An Active Suspension System for Mitigating Motion Sickness and Enabling Reading in a Car

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INTRODUCTION: The advent of autonomous automobiles raises new challenges for maintaining passenger safety and comfort. The challenge addressed here is how to predict and mitigate motion sickness when passengers read in a moving vehicle.

METHODS: We utilized a car equipped with a commercial active suspension system developed for attenuating the transmission of road surface fluctuations to passengers. The system was used to reproduce, in a parked car, either the vibrations that would be experienced in a moving car equipped with a conventional suspension system (unmitigated ride) or the attenuated vibrations that would occur on the road with the active cancellation system engaged (mitigated ride). We evaluated the consequences of these two simulated ride conditions for reading performance, comfort, and evocation of motion sickness.

RESULTS: Both ride conditions reduced the 0 to 0.8 Hz vibrations to below threshold for evoking motion sickness during passive exposure. Only the mitigated ride condition attenuated frequencies in the 0.8 to 8 Hz band where visual suppression of the vestibulo-ocular reflex is known to break down, and this condition also reduced the motion sickness induced by reading and increased reading comprehension and comfort relative to the unmitigated ride.

DISCUSSION: The palliative effects of 0.8 to 8 Hz attenuation are discussed in terms of the different mechanisms underlying motion sickness evoked by reading in a vehicle versus mere exposure to vehicle motion without reading. Implications for ISO-2631 standards for human exposure to vibration are also discussed.

KEYWORDS: car sickness, retinal slip, vestibulo-ocular reflexes, autonomous vehicle.

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Motion sickness has multiple manifestations and causal factors, including physical stimuli, individual differences, and the activities one performs.[10,20,21] This report focuses on the consequences of reading in a car for non-driving passengers. With the advent of self-driving cars, everyone will become a passenger and become more susceptible to motion sickness because of two factors known to increase motion sickness incidence and severity: first, lack of control over and a related fall-off in anticipation of self-motion increase motion sickness incidence;[32,34] and second, reading and other focal visual tasks in a vehicle evoke motion sickness beyond that attributable to mere exposure to motion.[17,31] It will be increasingly commonplace for passengers in self-driving cars to use hand-held or console-fixed visual devices for job related activities and leisure and entertainment while in transit.[7]

Understanding and ameliorating the component of motion sickness due to reading is important, but it is currently only understood in broad terms. Motion sickness in land vehicles,[27,39] ships,[4] and laboratory motion simulators[6] is increased when natural ambient optical flow is absent, restricted or distorted relative to physical, felt motion. A passenger attending to text rather than watching the road has a field of view dominated by the interior of the car rather than the exterior world visible through the car windows. Attending to head-fixed stimuli during inertial head motion has been implicated in motion sickness evocation[18,33,40] and degradation of visual acuity.[16] In addition, the posture and movement of the head and body during motion are key factors in motion sickness.[11,22,24] Reading may place the head in a vulnerable attitude and may compromise the stability of its attitude. Our goal was to determine whether an active car suspension system that attenuates the

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transmission of road vibration to the passenger would mitigate the motion sickness elicited by reading vehicle-fixed text.

We conducted our tests in a parked vehicle that was equipped with an active suspension system designed for delivering a smoother ride than possible with conventional passive shock absorbers. It was reconfigured and employed in our experiment to selectively reproduce vibrations that were previously recorded on road trips. Passive exposure of an individual in darkness to vertical linear oscillations in a frequency band centered near 0.17 Hz is a major factor in the induction of motion sickness in experimental oscillators[28] and ships.[23,25] Conventional surface vehicles such as cars,[14] buses,[39] and trains[5] generate significant fore-aft and lateral linear accelerations and yaw angular accelerations in this band and comparable power above 1 Hz for heave linear accelerations and pitch and roll angular accelerations. Passive exposure in our parked experimental vehicle reproduced only a fraction of the low frequency, circa 0.17 Hz undulations associated with large-scale travel to a destination and was therefore not expected to produce any motion sickness for an inactive subject. Reading and other focal visual tasks become nauseogenic during passive head rotation and translation above approximately 0.9 Hz, where the gain of the vestibulo-ocular reflex (VOR) becomes greater than that of visual pursuit.[1] Our active playback system permitted experimental manipulation of this frequency band of accelerations and vibrations, which normally results from the car tires rolling over an uneven road. Any motion sickness evoked in subjects attempting to read during a simulated ride in our experimental vehicle vibrating above 0.9 Hz can be related to interaction of the VOR and voluntary eye movement control and not to mere exposure to low frequency motion, which cannot be reproduced with sufficient power in the parked car. Our goal was to evaluate the effect of mitigating power in this band on the motion sickness induced by reading. Our test environment allows us to experimentally single out factors eliciting motion sickness due to reading in a car. The repeatability that our playback system can achieve in a parked vehicle is essential for a sensitive experimental test of the consequences of reading, whereas individual road tests over the same route would inevitably involve variations in driving speed and steering, which in turn would vary both low frequency accelerations and high frequency road vibration, causing each subject to have a different pattern of motion exposure.

