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Using Active Seat Belt Retractions to Mitigate Motion Sickness in Automated Driving

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Abstract: The introduction of automated-driving functions provides passengers with the opportunity to engage in non-driving related tasks during the ride. However, this benefit might be compromised by an increased incidence of motion sickness. Therefore, we investigated the effectiveness of active seat belt retractions as a countermeasure against motion sickness during inattentive automated driving. We hypothesized that seat belt retractions would mitigate motion sickness by supporting passengers to anticipate upcoming braking maneuvers, by actively tensioning their neck muscles and, thereby, reducing the extent of forward head movement while braking. In a motion base driving simulator, 26 participants encountered two 30 min automated drives in slow-moving traffic: one drive with active seat belt retractions before each braking maneuver and a baseline drive without. The results revealed that there was no difference in perceived motion sickness between both experimental conditions. Seat belt retractions resulted in an increased activity of the lateral neck muscles and supported drivers to anticipate braking maneuvers. However, at the same time, the retractions led to an increased magnitude of head movement in response to braking. This research lays the groundwork for future research on active seat belt retractions as a countermeasure against motion sickness and provides directions for future work.

Keywords: motion sickness; automated driving; active seat belt retractions; countermeasure

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1. Introduction

Automated driving allows drivers to disengage from the driving task and to carry out non-driving related tasks (NDRT) such as working, reading, watching a movie, or relaxing. This changes the role of the person in the driver's seat from an active driver to a passive passenger. Performing visually demanding NDRT increases the likelihood of motion sickness [1–4]. Motion sickness can be caused by the use of various means of transportation, on land, on the sea, or in the air, and is characterized by the primary symptom of nausea that can lead to vomiting [5]. Other symptoms that often accompany or precede the nausea are headache, (cold) sweat, burping, fatigue, pallor, or dizziness [6,7]. There is a significant percentage of people who are susceptible to motion sickness [8,9].

There is a risk that the user experience of automated driving could be compromised by an increased incidence of motion sickness and aggravated symptoms [10]. Moreover, the effects of motion sickness on drivers' ability to take over vehicle control at system limits are unclear [11,12]. The first and most common area of use for automated vehicles is expected to be the highway initially [13,14]. On the highway, especially in slow-moving traffic or stop-and-go traffic, drivers will experience longitudinal accelerations which can have an impact on the development of motion sickness [15]. To ensure that the successful introduction of automated driving is not limited by the undesirable negative effects of increased motion sickness, it is important to develop practical countermeasures for the prevention of motion sickness and to examine their effectiveness. In the present study, we investigated the effectiveness of moderate reversible seat belt retractions to announce braking maneuvers and stabilize the inattentive occupant during braking, potentially reducing

motion sickness. To the best of our knowledge, this study was the first to investigate active seat belt retractions as a countermeasure against motion sickness.

1.1. Motion Sickness in Automated Driving

For passengers of automated vehicles, there are several factors that may be unfavorable with respect to the development of motion sickness compared to an attentive manual driver. To stabilize the human body under the influence of externally caused movements, humans build an internal model that includes sensory information from the visual (e.g., curvature), sensory–motor (e.g., brake pedal force, steering wheel vibration), and vestibular channel (e.g., translational and rotational acceleration) [16]. This internal model is constantly updated. Compared to visually attentive active manual drivers, visually inattentive passengers of automated vehicles perceive the driving movements exclusively by the vestibular channel. As soon as the driver takes their feet off the pedals and hands off the steering wheel, they lose perceptions from the sensory-motor channel. The ability to engage in NDRT while driving causes passengers to divert their visual attention from the road. Due to the restricted field of view to the traffic environment outside the vehicle, the visual channel does not perceive any vehicle movements but a static movement. Therefore, there is a conflict between the perceptions of the visual and vestibular channels. According to the sensory conflict theory, motion sickness is a consequence of this sensory conflict [17]. The theory postulates that motion sickness is caused by mismatches between sensory channels (visual, vestibular, and somatosensory inputs). Therefore, visually inattentive passengers are more susceptible to get motion sick than drivers or passengers who draw their visual attention to the road. As a further development of the sensory conflict theory, the sensory rearrangement theory additionally attributes importance to anticipated sensations [17]. The theory postulates that a discrepancy between anticipated and actual vestibular and visual perceptions increases the risk of motion sickness. A passenger engaged in a visually demanding task is out of the visual feedforward control loop and is, thus, not able to anticipate upcoming curves, uneven road surfaces, or driving maneuvers of other vehicles. Accordingly, any lateral or longitudinal change in vehicle motion results in discrepancies between expected and perceived vehicle motions. This, in turn, increases the risk of motion sickness. Several studies provide evidence that stimuli that help occupants to anticipate upcoming movements reduce motion sickness [18–23]. Accordingly, anticipatory cues may be a promising countermeasure for motion sickness.

1.2. Postural Instability and Head Movements during Automated Driving

During automated driving and especially during engagement in NDRT, the passenger is less able to predict upcoming driving maneuvers of the automated vehicle, resulting in impaired control strategies to stabilize their body. According to the postural instability theory [24], prolonged postural instability can result in motion sickness. Prior research has already shown differences in body and head stability between drivers and (visually inattentive) co-drivers. Drivers tilt their head centripetally in a curve (to the curve direction = opposite direction from the vehicle roll), while co-drivers tilt their head centrifugally in a curve (vehicle roll and passenger roll are aligned, i.e., head follows the centrifugal forces) [25,26]. One explanation for drivers tilting their head to the direction of the curve could be that this movement reduces acceleration load and increases the accuracy of visual information [27]. Brietzke et al. [28] analyzed head movements of passengers during a stop-and-go scenario. They found similar results with respect to the head movements of visually attentive and inattentive passengers during alternating longitudinal vehicle movements. Passengers who were visually inattentive while being engaged in a secondary task performed head movements that followed the current deceleration (head tilts forward) or acceleration (head tilts backwards). In contrast, passengers watching the vehicle in front showed exactly the opposite head movements, presumably to anticipate the expected accelerations.

The differences in head movements between drivers and passengers might be related to the occurrence of motion sickness [25]. Previous research has shown that the risk of motion

sickness increases when the head follows the acceleration forces, both in curves [26,29–31] and in stop-and-go traffic [32]. Results from several studies suggest that control strategies to improve trunk and head stability reduce the likelihood of motion sickness. Wada and colleagues [29,31] have found that motion sickness can be significantly decreased when passengers actively tilt their head toward the centripetal acceleration imitating the drivers' head tilt. This effect was found for visually attentive as well as visually inattentive passengers (eyes closed) [31]. Golding et al. [33] compared active and passive head-tilting strategies in their effectiveness to reduce motion sickness. While being exposed to continuous horizontal translational oscillation, subjects who actively aligned their head to the gravito-inertial force by visual cues had a higher time until moderate nausea was achieved than subjects with misaligned head tilts. However, a passive alignment of head tilt to the gravito-inertial force realized by a suspension machinery contributed to an earlier onset of motion sickness compared to a passive misalignment. Based on these results, the authors concluded that the active control of a person to compensate head tilt protects against motion sickness.

