.57, p < .001, \eta_p^2 = 0.41$
TS*	34.61 (4.34)	44.10 (5.32)	$F = 8.05, p = .01, \eta_p^2 = 0.27$

4.2 Observations and Physiological Measurements

Stimulus Exposure and Experimenter Observations: Participant-initiated coping strategies that were observed more than once were[1]: opening a window (9x during BL, 5x LV, 4x GG), fixating the horizon (7x BL, 2x LV, 3x GG), conscious breathing (5x BL, 3x LV, 3x GG), burping (2x BL, 3x LV), and verbally requesting to stop the NDRT (10x BL, 3x LV, 4x GG) and/or the drive (10x BL, 5x LV, 3x GG). Additionally, 2 participants suffered from gastric emptying after early drive terminations: once following the second drive (LV), once after the last EGG measurement (post-BL). Descriptive statistics of task engagement durations are shown in Figure 4.

Shapiro Wilk's tests for normality have consistently reported non-normally distributed data. Thus, we applied non-parametric tests. Mann-Whitney-U tests for the between-subjects factor *Scent* reported no statistically significant differences ($p > .05$). Testing the within-subjects factor *Treatment* (BL vs. SC) using Wilcoxon's signed ranks tests also revealed no statistically significant differences, whereas the NDRT engagement time in the LV group showed effects, but no significance ($p = 0.069, Z = 1.82, r = 0.53$) with NDRT engagement being longer in the SC than the BL condition. Such a trend was not observable in the GG group.

Electrogastrography and Electrocardiography: EGG/ECG measurements were recorded prior to experiment execution (pre-test) and after each drive (post-task; i.e., post-BL, post-SC). Data processing and indicator extraction was performed using the freely available Matlab package EGGDWpack v2.60 by Dariuz Komorowski [31], who also kindly provided direct support via email. Default analysis parameters and "Filter Method 1" for automated artifact extraction were used. Due to several recordings not meeting the necessary

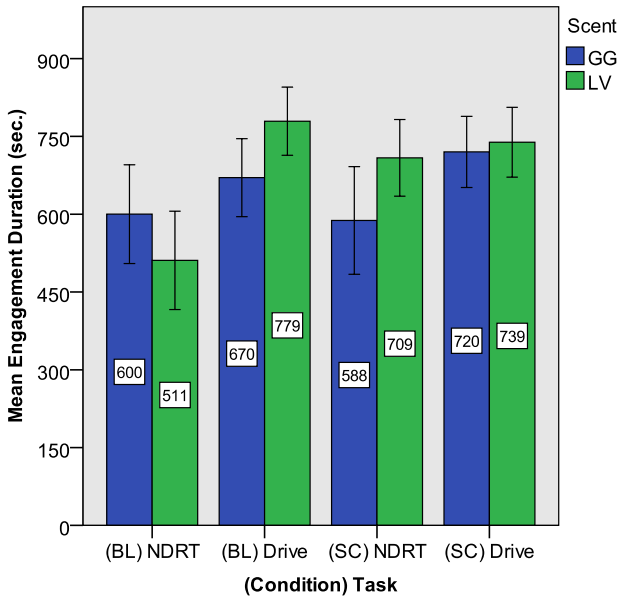


Figure 4: Task engagement durations, whereas a drive could not be stopped without also stopping NDRT engagement. Labels on bars represent the mean value and error-bars depict the standard error of means. Minimum time was 0 seconds (no engagement) and maximum engagement time 900 seconds (full drive) per condition.

[1]Please note that throughout the study there were 24 BL drives, 12 LV and 12 GG drives due to the split-plot design.

Table 3: Descriptive statistics of EGG (Tachygastria, Arrhythmia, Dominant Frequency DF, Maximum Power Spectrum Density MPSD) and ECG (RR-Intervals RR, Root Mean Square of Successive Differences RMSSD, Low-Frequency/High-Frequency ratio) measurements with mean (M) and standard deviation (SD) in brackets. Listed figures are based on the analyzable sample (after data quality assessment) of $n_{GG} = 11$ and $n_{LV} = 7$.