We know of no other study that addresses the frequency-specific mechanisms underlying the motion sickness elicited by performing a focal visual task during physical body movement as well as controls for other factors such as exposure to inertial motion per se. A pilot study suggested that attenuating the 0.8 to 8 Hz frequency band of vehicle vibration during reading would mitigate motion sickness, and it also contributed to the ultimate design of the present study.[8]

METHODS

Subjects

Subjects were recruited with a Craigslist advertisement as well as by word of mouth. Prospective participants were excluded if they had never experienced motion sickness in their lifetime; the included subjects ranged between the 5^{th}–94^{th} percentile on the Golding motion sickness history questionnaire.[9] Applicants were also excluded if they self-reported visual, vestibular, psychiatric, neurological, cardio-vascular, or skeletal-muscular problems, or claustrophobia. Originally, 32 individuals were included in the study, but only 27 served as subjects in the full protocol and are included in data analysis; 3 were dropped because they did not schedule their second session within the period available for experimentation and 2 because of technical problems. The 27 subjects included 1 ClearMotion employee and 3 employee spouses or friends, three Graybiel Laboratory staff and one friend. The rest had responded to the Craigslist ad. Subjects ranged in age from 21 to 59 ($M = 37.15$, $SD = 12.82$ yr), and included 19 men and 8 women. All gave informed consent to participate in the test protocols which had been approved by the Brandeis University IRB.

Equipment

Two 2012 BMW model 535xi automobiles were used in the experiment. The one used to collect road data had the stock BMW “comfort mode” suspension system option, and the one used for playback while parked was equipped with the ClearMotion corporation active suspension system. Both vehicles were fitted with a sensor suite for research and development, which included four vertical axis (heave) linear accelerometers (Continental model BSZ04, Continental Automotive World, Hanover, Germany) on the frame above each wheel and a pitch and roll sensor (XSens MTi-G-700, Xsens Technologies B.V., An Enschede, The Netherlands) attached to the floor of the passenger compartment, on the centerline immediately behind the console. These sensor data were sampled at 400 Hz. Conditions for data recording with the conventional suspension system are described below. The active suspension playback system includes four proprietary electro-hydraulic actuators with integral hydraulic dampers, plus accelerometers on each wheel. The actuators are individually or jointly-controllable with software for pushing and pulling the wheels, adding or removing energy, to attenuate vehicle vibration in real time (bandwidth up to 30 Hz). The parked vehicle effectively had three degrees of freedom—heave, pitch, and roll. Because the suspension system actuators are configured to accept force command input and the recorded road data were heave acceleration and pitch and roll rates, the experimental mode utilized an inverse plant model to translate sensor data into force commands. The model accounts for coupling between heave, pitch, and roll. In addition, a 2^{nd} order low pass 8 Hz filter was applied to the commands fed to the playback algorithm to avoid pushing and pulling the wheels faster than the car body could follow. For experimental playback testing in the parked vehicle, the algorithm was tuned either to reproduce as accurately as possible the prerecorded road data fed to it (unmitigated ride) or to selectively attenuate the prerecorded motion in the 0.8 to 8 Hz band (mitigated ride).

A laptop computer (ThinkPad T439, 1366 × 768 screen resolution) was used to schedule events and to record subject responses during testing, as described below. The laptop rested on a tray across the lap of the subject who was in the rear driver's side seat. The cover was open to a comfortable screen viewing angle. A smartphone (LG Nexus 4) secured in a caddy strapped to the back of the driver's seat just above the laptop screen was used to present text for the subject to read. The average smartphone viewing distance across subjects was 47.5 cm (SD = 5.0 cm), and the displayed letter height of the text was 1.5 mm or 0.18° of visual angle. The text passages contained an average of 282 (SD = 64.5) words.

Procedure

Prior to subject testing, ride data were collected by driving the BMW vehicle equipped with a conventional suspension system over approximately 300 miles of highways and roads in the Greater Boston, MA, area, under various traffic conditions. One continuous 300 s segment of road data was selected for replay during testing. We selected the roughest segment by computing power spectral density (PSD) of heave acceleration, heave jerk, pitch rate, and roll rate for nonoverlapping 82 s segments of all the data and using the four consecutive segments whose average power was greatest across all four metrics. The raw data reflected excursions through space that would far exceed the travel limits of the playback system actuators. Therefore, the raw sensor data were filtered to remove low frequency, large amplitude components that the playback actuators could not attempt to neutralize without hitting their end stops, ± 70 mm. The gray trace in **Fig. 1A** represents the PSD of raw road data for the selected segment.

Subjects were tested in the unmitigated and mitigated ride conditions on separate days in balanced order, 2 to 4 d apart. They were tested one at a time, sitting in the rear driver's side seat of the test vehicle, wearing a seatbelt, with the doors closed. The experimenter sat next to the subject. Neither was informed of the experimental condition, though the difference in roughness between the two ride conditions was probably discriminable across test days. The test vehicle was parked in an indoor workshop bay, which was clearly visible through the rolled-up windows. The car engine was not running during test sessions, and power for all systems was supplied by an external source. Each test day began with a training period when the subject was familiarized (or refamiliarized) with the procedure for the reading task, the criteria for rating motion sickness symptoms, and the other questions they would be asked about their experience (see below). The data collection period included seven contiguous 5-min epochs. The first epoch was a preride baseline stationary period, and in epochs 2–7 the designated ride exposure condition for that day was presented in continuous 5-min loops for 30 min. A 5-min postexposure interview concluded the session. The vehicle's environment control system was set to 72°F, and independent temperature measurements confirmed a small average temperature rise from 70.7 to 72.1°F over the course of data collection.