1.3. Active Seat Bealt Retractions as Potential Countermeasure

One approach to reduce head and upper body movements during braking maneuvers is the use of active seat belt retractions. This study was the first to investigate active seat belt retractions as a countermeasure against motion sickness. In prior research, seat belt retractions have been used to enhance driving experience in a driving simulator [34]. Active seat belt systems are an extension of passive seat belt systems which are non-reversible and are activated pyrotechnically in the event of an accident that can no longer be prevented [35]. In its original field of application, active seat belt systems provide reversible pre-tensioning of the belt shortly before a crash [35]. The belt is reversibly retracted with high force and speed, reducing belt slack shortly before an unavoidable crash [35]. This keeps the occupant in a better position and reduces the forces acting on the body during impact [35]. In controlled studies, active belt tensioning has been shown to result in significantly less forward head and shoulder movement during automated emergency braking compared to a standard passive belt [36–38]. Active seat belt retractions increase the activity of the neck muscles before braking and can result in reflexing tightening of the muscles [36,37]. After repeated exposure (active belt tightening + braking), participants showed anticipatory head and body movements inverse to acceleration forces [36].

Based on these findings, active seat belt retractions might be a useful countermeasure for motion sickness as it addresses both the sensory rearrangement theory and the postural instability theory. First, they can be used as anticipative cues to announce upcoming vehicle movements to an inattentive passenger shortly in advance. Second, they can stabilize the passenger's body and head during the driving maneuver.

However, in a pre-crash situation, the seat belt must be tensed with very high forces of at least 170 N [36–38]. As we intended to use the seat belt retractions for everyday uncritical driving maneuvers with rather low decelerations, the applied force must be reduced appropriately.

The aim of the study was to investigate the effectiveness of active belt retractions as a countermeasure against motion sickness during automated driving. We hypothesized that active seat belt retractions would help visually inattentive passengers to anticipate upcoming braking maneuvers, lead to active tensioning of the neck muscles and, thus, reduce the extent of head movement during braking. Improved anticipation and head stabilization might mitigate the development of motion sickness during automated driving (Figure 1).

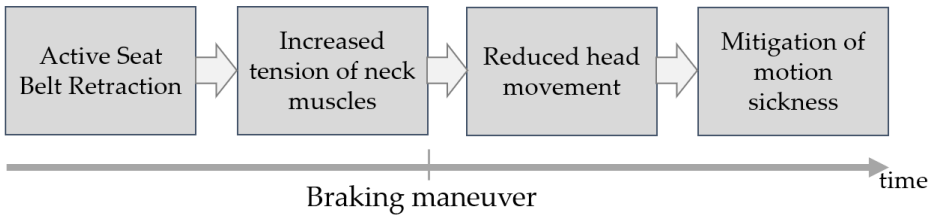


Figure 1. Illustration of examined hypotheses.

2. Methods

2.1. Participants

Previous to the study, we conducted an online survey using LimeSurvey to determine the participants' susceptibility to motion sickness. Survey links were sent to the WIVW (Wuerzburg Institute for Traffic Sciences, Veitshöchheim, Germany) driver test panel. Only people with a rather high susceptibility to motion sickness were invited to the later study, i.e., people who indicated that they usually feel motion sick after a short time or after 15 min in the test scenario (reading in slow-moving traffic on the highway). For ethical reasons, we did not invite people with very high susceptibility to motion sickness, i.e., participants who indicated to get motion sick after a short time when being a passenger on a highway without secondary task.

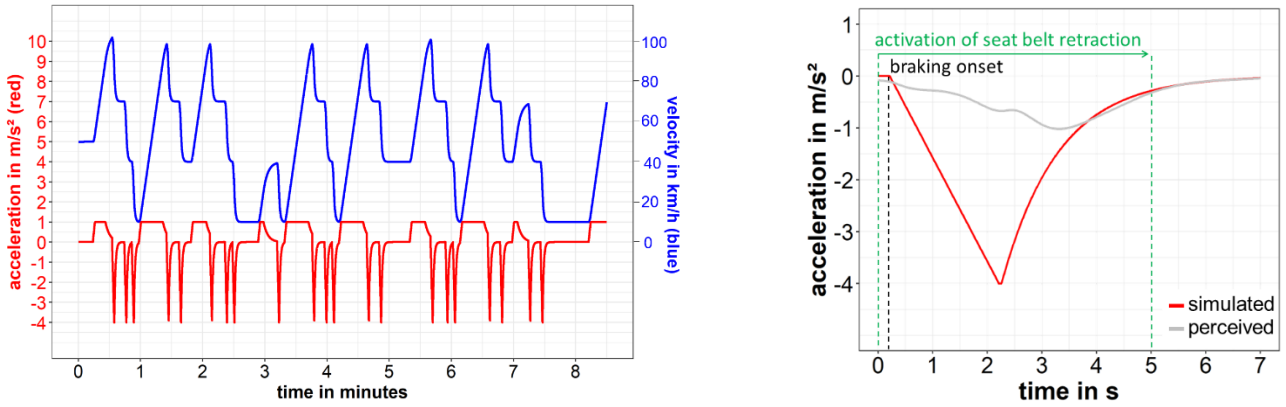
To avoid effects of simulator sickness which may bias the results in a simulator setting, only those people who had already received a special simulator training [39] and were not susceptible to simulator sickness were invited to the study. Simulator sickness, as a subform of motion sickness, can emerge when the alignment of visual and motion simulation is not accurate enough which, therefore, produces a sensory conflict [40]. Hence, the simulator training [39] helps the driver to accustom to the specific characteristics of simulator driving and successfully reduces the probability of simulator sickness [41].

A total of N = 26 participants (11 female) took part in the study. Participants were between 19 and 60 years old (M = 35.42, SD = 10.96). Within the study, the participants indicated their susceptibility to motion sickness on the Motion Sickness Susceptibility Questionnaire (MSSQ-short) [42] and obtained total scores of M = 16.8 (SD = 11.8, Min = 2.3, Max = 42.0).