Treatment	Pre-Test		Post-BL		Post-SC	
Scent	***GG***	***LV***	***GG***	***LV***	***GG***	***LV***
Tachygastria (%)	10.24 (7.78)	11.77 (13.05)	16.48 (14.05)	19.69 (5.72)	16.69 (10.64)	16.87 (18.98)
Arrhythmia (%)	18.22 (19.87)	12.98 (11.37)	15.96 (10.46)	14.64 (10.21)	12.15 (12.05)	9.77 (7.96)
DF (cpm)	2.41 (0.96)	2.76 (0.80)	2.71 (0.71)	2.82 (0.46)	2.88 (0.59)	3.11 (1.22)
MPSD (dB)	-72.64 (7.24)	-74.99 (6.21)	-77.23 (4.90)	-76.32 (5.10)	-76.29 (5.30)	-74.82 (5.49)
RR (ms)	899.44 (182.40)	860.46 (151.42)	971.59 (190.06)	948.05 (140.53)	984.94 (169.44)	928.90 (131.64)
RMSSD (ms)	55.20 (33.68)	71.69 (50.49)	68.78 (38.64)	73.65 (41.65)	72.53 (32.93)	78.06 (36.91)
LF/HF (ratio)	1.86 (1.18)	1.31 (0.61)	2.17 (2.37)	1.46 (1.17)	2.35 (2.09)	1.37 (0.66)

data quality requirements and some technical issues when recording, only the EGG/ECG recordings of the 18 participants (11 of the GG group and 7 of the LV group) could be used for statistical analysis. Considering this and Shapiro Wilk's tests not consistently indicating normally distributed data, we employed non-parametric statistical tests: Mann-Whitney-U for the between subjects factor *Scent*, and separate Friedman tests for within-subjects *Treatments* (*Pre-Test* vs. *BL* vs. *SC*) with Wilcoxon signed-ranks tests for pairwise comparisons. Descriptive statistics are listed in Table 3.

Mann-Whitney-U tests reported no strictly significant differences in EGG and HRV indicators. Friedman tests for within-subjects differences in group GG report a significant effect for MPSD ($p = .029$, $\chi^2 = 7.091$) and RR intervals ($p = .003$, $\chi^2 = 11.46$). Pairwise comparisons highlight that the MPSD is significantly higher in the pre-measurement, as compared to the baseline measurement ($p = .008, Z = 2.67, r = 0.80$) – a similar (but not significant difference) trend is observable in the MPSD comparison of pre vs. SC measurements ($p = .075$). RR intervals were found to significantly differ in the pre vs. BL ($p = .013, Z = 2.49, r = 0.75$) and pre vs. SC ($p = .003, Z = 2.93, r = 0.88$) results, with the BL and SC RR measurements being higher on average than the pre-test measurement. In other words, heart rate was significantly lower after a drive (BL or SC) than before both drives (pre-test). Considering RMSSD, we made similar observations in pairwise comparisons: the RMSSD was significantly higher in the pre-test measurement, in comparison to the BL ($p = .026, Z = 2.22, r = 0.70$) and SC ($p = .016, Z = 2.40, r = 0.72$) measurements.

In the LV group, Friedman tests only found a statistical significance for mean RR interval length ($p = 0.049$). Pairwise comparisons with Wilcoxon's signed ranks tests show significant differences in the pre vs. BL ($p = .028, Z = 2.18, r = 0.82$) and SC ($p = .003, Z = 2.67, r = 1.00$) pairwise comparisons. Both tests reveal the same picture as in the GG group: the drives caused heart rate to decrease. Arrhythmia slightly missed statistical significance in the BL vs. SC test ($p = .063, Z = 1.87, r = 0.70$) only indicating a trend that the SC condition might have caused more arrhythmia than the baseline condition.

We can summarize the main results from the physiological measurement analysis as follows: Significant differences in the between-subjects group variable *Scents* were not found. However, within-subjects pairwise comparisons highlight that the different drives (the baseline or scented drive) caused some physiologically measured effects, in comparison to the pre-test measurements: a lower post-task heart rate and post-task gastric signal power MPSD.

5 DISCUSSION

Initially, we assumed that ginger and lavender will reduce experienced motion sickness syndromes based on previous research examining their impact on the gastric and central nervous systems. However, results of the study hint at a contrary effect: Reports by users in the form of UX Curves and verbal notes, as well as observations, show consistently deteriorating well-being in all driving conditions. Supported by the behavioral actions in terms of early drive / NDRT engagement terminations, we saw no significant differences between employed scents (but also not in baseline vs. scented drives). The detailed SSQ scales on the severity of experienced sickness symptoms, show a slightly more diverse picture in regards to the baseline vs. scented drives. Here, we found significantly worse ratings with medium to high effect sizes in the scented conditions in the Total Severity and Disorientation symptom category. Additionally, we found the only statistically significant difference between *Scent* groups in all investigated measures: oculomotor symptoms were rated to be significantly worse in the lavender group than in the ginger group.

In regards to physiology, we found that heart rate and EGG's MPSD decreased and the LF/HF ratio and RMSSD increased significantly in baseline and test conditions, in comparison to pre-test measurements. In related literature increased motion sickness is connected to increasing RR intervals [57] and a significantly dominant sympathetic activity (increased LF/HF ratio, [23]). Holmes et al. [23], however, also argue that motion sickness induces significantly higher heart rate, which stems from increased sympathetic activity. We believe that our observed effects on the mean RR interval, i.e., heart rate, could stem from participants' pre-test nervousness and them calming down during the drives. Also the RMSSD indicated increased parasympathetic activity. Regarding EGG we could not show an average increase in relative tachygastria occurrence, but reduced normal dominant power (MPSD) in post-task measurements probably indicating increased motion sickness, whereas the scientific evidence is not very clear in this regard [5, 56].