In every ride exposure epoch, the same 300-s segment of road data was played back, with or without mitigation depending on the condition. At the beginning of each playback epoch, subjects

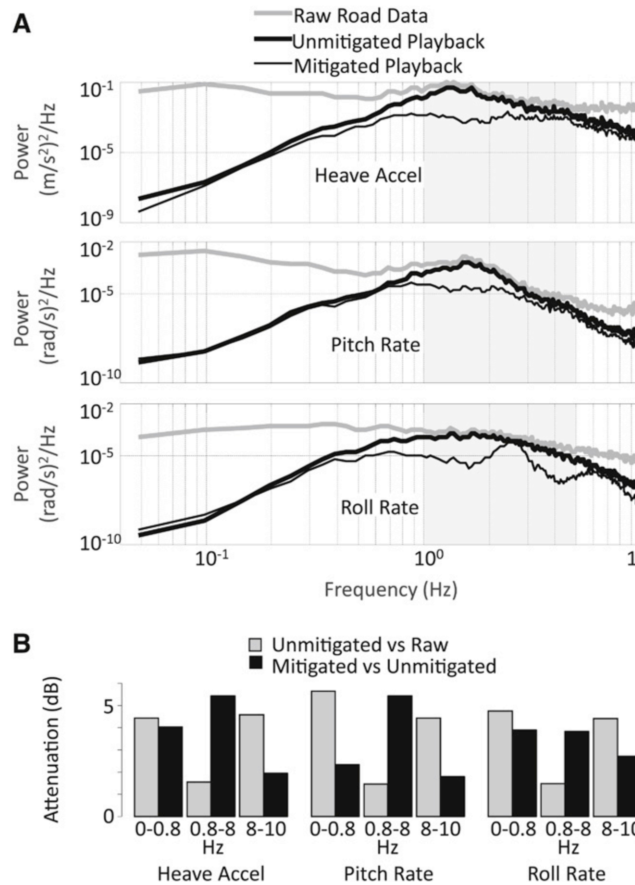

Fig. 1. A. Power spectral density plots of raw road vibration (gray lines), unmitigated ride playback (thick black lines), and mitigated ride playback (thin black lines) for three motion axes. B. Attenuation of heave acceleration and rates of pitch and roll between the road and unmitigated playback control condition, and between the mitigated experimental condition and the unmitigated control condition.

were told to open a designated text file in a folder on the smartphone and to read it silently for 3 min, until prompted to answer two multiple choice questions about their content. They had to remove the smartphone from its caddy and hold it in their hand while opening the file and then return it to the vehicle-fixed caddy to read. They were instructed to stop reading the text when prompted if they had not reached the end or to reread it from the beginning if they finished early. There were 14 different text files – one for each of the 14 epochs (7 per day). The order of text presentation was different for each subject and balanced across ride conditions. Subjects were directed to answer two multiple choice comprehension questions using the laptop keypad as soon as they finished reading. Next, they gave a 0 to 10 rating of the overall severity of their nausea symptoms, where 0 signified no nausea and 10 was nausea so severe that vomiting was imminent. Untrained observers can rapidly use such a scale to make self-ratings that are valid and sensitive.[19,29,39] Next, subjects answered the experimenter's questions about the seven cardinal signs and symptoms of motion sickness corresponding to the Graybiel diagnostic criteria.[12,13,26]

Subjects rated stomach symptoms (stomach awareness, stomach discomfort, and nausea), drowsiness, dizziness, salivation, and headache, and the experimenter rated pallor and sweating. The training period prior to ride exposure was used to familiarize subjects with the definitions of symptoms and the criteria for rating them as none, minimal, mild, moderate, major, and severe. The highly experienced experimenter rated pallor and sweating. The six levels of severity were later assigned values of 0, 1, 2, 4, 8, and 16, respectively, and summed for a total score. After rating their motion sickness symptoms, subjects rested until the ride segment began to repeat (usually about 1 min) and they were cued to read the next text passage. The preride baseline epoch followed the same protocol with no motion playback. After the last ride epoch on each day when the vehicle was again stationary, all subjects rated eye strain (0 = no strain, 10 = severe strain) over the entire 30-min ride period. The last 13 subjects also rated overall ride comfort (0 = very comfortable, 10 = very uncomfortable), text blurriness (0 = very clear, 10 = very blurry), reading comprehension difficulty (0 = very easy, 10 = very difficult), and smartphone handling difficulty (0 = very easy, 10 = very difficult). After their second session was complete, they were asked to compare the two ride conditions with respect to the same qualities, except for eye strain.

Statistical Analysis

Statistical analysis was performed with SPSS software (version 24). Repeated measures ANOVAs were used to examine the effects of reading epoch and ride condition on nausea ratings, reading performance, and subjective drowsiness, eyestrain, comfort, reading difficulty, and manual handling. When significant effects of epoch were found, polynomial contrasts were conducted to determine whether significant linear or higher order trends were present. Regression analysis was then performed across epochs including only the polynomial terms identified by the contrasts. Paired *t*-tests were used to compare the end of session ratings across the two ride conditions.