2.2. Driving Simulator and Active Seat Belt Retraction System

The study was conducted in the high-fidelity motion base driving simulator (mock-up: BMW 7) of WIVW GmbH. The motion system uses six degrees of freedom and can display a linear acceleration up to 5 m/s^2. To display accelerations, a combination of horizontal offset (max 670 mm) and tilt (up to 10°) is used. We used the driving simulation software SILAB. Participants in the vehicle and the experimenter in the operator room communicated via intercom.

For the study, ZF's reversible, electromechanical seat belt retractor system (Active Control Retractor Seat Belt System, [35]) was installed in the simulator mock-up and was connected to the simulator software SILAB. This allowed the seat belt retractions to be activated at any point in the simulated driving scenario. A pre-study with N = 16 participants identified a tension profile that is not perceived as uncomfortable by drivers and is suitable for promoting neck muscle tensioning before or during braking, as well as reducing the amount of head movement during braking (compared to braking without belt tightening). A profile was selected that retracts the belt with a fast retraction speed and a force of 50 N. Each seat belt retraction was activated 200 ms before braking onset and was held for 5 s (right panel of Figure 2).



(**a**) (**b**)

Figure 2. Illustration of the driving and braking profile: (**a**) First quarter of the implemented speed profile with the associated simulated accelerations; (**b**) Braking maneuver with a simulated minimum acceleration of -4 m/s^2 and a jerk of -2 m/s^3, and a perceived minimum acceleration of -1 m/s^2; green: illustration of seat belt retraction activation 200 ms before braking onset and a holding time of 5 s.

2.3. Experimental Design

The experiment used a repeated-measures design with the seat belt condition as the independent factor with two levels. In one condition, participants encountered the drive without active seat belt retractions (baseline). In the other condition, each braking maneuver was accompanied by a seat belt retraction. Each participant experienced the two seat belt conditions on two separate experimental sessions. To control for transition effects, the sequence of the two experimental conditions were permutated and subjects were evenly distributed to both sequences.

2.4. Driving Profile and NDRT

For each experimental session, the subjects experienced a 30 min fully automated drive on the highway in simulated slow-moving traffic. In order to give passengers as few stimuli as possible from which they could anticipate their own vehicle behavior, the surrounding traffic was masked out (Figure 3).



(**a**) (**b**)

Figure 3. Illustration of the traffic scenario on a highway in slow-moving traffic: (**a**) The ego vehicle behaved as in slow-moving traffic; (**b**) However, the participants could not see the surrounding traffic.

The speed range was between 10 and 100 km/h (Figure 2a). The experimental drive consisted of a total of 84 identical braking maneuvers, each with a simulated minimum deceleration of -4 m/s^2 (Figure 2). It must be noted that a calculation based on the platform acceleration of the simulator showed that the drivers actually experienced only a minimum deceleration of -1 m/s^2 during each braking maneuver. The right panel of Figure 2 shows the simulated and perceived decelerations for each braking maneuver. The depicted driving profile (Figure 2a) was experienced with seamless transition four

times in a row. Based on ISO 2631-1:1997 [43], the driving profile provoked a Motion Sickness Dose Value of 7.09 $m/s^{3/2}$. This ISO standard provides a guidance how to measure, evaluate, and assess the effects of whole-body vibration on motion sickness. The calculation used the actual accelerations imposed to the driver in the simulator setting, composed of platform acceleration and tilt coordination (use of gravitational acceleration trough platform inclination).

As NDRT, a reading task was implemented on a tablet. The texts were easy-to-understand knowledge texts on the topics of seasons and animals. To achieve standardized conditions, participants were instructed to position the tablet on their thighs and to lean it against the steering wheel (Figure 4). Dependent on different body dimensions, the head angle during reading varied to a certain extent between participants. The angle between torso and x-axis of the head of participants with a longer torso is smaller when they look at the tablet from above than the head angle of people with a shorter torso. The text was to be read continuously during the entire drive.

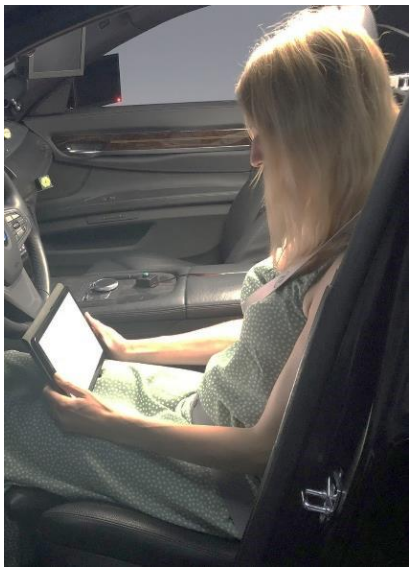


Figure 4. Instructed sitting and head position in which the reading task was performed.

2.5. Dependent Measures and Measuring Instruments

The dependent variables were drivers' subjective motion sickness ratings before, during, and after the drive, as well as their neck muscle tension and head movement during each braking maneuver.

We measured the motion sickness before and after the drive using the Motion Sickness Assessment Questionnaire (MSAQ) [44]. The MSAQ uses a multidimensional scale consisting of four dimensions. These dimensions are gastrointestinal (e.g., "I felt queasy"), central (e.g., "I felt dizzy"), peripheral (e.g., "I felt sweaty"), and sopite symptoms (e.g., tired/fatigued). We added a fifth dimension "Head" with two items ("I felt head pressure", "I had headache") to the questionnaire. Participants were instructed to rate how accurately the statements describe their current feeling on a nine-point scale from 1 ("not at all") to 9 ("severely").

Together with employees of Robert Bosch GmbH and Hochschule der Medien Stuttgart, we developed a new scale to assess motion sickness at regular intervals during the experimental drive [45]. In contrast to other scales that are commonly used for regular assessment of motion sickness symptoms [7,46], the new "Motion Sickness Task Tolerance" (MSTT) scale (Figure 5) assesses the impact of the motion sickness symptoms on the tolerance of the secondary task, using linguistic anchoring of the scale items. The structure of the MSTT scale is based on the situation rating scale of Neukum et al. [47]. The scale consists of verbal categories that are further subdivided into numerical scale points, and was permanently

displayed on the central information display. The scale was entitled with the question "How severe are your motion sickness symptoms at this moment?".