Overall, it has to be noted that despite the fact that only 3 participants actively mentioned noticing the deployed scents, on average, scented drives were still rated as worse in regards to motion sickness symptoms than the baseline drives. Hence, an interpretation that the effects in this study are caused by explicit individual preferences (such as reported with *pleasant* music [28] and scents [29]) is at least questionable. This perspective, however, still may hint at the fact that the fragrances were subliminally perceived or causing some specific physiological reaction, leading to increased perceived motion sickness symptoms. Effectively, this study's results contribute to the controversial landscape of research investigating ginger or lavender as motion sickness mitigator by providing further evidence that they may as well lead to a stronger elicitation of symptoms – also with olfactory perception (many, if not the most, medical trials are using oral inhalation or intake with flavored lozenges). Reasons for these results besides the scents themselves could include the context of use (automated driving with gaze-down NDRT), scenario (test track with strongly motion sickness inducing maneuvers), delivery strategy (felt with essential oil), participant pool (relatively young) or assessment methods. Hence, the results may not be directly transferable to other combinations of these.

6 LIMITATIONS AND FUTURE WORK

We consider this work to be a first step in investigating scents and their effects on motion sickness in automated driving to support productivity and well-being. Due to technical issues, the sample used for statistical analysis of physiological parameters was limited. However, results were still somewhat consistent in line with self-ratings. Additionally, we cannot completely exclude the possibility of a small bias introduced by the utilized vehicles (in regards to brand experience and the like) and the effects of a human chauffeur driving instead of an actual fully automated driving system. Furthermore, we limited the study to two scents, while related research mentions a whole plethora of potentially beneficial odors like rosemary, peppermint, lemon, and many more. For example, vanillin and menthol were shown to have a positive effect on the emotional state of users [1, 43] and might thus also be beneficial for motion sickness mitigation, similar to pleasant music [28].

Future studies need to include a wider sample of participants, scents, possibly other physiological parameters (like EEG, [38]), as well as improved scent delivery techniques (cf. [15]) and strategies in "real" fully automated driving (which should then be repeatable, e.g., on a test track with an instrumented vehicle), and specifically include the user acceptance and emotional influence of the various types of mitigation measures. Additionally, we plan to utilize advanced statistical methods (specifically Bayes Factors and regression analyses) to investigate the complex relationship between motion sickness, odors, physiological and self-rated responses in more detail.

7 CONCLUSION

We regard the presented study as another important step of investigating potential motion sickness mitigation measures on the way to enable side effect-free engagement in NDRTs. The main advantage of olfaction is the non-invasive utilization a sense that is not already as cluttered with information and notifications like the visual or auditory channels. In this study, we therefore analyzed two fragrances: ginger with a supposedly beneficial impact on the gastric system, and lavender as scent stimulating the central nervous system with calming effects improving task performance. The split-plot design user study (N=24) simulated automated driving with chauffeured drives on a test track, and used a triangulation assessment methodology with physiological measures, observation, and self-ratings to reveal somewhat surprising but carefully to be interpreted results. **In contrast to our hypothesis, physiological measures could not find differences between baseline and scented drives. However, in comparison to pre-test measurements, all drives were detrimental to motion sickness. Users' self-rated severity of sickness symptoms highlighted though that the scented drives were more detrimental to well-being of users than the baseline drives (Total Severity and the Disorientation symptom category).** Here, we also saw a small effect showing how ginger elicited slightly less severe oculomotor symptoms in comparison to lavender. In summary, we can conclude that ginger and lavender scents in the employed form and context were not able to reduce, but in fact partly worsened motion sickness. Further research with other scents, scent delivery techniques, less harsh driving tracks, etc. is clearly needed. Additionally, as a community, we should increasingly look into the issues of how to combine multiple types of information and stimulants for psycho-physiological processes (such as the CNS and the gastric system) in order to not interfere/overwrite each other or overload the user – establishing new channels, such as olfaction, for subliminal or direct interaction might be a path worth following that is, however, limited in its extent.

To conclude: We could not enable a working / relaxing place automated vehicle with the investigated olfactory stimulation. Thus, Diels et al.'s statement that *"self-driving cars cannot be thought of as living rooms, offices, or entertainment venues on wheels and require careful consideration of the impact of a moving environment"* [10] – due to issues such as motion sickness and others – still stands for now until suitable solutions (or more successful variations of the investigated olfaction) are found.

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