RESULTS

Fig. 1A illustrates PSDs of the raw road data in gray, the unmitigated, filtered playback data in thick black lines, and the mitigated ride data in thin black lines, and **Fig. 1B** compares the attenuation of heave acceleration, pitch rate and roll rate for the frequency bands relevant to motion sickness across the different ride conditions. The raw ride data showed ample power at frequencies below 0.8 Hz where humans are susceptible to motion sickness during passive exposure and where visual suppression of the VOR is adequate to prevent retinal slip during reading. Ample power is present well above 0.8 Hz where humans are not susceptible to motion sickness during passive exposure but where retinal slip would be expected during reading due to inadequate visual suppression of the VOR. Heave acceleration showed a local peak absolute power of 0.08 $(m \cdot s^{-2})^2$/Hz at 1.4 Hz, falling off monotonically with increasing frequency and at a lower rate with decreasing frequency and leveling off at very low frequencies, which corresponds with previous road data from cars published by Griffin and Newman.[15] The raw pitch rate showed a local peak power of 0.001 $(rad \cdot s^{-2})^2$/Hz at 1.6 Hz, falling off monotonically at higher and lower frequencies and leveling off at very low frequencies. Raw roll rate had a maximum power of about 0.0006 $(rad \cdot s^{-2})^2$/Hz at 0.4 Hz and fell off at lower and higher frequencies.

The low and high frequency unmitigated playback data were attenuated relative to the raw road data due to the high pass filter that was imposed to avoid exceeding the suspension system actuator limits and the low pass filter that prevented wheel resonance. In the low frequency range from 0 to 0.8 Hz, the unmitigated experimental ride was strongly attenuated: 6.73, 8.58, and 6.15 dB RMS for heave acceleration, pitch rate, and roll rate, respectively (see Fig. 1B). In the midfrequency range 0.8 to 8 Hz, which is most associated with retinal slip during reading, the unmitigated experimental ride was only slightly attenuated relative to the raw, conventional road ride by 1.75, 1.56, and 1.63 dB RMS for heave, pitch, and roll, respectively. In the high frequency range 8 to 10 Hz, where the antiresonance filter was active, the unmitigated experimental ride was attenuated relative to the raw, conventional road ride by 6.63, 6.81, and 6.85 dB RMS for heave, pitch, and roll, respectively. The mitigated experimental ride was attenuated relative to the unmitigated control condition in the range 0.8 to 8 Hz where retinal slip would be most prominent: 5.06, 5.07, and 4.82 dB RMS for heave, pitch, and roll, respectively. In the bands below 0.8 Hz and above 8 Hz, the attenuation is lower across all motion axes for the mitigated ride condition, ranging from 0.96 to 2.13 dB.

All subjects completed the full 30 min in both conditions, and none vomited. The reading task elicited monotonically increasing Nausea 0–10 scores over successive epochs for both ride conditions. **Fig. 2A** presents the change in Nausea 0–10 ratings for all subjects as a function of ride exposure time while subjects performed the reading task. The average Nausea 0–10 score for all 27 subjects was zero in the baseline periods just prior to motion onset and increased monotonically to 2.7 (SD = 2.81) at the end of the unmitigated ride condition and to 1.50 (SD = 1.90) at the end of the mitigated ride condition. The Nausea 0–10 scores at the ends of the 30 min ride exposures were significantly greater than zero for both ride conditions [1-tailed *t*-tests for difference from zero, $t(26) = 3.645$, $P = 0.000585$ at least], and the mean in the unmitigated condition was significantly higher than in the mitigated condition [1-tailed, paired *t*-test, $t(26) = 2.873$, $P = 0.004$]. A repeated measures ANOVA conducted to determine the effects of ride condition and epoch on nausea showed that the ride × epoch interaction violated the ANOVA sphericity assumption, so Greenhouse-Geisser corrections were used for computing significance levels. The unmitigated ride produced significantly more nausea [$F(1,26) = 18.54$, $P = 0.00021$] than the mitigated ride, and successive ride epochs intensified nausea [$F(1.713, 44.54) = 11.42$, $P = 0.0002$]. There was an interaction of the two factors [$F(1.137, 29.556) = 13.96$, $P = 0.0018$] in which successive epochs produced incrementally more nausea in the unmitigated than in the mitigated ride condition. Polynomial