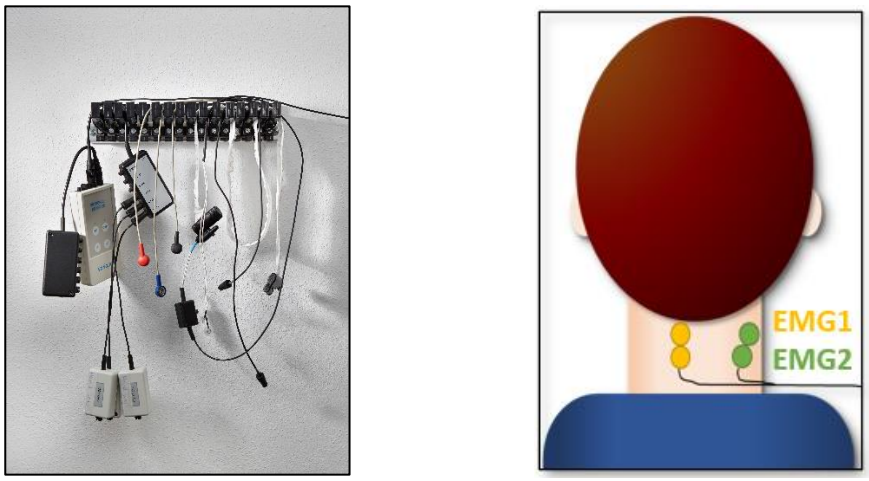


Figure 5. Motion Sickness Task Tolerance (MSTT) Scale used to assess motion sickness at regular intervals during the drive.

To determine the anticipatory effect of the seat belt pretensioner, drivers answered the item "I could easily (1)/poorly (6) predict vehicle behavior" on a 6-point scale after driving.

The tension of the neck muscles was measured using electromyography (EMG) electrodes (Varioport from Becker Meditec, Karlsruhe, Germany, Figure 6a). The positioning and assignment of the EMG electrodes are shown in Figure 6b. The channel EMG1 measured the activity of the posterior neck muscles and EMG2 the activity of the lateral neck muscles. Both EMG channels were analyzed separately. The dependent variables were the maximum muscle tension during braking maneuvers, the time between 200 ms before braking onset (=activation of seat belt retraction) and maximum muscle tension and the mean value of muscle tension. These values were averaged over all encountered braking maneuvers. With regard to the maximum muscle tension, the EMG signals were relativized on the basis of the Maximum Voluntary Contraction (MVC). The MVC was documented before the test drive. To do this, the participants were instructed to press their head against the headrest 3 times so hard that it was just not uncomfortable for them. The MVC corresponds to 100% of the muscle tension. Accordingly, all amplitudes are given in % of the MVC. This method compensates for the variance caused by the measurement (e.g., skin conductivity, muscle tone, etc.).

Head movements were measured using Pupil Invisible goggles (Pupil Labs) which are equipped with inertial-sensor technology [48]. The relevant variable was the relative head angle. We measured the head movement in degrees relative to the initial head position at the onset of each braking maneuver (see Figure 7). The initial head position was always set to 0°. Forward head movements are characterized by positive values, backward movements by negative values. The dependent variables were the maximum and minimum relative head angle, and the delta between maximum and minimum head angle. These values were averaged over all encountered braking maneuvers. Figure 7 illustrates the dependent variables that were analyzed and compared between the condition with and without seat belt retractions using an exemplary plot of the relative head angle during a braking maneuver.



(**a**) (**b**)

Figure 6. Illustration of the set up for the measurement of neck muscle tension: (**a**) Varioport with EMG electrodes; (**b**) Positioning of EMG electrodes on the posterior (EMG1) and lateral (EMG2) neck muscles.

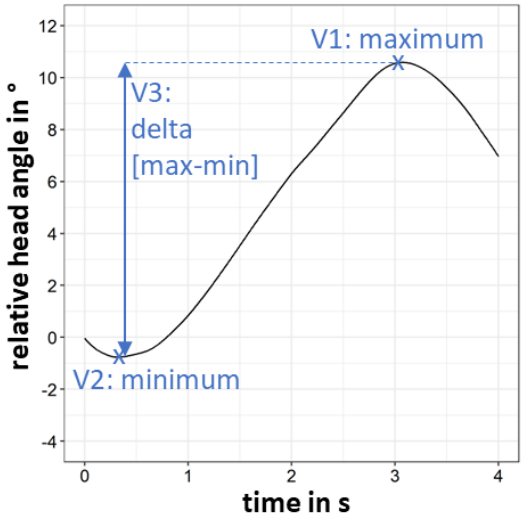


Figure 7. Exemplary plot of the relative head angle during a braking maneuver with an illustration of the four dependent variables of interest (V1–V3).

2.6. Procedure

The study is based on an ethics concept, which was internally reviewed by the responsible ethics officer and an additional independent member of the RUMBA project consortium (www.projekt-rumba.de, accessed on 15 May 2022). To ensure ethical defensibility, study execution was guided by different measures coordinated with the ethics officer. Based on these measures (e.g., definition of termination criteria, specific training of experimenters), the ethics officers declared the study to be ethically unobjectionable.

Upon arrival, participants received information about the objective of the study and the expected duration. They signed a consent form that informed them about their right to decline to participate and to withdraw from the study at any point and the method of data anonymization. Participants were told that the study examines how different factors affect the development of motion sickness during automated driving. In the experimental preparation room, participants answered the MSAQ and MSSQ-short. Then, the EMG electrodes were attached to the neck. The experimenter explained that the participant was going to experience a fully automated drive without any take over situations and that their task was to constantly read the texts on the tablet without looking ahead. Subsequently,

the experimenter elucidated the application of the MSTT scale (see Section 2.5). Then, the participant encountered the 30 min experimental drive either with seat belt retractions or in the baseline condition. During the drive session, the study leader was in a separate control room from where she monitored the driver and their answers to the MSTT scale. Every 2.5 min, a chime sounded, prompting participants to answer the question "How severe are your motion sickness symptoms at this moment?" using the scale. They typed their answer into a number pad. In case the participant gave a rating of 7 or higher, the study leader stopped the simulated drive and the experiment. After the drive, the participants again answered the MSAQ. Overall, each experimental session took about 1.25 h per participant. Both experimental sessions took place on different days whereby at least three days lay between both sessions. The order of the sessions was counterbalanced. At the end of the second experimental session, the participant received a financial compensation.

2.7. Data Analysis

Data analyses were carried out using SPSS statistics software (Version 24) and R (Version 4.1.2). We conducted dependent *t*-tests for paired samples and multivariate analyses of variance (MANOVAs). The significance level was set at $\alpha = 0.05$ for all analyses. The meaning of the statistical parameters of the analyses (e.g., alpha, *t*, *p*, *F*) can be found in the glossary of [49].

Head angle and neck muscle tension variables that were analyzed in the dependent-sample *t*-tests were averaged values of all braking maneuvers during one experimental condition. With regard to the MSTT score, the maximum rating for each experimental drive was used for the dependent *t*-test.

For the analysis of the MSAQ, the overall motion sickness score and the subscale scores were calculated as specified by the authors [44]. The scores represent the percentage of the total points scored, e.g., (sum of points from all items/maximum possible score) × 100.

Various technical problems led to a comparatively high failure rate in the EMG data, so that for the EMG1 channel the data of $N = 18$ and for the EMG2 channel the data of $N = 9$ subjects can be evaluated. Technical problems with the Pupil Invisible goggles also led to data losses in the measurement of head movements, so that the data of $N = 21$ subjects are completely available here.

3. Results

3.1. Motion Sickness

To test whether the seat belt retractions were effective in reducing motion sickness compared to the baseline condition, responses to the MSTT Scale and the MSAQ were analyzed.

With regard to the MSTT scale, a dependent-sample *t*-test for directional hypotheses tests was carried out to compare the maximum scores achieved on the scale between conditions seat belt retractions and baseline. Seat belt retractions had no significant effect on subjectively perceived motion sickness during driving ($t(25) = 0.50$, $p = 0.311$, $d = 0.10$). Three trials were terminated early due to high motion sickness (i.e., ratings on the scale greater than or equal to 7 or participants wished to terminate the session); one time with seat belt retractions and two times in the baseline. Figure 8 presents the distribution of the data in the form of boxplots (8a) and the progression of motion sickness ratings with the MSTT scale across the ride for both seat belt conditions (8b).

The MSAQ assessed motion sickness symptoms before and after driving. A multivariate two-factorial analysis of variance was calculated with two repeated-measures factors seat belt condition and time of measurement (before and after driving) and the different scales of the MSAQ as dependent variables. It was assumed that motion sickness would be higher after driving in the baseline than with the seat belt retractions. Before driving, there should not be a difference between the conditions. The analysis did not show a multivariate significant interaction effect (Wilks' $\lambda = 0.86$, $F(5, 21) = 0.69$, $p = 0.635$, $\eta_p^2 = 0.14$). Neither before nor after the test drive, motion sickness scores differed between the experimental conditions. For the different scales, motion sickness scores were significantly higher in both

conditions after the ride than before the ride (Wilks' $\lambda = 0.29$, $F(5, 21) = 10.56$, $p < 0.001$, $\eta_p^2 = 0.72$). Figure 9 illustrates means and 95% confidence intervals.

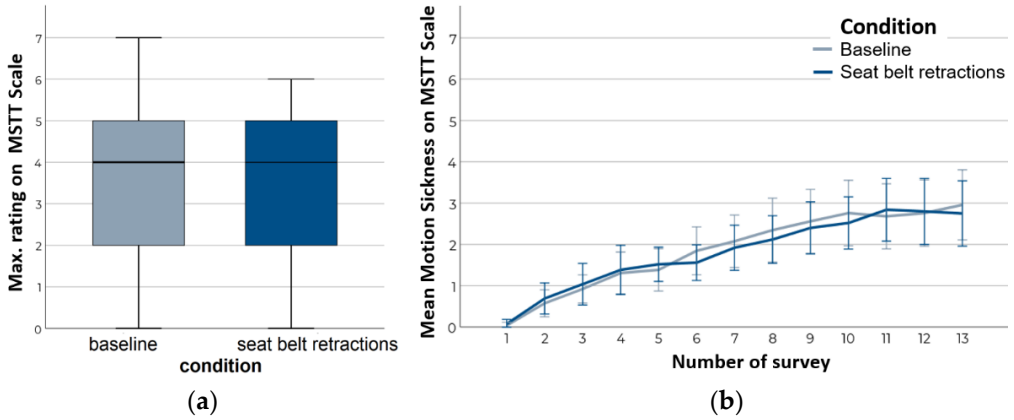


Figure 8. Illustration of ratings on the MSTT scale: (**a**) Distribution of the maximum ratings on the MSTT scale in the baseline and with seat belt retractions; (**b**) Progression of motion sickness rating across the ride.

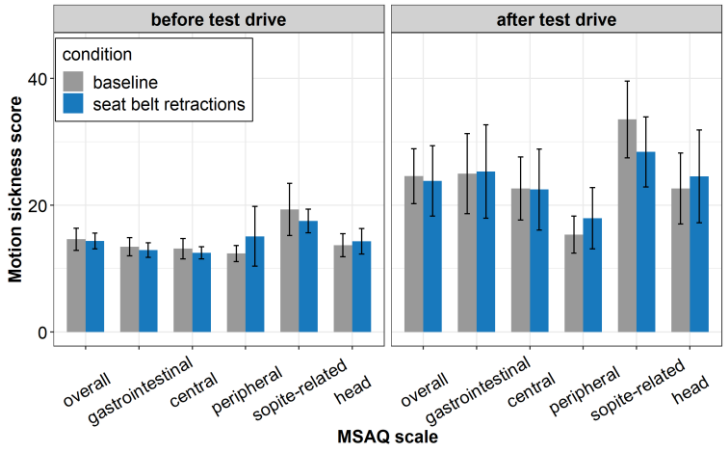


Figure 9. Means of MSAQ motion sickness ratings before and after the test drive in the baseline and with seat belt retractions. Error bars display 95% confidence intervals.

3.2. Anticipatory Effect

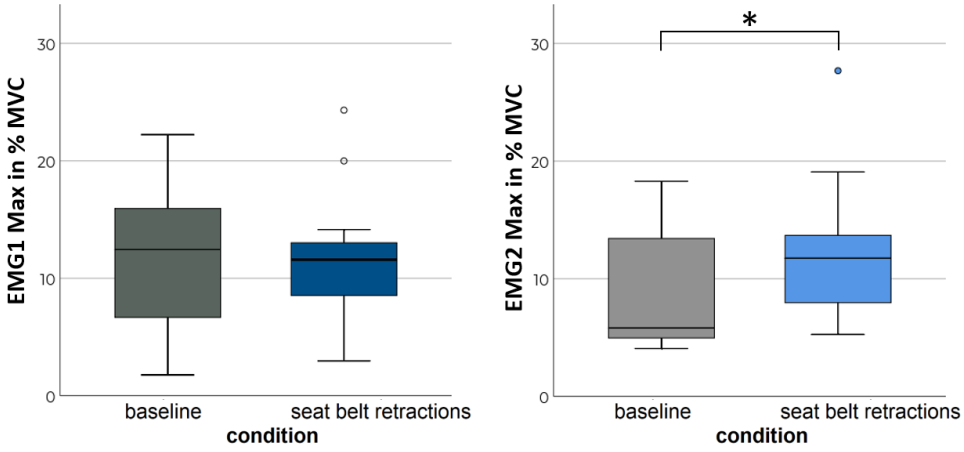
To test whether the seat belt retractions supported drivers to anticipate upcoming vehicle maneuvers, we conducted a dependent-sample *t*-test for directional hypotheses tests. Drivers found it significantly harder to anticipate vehicle behavior in the baseline condition ($M = 2.31$, $SD = 1.12$) than in the condition with seat belt retractions ($M = 2.85$, $SD = 1.35$) before each braking maneuver ($t(25) = -2.16$, $p = 0.020$, $d = 0.42$).