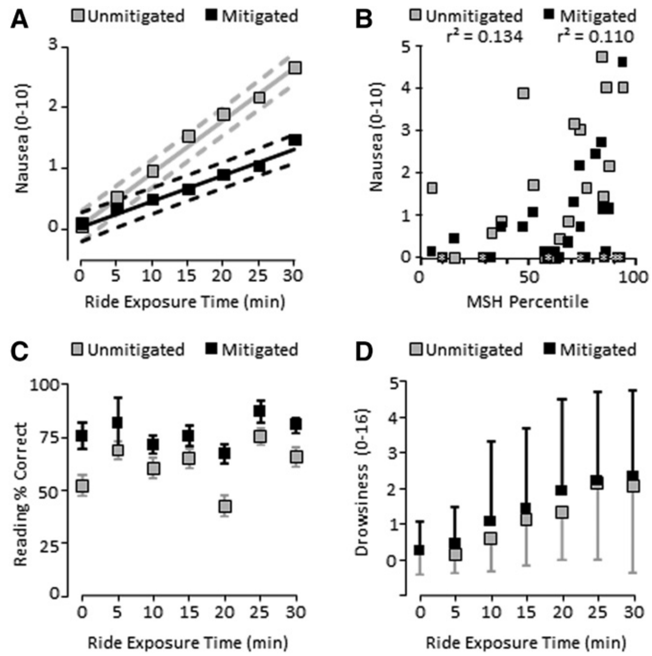

Fig. 2. A. Nausea ratings as a function of ride exposure time for the unmitigated and mitigated ride conditions. Each 5-min interval of ride exposure contains one 3-min reading epoch. B. Scatterplot of peak nausea ratings in both ride conditions vs. the percentile ranking on motion sickness history (MSH) for each subject. (Some gray points on the x axis are hidden by black points.) C. Percentages of reading comprehension questions answered correctly as a function of exposure in each ride condition. D. Self-rated drowsiness (Graybiel Scale subitem) as a function of exposure in each ride condition. $N = 27$ for all plots.

contrasts showed a significant linear trend for the ride type × epoch interaction [$F(1,26) = 8.996$, $P = 0.0013$] but no significant higher order trends ($P > 0.055$). This pattern means that the rate of increase of nausea as a function of each ride condition can be captured with a linear model. Examination of the nausea by epoch plots for individual subjects confirmed this. Different subjects began to experience nausea in different epochs but once they experienced nausea, it increased in a linear fashion with very similar slopes across subjects in the same test conditions and different slopes across conditions.

The above analyses justified performing linear regression analyses for each ride condition. The solid lines in Fig. 2A represent the best fitting linear regression lines for the average Nausea 0–10 ratings across subjects per epoch for each ride condition. The linear model explained at least 97% of the variance across ride conditions. The slope of increasing nausea over epochs in the unmitigated ride condition (0.087) was about twice that of the mitigated ride condition (0.043), a significant difference [1-tailed, paired *t*-test, $t(26) = 4.459$, $P = 0.00007$]. Regression lines were also computed for each individual subject beginning with the first epoch when they reported any nausea. The average of the slopes across individuals was significantly higher [$t(26)=5.296$, $P = 0.00000992$] in the unmitigated (0.205) than the mitigated (0.067) condition. The broken lines flanking the trend lines in Fig. 2A represent the 95% prediction intervals for each ride condition. These intervals indicate with 95% probability where a single future measured value would fall given the empirically determined regression model.[37] (Prediction intervals around a regression line are wider than the more commonly used confidence intervals because of the greater uncertainty involved in predicting a specific value rather than the mean value for a given predictor value.) The intervals for the two ride conditions cease to overlap at 9.91 min of exposure. This means that the mitigated ride would produce a statistically repeatable mitigation of nausea in rides ~10 min or longer under the rough road conditions and reading conditions of the tests. The eight subjects who were associated with ClearMotion or the Graybiel laboratory showed the same slopes of increasing nausea as a function of ride duration as the 19 other subjects.

The scatterplot in **Fig. 2B** illustrates the relationship of peak nausea experienced in both ride conditions relative to previous motion sickness history. The subjects in our sample ranged between the 5th (least susceptible) and 94th (most susceptible) percentiles on the motion sickness history questionnaire. The Pearson correlation coefficients between history scores and nausea scores reached the criteria for significance in both ride conditions, $r = 0.332$, $P = 0.045$ for the unmitigated ride and $r = 0.366$, $P = 0.029$ for mitigated. These associations would have been higher without 7 subjects who experienced no nausea or other motion sickness symptoms in either experimental ride condition (black points with asterisks on the x axis) and ranged from the 10th to the 93rd percentile on their motion sickness history scores. When the above analyses were repeated on the 20 susceptible subjects, the differences between the mitigated and unmitigated ride became larger.

The Graybiel scale motion sickness scores showed a similar pattern to the Nausea 0–10 scores, rising monotonically, faster and to higher ultimate values in the unmitigated than the mitigated ride condition (plots not shown). The Graybiel scale total scores averaged 13.7 (SD = 6.4) and 9.3 (SD = 5.1) at the end of the unmitigated and mitigated conditions, respectively (plots not presented). When all subjects and epochs were aggregated, all cardinal signs and symptoms of the Graybiel scale were reported in both ride conditions, including moderate nausea in the unmitigated ride condition and mild nausea in the mitigated condition. Every individual item showed a significant positive slope. The three items that accounted for the largest fraction of the total score were stomach symptoms (stomach awareness, stomach discomfort, and nausea combined), drowsiness, and dizziness (eyes closed and eyes open combined).

Figs. 2C-D illustrate the evolution of scores for reading comprehension performance and subjective fatigue across ride exposure epochs. For subjective fatigue scores, we used the reported drowsiness item of the Graybiel scale. Fig. 2C shows that reading comprehension was better in the mitigated (M = 78.0, SD = 4.92) than the unmitigated ride condition (M = 62.6, SD = 3.37) for every epoch. A repeated measures ANOVA confirmed that the effect of ride mitigation was significant [$F(1,26) = 8.79$, $P = 0.0066$] and that there were no effects of an epoch and ride × epoch interaction. Fig. 2D shows that subjects got drowsier as they read more during both ride conditions, but the induction of drowsiness did not differ between ride conditions. A repeated measures ANOVA confirmed that the main effect of epoch was significant [$F(6,156) = 36.9$, $P < 0.0001$], but there was no main effect of ride condition or interaction with epoch.

Fig. 3 compares the subjective ratings given at the end of each session. Reading during the mitigated ride was rated more comfortable overall. In the mitigated condition, the text looked less blurry and seemed easier to comprehend, the smartphone seemed easier to manipulate, and reading produced less eye strain. All of these differences were significant, except the smartphone handling rating (Bonferroni-corrected paired *t*-tests). The 13 subjects who were asked to compare ride conditions after having experienced both of them rated the mitigated ride better for comfort, blurriness, comprehensibility, and handling in 10, 11, 10, and 9 cases, respectively. These comparisons are significant because the binomial probability for one ride being chosen as better in 9 of 13 cases is 0.046.

DISCUSSION

Our unmitigated ride condition generated a faithful laboratory reproduction of the 0.8 to 8 Hz heave, roll, and pitch power that was recorded in a vehicle equipped with a conventional suspension system during a road trip, within the mechanical limits of the active suspension system. The mitigated ride condition selectively attenuated power in the 0.8 to 8 Hz range. When subjects performed the reading comprehension task during the faithfully simulated unmitigated ride, they experienced more intense motion sickness, which escalated faster, than during the mitigated ride. Comprehension of the reading material was also impaired during the unmitigated relative to the mitigated ride condition. Subjects rated the text to be harder to read, harder to comprehend, and a source of more eye strain, and more soporific during exposure to the unmitigated ride condition. These results show that attenuation of the power in the 0.8 to 8 Hz frequency range protects against the car sickness induced by reading and improves objective and subjective reading performance as well as overall passenger comfort.

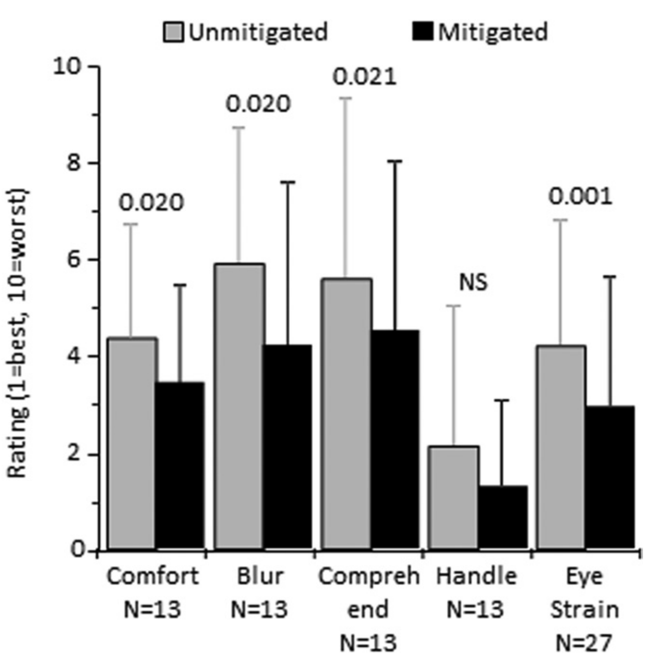

Fig. 3. Subjective ratings of overall ride comfort (Comfort), blurriness of the text being read (Blur), comprehension difficulty (Comprehend), manipulation of the smartphone on which text segments were read (Handle), and eye strain (Eye Strain) that subjects gave at the end of each experimental session. The *P*-values (Bonferroni corrected) for *t*-tests comparing the unmitigated and mitigated rides are presented above each pair of bars.

The 0 to 0.8 Hz range of motion was equally strongly attenuated in both of our playback ride conditions relative to road conditions. The 0.8 to 8 Hz motion was played back faithfully in the unmitigated condition relative to the real road data but was strongly attenuated in the mitigated ride condition. Thus, power in the 0 to 0.8 Hz motion band was too low to evoke motion sickness in both playback conditions. The power in the 0.8–8 Hz band was also insufficient to evoke motion sickness without reading in the unmitigated ride condition because its magnitude was typical of natural road conditions and the evidence-based[23,25,28] standards of ISO 2631[36] indicate that susceptibility to motion sickness without reading is 1000 times lower in the 0.8 to 8 Hz band than in the 0–0.8 Hz band. In other words, both the attenuated 0 to 0.8 Hz motion and the unattenuated 0.8 to 8 Hz motion that our subjects experienced were below threshold for generating motion sickness in the absence of reading. While the cited research makes it implausible that vibration without reading (or even repeated reading epochs without vibration) were factors in the observed results, to definitively rule out these factors would require running additional control conditions. The view of the stationary world outside the window and the vestibular motion signals were consistent in both bands. Thus, the additional attenuation of the 0.8 to 8 Hz band in the mitigated ride condition probably did not contribute to the reduction of motion sickness through a reduction of visual-vestibular conflict.