3.3. Neck Muscle Tension

To test the hypothesis that seat belt retractions lead to increased neck muscle tension, both EMG channels were analyzed separately and dependent-sample *t*-tests for directional hypotheses tests were carried out. Since both EMG channels are considered separately, *p*-values are Bonferroni-corrected. The dependent variables were maximum muscle tension during braking, duration to maximum muscle tension, and mean muscle tension.

There was a significant effect of seat belt condition on maximum tension in the lateral neck muscles (EMG2). Seat belt retractions resulted in greater maximum tension in the lateral neck muscles (EMG2) compared to baseline ($t(8) = 2.52$, $p = 0.036$, $d = 0.84$). In EMG1, no significant differences were found with respect to maximum muscle tension of the

posterior neck muscles ($t(17) = 0.13$, $p > 0.999$, $d = 0.03$). Figure 10 shows the distribution of the data in the form of boxplots as well as the significant pairwise comparisons graphically.



(**a**) (**b**)

Figure 10. Distribution of maximum neck muscle tension in the baseline and with seat belt retractions: (**a**) EMG1; (**b**) EMG2. * $p < 0.05$.

A closer look at the values over time revealed indications that seat belt retractions achieved the hypothesized effect especially at the beginning of the drive. After a few encounters, this effect decreased, possibly due to a habituation effect (Figure 11). Visual analysis of the individual braking maneuvers per test period revealed indications of startle reactions.

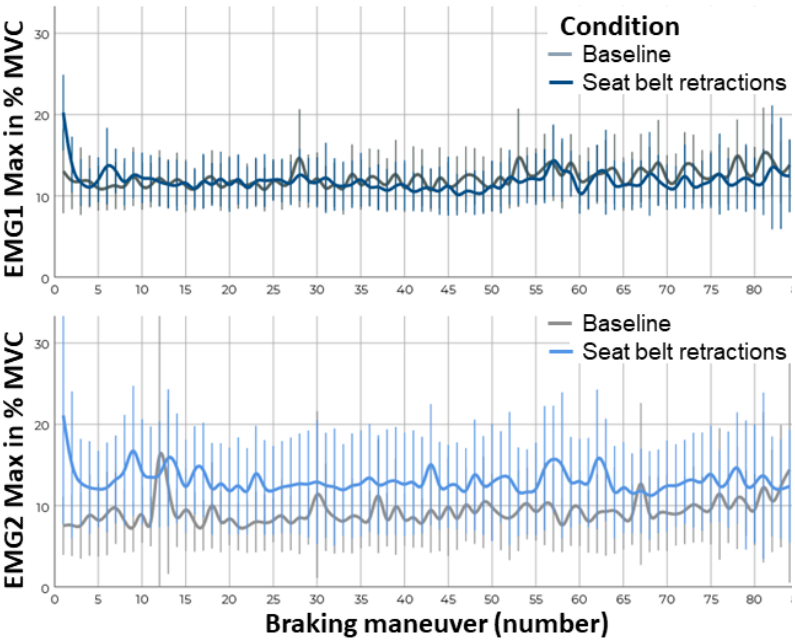
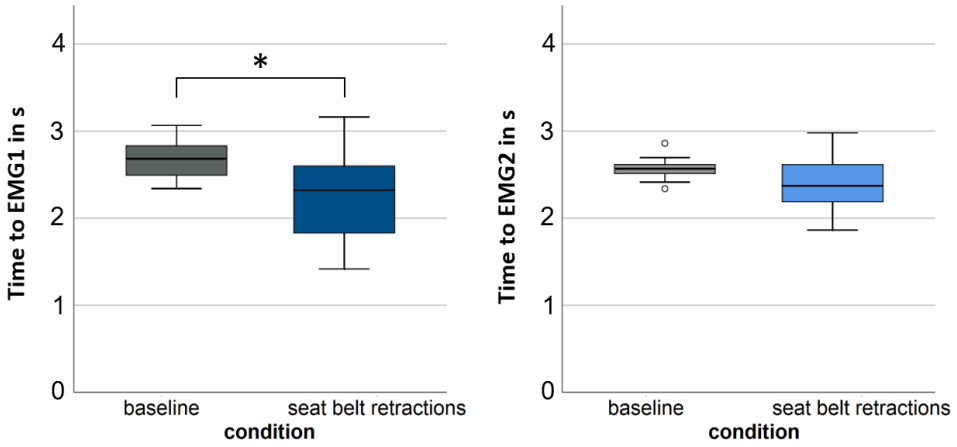


Figure 11. Course of the maximum neck muscle tension over the brakings encountered per experimental condition (upper part: EMG1; lower part: EMG2). Error bars display 95% confidence intervals.

The analysis of the time to maximum muscle tension revealed that the seat belt condition had a significant effect on the time to maximum muscle tension for EMG1 ($t(17) = 0.13$, $p = 0.008$, $d = 0.70$). Accordingly, on average, the seat belt retractions lead to an earlier activation of the posterior neck muscles. For the lateral neck muscles (EMG2), there was a similar tendency that did not reach statistical significance ($t(8) = 1.47$, $p = 0.180$,

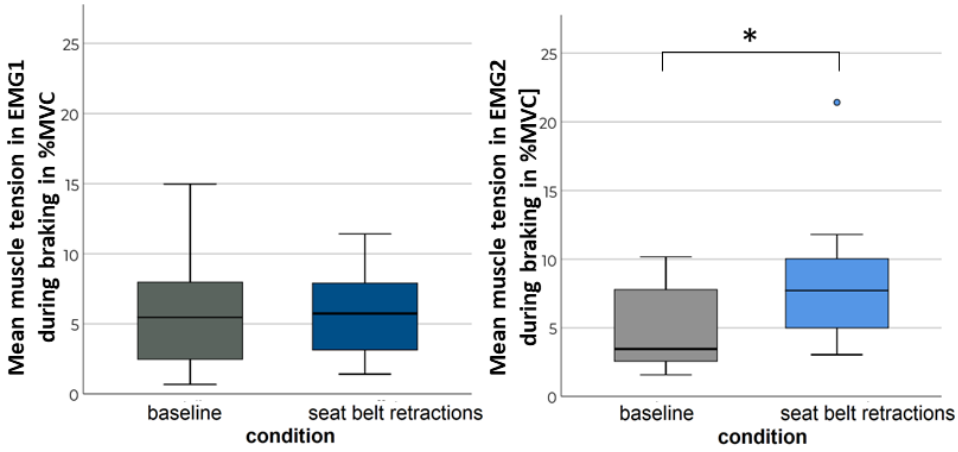
d = 0.49). Figure 12 illustrates the distribution of the data in the form of boxplots as well as the significant pairwise comparisons.