We found that mitigating the 0.8 to 8 Hz band was effective for reducing motion sickness during reading, and we propose that this was likely due to decreased retinal slip. The VOR that would keep the eyes stable in space by counterrotating them during head tilt and translation has a high gain at 0.8 to 8 Hz. However, our reading display device was not world-fixed but instead moved roughly in phase with the head due to their common, albeit loose, mechanical coupling to the car frame. The VOR would tend to displace the eyes relative to the display, which would result in retinal slip if not fully cancelled by visual pursuit[1] or other voluntary mechanisms[3], all of which have low gain above 0.8 Hz and 80°/s, especially for targets closer than 1 m.[30] Thus, the test conditions make it probable that retinal slip differed across ride conditions in the 0.8–8 Hz band. Greater retinal slip in the unmitigated ride condition is consistent with the degradation of reading comprehension (such as seen in studies that measured eye movements[2]) in that condition compared to the mitigated ride condition (Fig. 2C). Differential retinal slip in the mitigated and unmitigated conditions is also compatible with our subjects' perceived increases in visual blur and eye strain and their reported difficulty in handling the reading device in the unmitigated condition. To test the retinal slip hypothesis, we are currently measuring eye and head movements during comparable experimental conditions.

A causal link between retinal slip and motion sickness is also supported by evidence that eliminating retinal slip by stroboscopic illumination attenuates motions sickness.[18,33,40] Melvill Jones and Mandl[18] had subjects make voluntary head movements during left-right vision reversal under normal and stroboscopic illumination conditions. They found severe motion sickness occurred under continuous illumination. With stroboscopic illumination during head movements sickness was absent. Retinal slip may be the causative factor in broader forms of visual-vestibular conflict as well as reading in a car. For example, sickness in fixed-based simulators is evoked by a moving visual display of natural scenes that needs to be stabilized on the retina by optokinetic and other relatively slow visual and predictive processes because of the absence of physical motion that would normally evoke faster, synergistic vestibular reflexes.[19]

Our results indicate that industry standards for engineering a comfortable, malaise-free ride are inadequate in scope. The current design standard is ISO 263,[36] which is based on evidence from evaluating motion sickness in subjects passively exposed without an external visual reference.[28] The current standard identifies acceleration frequencies around 0.2 Hz, depending on the axis of tilt or translation, as being the most provocative with a monotonic fall-off at lower and higher frequencies. Above 1 Hz, the risk is attenuated 1000-fold. Our results indicate that for reading in a car there is significant risk in the 0.8 to 8 Hz range that we experimentally manipulated. Our results do not exclude the possibility that reading is also provocative during exposure to frequencies below 0.8 Hz and above 8 Hz because our experimental conditions did not differentially alter the ride in those bands. It is possible that some of the nausea elicited in our mitigated condition was due to residual vehicle vibration or retinal slip from reading during residual oscillations below 0.8 Hz that were equivalent in the unmitigated and mitigated conditions, or retinal slip occurring during reading due to the unattenuated 8 to 10 Hz band of the ride. From a practical standpoint, our study shows that mitigating the 0.8 to 8 Hz range of the ride profile improves comfort and performance and reduces motion sickness. To determine exact dose-response relationships for the amount and duration of vibration during reading will require additional control tests comparing reading and no-reading conditions. Future studies are also required to determine the full spectrum over which reading elicits motion sickness and performance degradation, and the specific bands of motion attenuation that will counter these negative effects.

It could be suggested that we have overestimated the impact of reading because we selected a rough road segment for our tests. However, our accelerometer readings are consistent with studies that measured driving on average roads.[38] We also tested a subject group with a very broad range of motion sickness susceptibilities based on their self-reports. It could be argued that our 30-min exposure periods were too brief to estimate the full impact of reading and benefits of mitigating the 0.8 to 8 Hz vibrations. Longer durations would be useful for assessing the physiological bases of motion sickness and testing additional countermeasures. However, our tests are practically relevant because in 2009 the average American driver was estimated to have made 3.9 trips per day in a private vehicle, each lasting 15.3 min, on weekdays.[35] When autonomous vehicles become available such trips will frequently involve focal visual tasks. Motion sickness has multiple etiologies and manifestations,[10,20,21] and the response to one stimulus can sensitize subjects to another.[22] For practical reasons, our experiment excluded some elements of acceleration that are known to be provocative, such as fore-aft and lateral linear acceleration and yaw rotation frequencies below 0.2 Hz in all axes. Road tests are a potential way to resolve how reading might interact with motion sickness from low frequency acceleration. Road tests lack the repeatable control of the vehicle motion profiles that our laboratory tests provided. However, the loss of experimental control such variance would produce could be offset in road tests by direct measurement of head, eye and vehicle motions. Eye and head movement recordings would also help link the observed efficacy of attenuation in specific frequency bands to the physiological causes of motion sickness and reading decrements.

In conclusion, reading in cars induces motion sickness – a problem autonomous cars will worsen by freeing drivers for work or entertainment involving focal visual attention. We used an active suspension system to attenuate 0.8 to 8 Hz frequency vibrations in one of two simulated ride conditions lacking low frequencies that normally elicit motion sickness without reading. Selective attenuation of 0.8 to 8 Hz vibration decreased motion sickness and improved reading performance, which suggests that: a) retinal slip or its correlates is an independent risk factor that an active suspension system can mitigate; and b) standards for exposure to vibration with respect to motion sickness and performance should include consideration of the presence of a focal visual task during exposure.