(**a**) (**b**)

Figure 12. Distribution of time to maximum neck muscle tension in the baseline and with seat belt retractions: (**a**) EMG1; (**b**) EMG2. * $p < 0.05$.

With regard to the mean muscle tension during the braking maneuvers, the results show that the seat belt retractions resulted in significantly higher activity in the lateral neck muscles (EMG2) compared to the baseline condition ($t(8) = 2.49$, $p = 0.037$, $d = 0.83$). In contrast, there was neither a statistical nor a descriptive difference in the posterior neck muscles (EMG1) ($t(17) = 0.07$, $p > 0.999$, $d = 0.02$). Figure 13 shows the distribution of the data in the form of boxplots as well as the significant pairwise comparisons.



(**a**) (**b**)

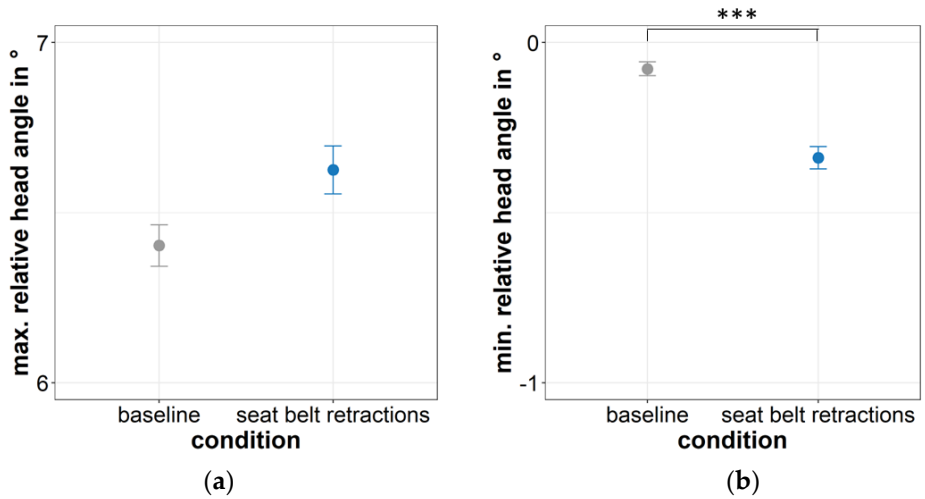
Figure 13. Distribution of mean neck muscle tension during the braking maneuvers in the baseline and with seat belt retractions: (**a**) EMG1; (**b**) EMG2. * $p < 0.05$.

3.4. Head Movements

To test the hypothesis that seat belt retractions would reduce the magnitude of head movement in response to braking, dependent-sample t-tests were performed with seat belt condition (baseline vs. seat belt retractions) as independent variable.

The t-test did not reveal a significant difference in the maximum head angle between braking maneuvers with and without seat belt retractions ($t(20) = -1.28$, $p = 0.215$, $d = 0.28$). However, seat belt retractions resulted in a significantly lower minimum head angle

compared to the baseline ($t(20) = 3.79$, $p = 0.001$, $d = 0.83$). Figure 14 shows the means, confidence intervals, and significant pairwise comparisons of the reported analyses for maximum and minimum head angle.



(**a**) (**b**)

Figure 14. Means of maximum and minimum relative head angles grouped by seat belt condition; (**a**) Maximum relative head angle; (**b**) Minimum relative head angle. Error bars display 95% confidence intervals. *** $p < 0.001$.

There was a significant effect of seat belt condition on the delta of the head angle ($t(20) = -2.43$, $p < 0.05$, $d = 0.53$). Thus, seat belt retractions resulted in a significantly higher magnitude of head movements during braking maneuvers than the baseline (Figure 15).

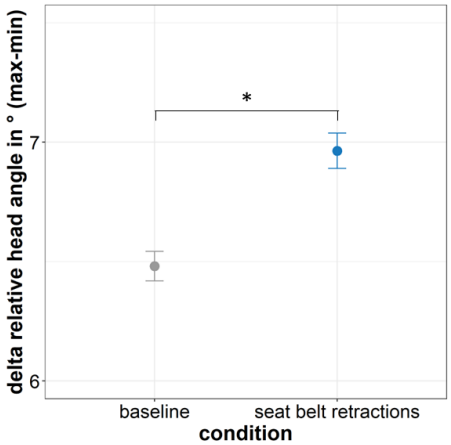


Figure 15. Means of delta relative head angle grouped by seat belt condition. Delta represents the deviation between the maximum and minimum head angle during a braking maneuver. Error bars display 95% confidence intervals. * $p < 0.05$.

4. Discussion

The aim of this driving-simulator study was to gain insights into the effectiveness of active seat belt retractions as a measure to mitigate the development of motion sickness in automated and visually inattentive driving. It was assumed that active seat belt retractions would improve anticipation of upcoming braking maneuvers, increase neck muscle activity and head stabilization during braking, and thereby avoid or reduce motion sickness. In a repeated measures design, $N = 26$ participants encountered two 30 min automated drives in slow-moving traffic with frequent braking maneuvers in two separate experimental sessions. In one experimental condition, each braking maneuver was accompanied by a seat belt retraction and in the other condition, no seat belt retractions were applied (baseline).

The results did not support our hypothesis that the seat belt retractions would reduce the level of experienced motion sickness. Neither the regular assessment of motion sickness during the drive (MSTT scale) nor the before–after comparison of motion sickness symptoms (MSAQ) revealed statistically relevant differences to the baseline. However, the seat belt retractions supported participants to anticipate upcoming vehicle movements compared to the baseline. These findings are contrary to previous studies which have suggested that anticipatory cues reduce motion sickness [18–22]. These results are likely to be related to the findings on head movements. Contrary to our hypothesis and to the findings of the pre-study, the selected tension profile resulted in a higher magnitude of head movement in response to braking than the braking maneuvers in the baseline drive. The results of the pre-study suggested that this profile was effective in reducing the amount of head movement during braking compared to baseline braking. The data of the reported study showed that the higher magnitude (delta between maximum and minimum head angle) was based on the fact that the seat belt retractions led to an initial rearward inclination of the head and subsequently the maximum forward head movement did not differ from the baseline. It is nevertheless important to note that the seat belt retractions led to an increased activity of the lateral neck muscle activity. However, without increased activity of the posterior neck muscles, this was not enough to reduce the forward head movement. The discrepancy between the effects of the tension profile in the pre-study and in the present study could be attributed to the motion sickness susceptibility of the participants. In the pre-study, we invited subjects who are not susceptible to motion sickness. Due to our focus on investigating the effectiveness of different tension profiles to reduce head movement and increase neck muscle activity, we wanted to avoid making participants nauseous for ethical reasons. In contrast, in the present study, we specifically recruited subjects with a high susceptibility to motion sickness. Prior research has shown that motion sickness susceptibility is associated with postural instability [50,51]. It seems possible that less susceptible persons with a better postural stability benefit more from seat belt retractions as a stabilization measure during braking than persons more susceptible to motion sickness. Due to their fundamentally poorer postural stability, the belt retractions might have led to the initial retraction of the head and, finally, to similar forward movements of the head as in the baseline. This hypothesis offers room for further research.

The applied reading task was initially conceptualized to be carried out without head movements. However, it cannot be excluded that some participants moved their head instead of their eyes to read the texts. Previous studies showed that this perceptual style also depends on the individual susceptibility to motion sickness, e.g., [52,53]. Subsequent studies should, therefore, consider the interaction of head and eye movements.

In an open-ended follow-up survey, participants were further asked if they had any ideas about why the belt was tightened and at what times, and what they liked or disliked about the seat belt retractions. A total of 23 of the 26 participants gave the correct answer that the belt was always tightened just before or during braking. Among the positive comments, seven participants mentioned the body-stabilizing function of the seat belt system, seven persons mentioned the possibility of predicting braking maneuvers, and three subjects explicitly said that the belt retractions made them better able to tolerate reading while driving. In terms of critical comments, the implementation of the seat belt retractions was particularly criticized. Twelve subjects said that they felt the retraction speed was too high ('too abrupt, jerky, sudden') and eight participants mentioned that the retraction force was too high. As a result, five people perceived pressure on certain parts of the body and described it as unpleasant. Two further interesting comments were that the tension intensity should be better adapted to the braking intensity.

Limitations and Future Research

A potential limitation of the current study might have been that the implementation of the driving profile of slow-moving traffic in the driving simulator did not reach the same Motion Sickness Dose Value [43] as the same driving profile would have caused in a

real vehicle. Although target decelerations of -4 m/s^2 were specified in the simulation programming, a calculation based on the platform acceleration of the simulator showed that the drivers actually experienced only a deceleration of -1 m/s^2 during each braking maneuver. If the simulator had been able to realize decelerations of -4 m/s^2, the MSDV would have been significantly higher than the value obtained with the present decelerations of -1 m/s^2 (24.47 m/s$^{3/2}$ instead of 7.09 m/s$^{3/2}$). Therefore, it is conceivable that the seat belt retractions would have been more effective in preventing motion sickness in a real traffic setting. On the other hand, prior research has compared drivers' motion sickness in the same driving simulator used in the current study to their motion sickness in a real vehicle [54]. The authors found that the development of motion sickness was comparable in both settings. Based on these results, relative validity seems to be given in the used high-fidelity motion base simulator. Relative validity means that relative differences between experimental conditions have the same direction and order as in real traffic (absolute values might differ) [55]. Nevertheless, we are of the opinion that the results of this study in the driving simulator should not yet lead to the final conclusion that seat belt retractions are not an effective measure against motion sickness. The effectiveness should be investigated in a real vehicle first. In addition, there are other modification measures that could increase the effectiveness of the seat belt retractions. The open follow-up survey showed that many drivers found the implementation of the belt tensioners uncomfortable. More specifically, the retraction speed was perceived as too fast and the force as too high. Even though the profile used was selected on the basis of data from the results of the pre-study, a different profile might have been more suitable for the frequent use of 84 times per experimental run. The challenge, however, is that tension profiles that apply a lower force are unsuitable for stabilizing the body and head during braking. From our perspective, there are two approaches to deal with this dilemma. The first approach is to focus further research only on the anticipatory effect of seat belt tightening to announce driving maneuvers. This means that profiles with lower forces and lower speeds are used which are experienced as more comfortable but no longer have a stabilizing effect. Future studies on this approach are therefore recommended. The other approach would be to continue to use profiles with a stabilizing effect and correspondingly a higher force, but no longer use them before every braking maneuver but only before braking of a certain intensity. In this context, further research should be undertaken to investigate from what braking-intensity seat belt retractions should be used and how exactly these belt retractions should be implemented.

When interpreting the findings on neck muscle tension, it must be considered that various technical problems led to a significant reduction in the data set. Due to data loss and necessary corrections, the statistical power of the EMG evaluations is reduced.

5. Conclusions

The purpose of the current study was to gain insights into the effectiveness of active seat belt retractions as a measure to mitigate the development of motion sickness in automated and visually inattentive driving. Contrary to our hypotheses, the results of this investigation did not show a beneficial effect of seat belt retractions in reducing motion sickness. In line with this finding, the used implementation of the seat belt retractions was not suitable to reduce the extent of head movements during the braking maneuvers and, thus, did not contribute to postural stability. However, the seat belt retractions supported participants to anticipate upcoming vehicle movements.

This study was the first comprehensive investigation of seat belt retractions as a potential measure against motion sickness. The findings of this research provide insights for the use of seat belt retractions for announcing driving movements for visually inattentive drivers during automated driving and lays the groundwork for future research on this countermeasure for motion sickness. Future research should examine the effectiveness of this measure under real traffic conditions, as well as investigate different implementations and activation strategies of seat belt retractions.

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Institutional Review Board Statement: The study was conducted in accordance with the Guidelines to ensure good scientific practice of the German Research Foundation ("Deutsche Forschungsgemeinschaft", DFG) as well as the Professional Ethical Guidelines of the Professional Association of German Psychologists e.V. and the German Psychological Society e.V., and approved by the Ethics Committee of WIVW GmbH (protocol code V541 and date of approval 29 October 2021) and RUMBA project consortium (protocol code WIVW2021b and date of approval 2 November 2021).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to data protection reasons.

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