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REFERENCES

1. Barnes GR, Benson AJ, Prior AR. Visual-vestibular interaction in control of eye-movement. Aviat Space Environ Med. 1978; 49(4):557–564.
2. Barnes GR, Smith R. The effects on visual discrimination of image movement across the stationary retina. Aviat Space Environ Med. 1981; 52(8):466–472.
3. Barr CC, Schultheis LW, Robinson DA. Voluntary, non-visual control of the human vestibulo-ocular reflex. Acta Otolaryngol. 1976; 81(5–6): 365–375.

4. Bos JE, MacKinnon SN, Patterson A. Motion sickness symptoms in a ship motion simulator: Effects of inside, outside, and no view. Aviat Space Environ Med. 2005; 76(12):1111–1118.
5. Cohen B, Dai M, Ogorodnikov D, Laurens J, Raphan T, et al. Motion sickness on tilting trains. FASEB J. 2011; 25(11):3765–3774.
6. Dichgans J, Brandt T. Optokinetic motion sickness and pseudo-Coriolis effects induced by moving visual stimuli. Acta Otolaryngol. 1973; 76(5): 339–348.
7. Diels C, Bos JE. Self-driving carsickness. Applied Ergonomics. 2016; 53 Pt B:374–382.
8. Ekchian J, Graves W, Anderson Z, Giovanardi M, Godwin O, et al. A high-bandwidth active suspension for motion sickness mitigation in autonomous vehicles. Warrendale (PA): SAE; 2016; SAE International Technical Paper 2016-01-1555.
9. Golding JF. Motion sickness susceptibility questionnaire revised and its relationship to other forms of sickness. Brain Res Bull. 1998; 47(5):507–516.
10. Golding JF. Motion sickness susceptibility. Autonomic Neuroscience - Basic Clinical. 2006; 129(1–2):67–76.
11. Golding JF, Markey HM, Stott JR. The effects of motion direction, body axis, and posture on motion sickness induced by low frequency linear oscillation. Aviat Space Environ Med. 1995; 66(11):1046–1051.
12. Graybiel A, Clark B, Zarriello JJ. Observations on human subjects living in a "slow rotation room" for periods of two days. Arch Neurol. 1960; 3(1):55–73.
13. Graybiel A, Wood CD, Miller EF II, Cramer DB. Diagnostic criteria for grading the severity of acute motion sickness. Aerosp Med. 1968; 39(5):453–455.
14. Griffin MJ, Newman MM. An experimental study of low-frequency motion in cars. Proc Inst Mech Eng, D J Automob Eng. 2004; 218(11, D11)1231–1238.
15. Griffin MJ, Newman MM. Visual field effects on motion sickness in cars. Aviat Space Environ Med. 2004; 75(9):739–748.
16. Herdman SJ, Tusa RJ, Blatt P, Suzuki A, Venuto PJ, Roberts D. Computerized dynamic visual acuity test in the assessment of vestibular deficits. Am J Otol. 1998; 19(6):790–796.
17. Isu N, Hasegawa T, Takeuchi I, Morimoto A. Quantitative analysis of time-course development of motion sickness caused by in-vehicle video watching. Displays. 2014; 35(2):90–97.
18. Jones GM, Mandl G. Motion sickness due to vision reversal: its absence in stroboscopic light. Ann N Y Acad Sci. 1981; 374(1 Vestibular an):303–311.
19. Kennedy RS, Lilienthal MG, Berbaum KS, Baltzley DR, McCauley ME. Simulator sickness in U.S. Navy flight simulators. Aviat Space Environ Med. 1989; 60(1):10–16.
20. Lackner JR. Motion Sickness. In: Adelman G, Smith B, editors. Encyclopedia of Neuroscience. Amsterdam: Elsevier Science; 1996.
21. Lackner JR. Motion sickness: more than nausea and vomiting. Exp Brain Res. 2014; 232(8):2493–2510.
22. Lackner JR, Graybiel A. Elicitation of motion sickness by head movements in the microgravity phase of parabolic flight maneuvers. Aviat Space Environ Med. 1984; 55(6):513–520.
23. Lawther A, Griffin MJ. Prediction of the incidence of motion sickness from the magnitude, frequency, and duration of vertical oscillation. J Acoust Soc Am. 1987; 82(3):957–966.
24. Manning GW, Stewart GW. Effect of body position on incidence of motion sickness. J Appl Physiol. 1949; 1(9):619–628.
25. McCauley ME, Pierce EC, Matsagas P. The high-speed navy: Vessel motion influences on human performance. Nav Eng J. 2007; 119(1):35–44.
26. Miller EFI, Graybiel A. A provocative test for grading susceptibility to motion sickness yielding a single numerical score. Acta Otolaryngol Suppl. 1970; 274:1–20.
27. Mills KL, Griffin MJ. Effect of seating, vision and direction of horizontal oscillation on motion sickness. Aviat Space Environ Med. 2000; 71(10): 996–1002.
28. O'Hanlon JF, McCauley ME. Motion sickness incidence as a function of the frequency and acceleration of vertical sinusoidal motion. Aerosp Med. 1974; 45(4):366–369.
29. Oman CM, Lichtenberg BK, Money KE. Space motion sickness monitoring experiment: Spacelab 1. In: Crampton GH, editor. Motion and Space Sickness. Boca Raton (FL): CRC Press; 1990:217–246.
30. Paige GD, Telford L, Seidman SH, Barnes GR. Human vestibuloocular reflex and its interactions with vision and fixation distance during linear and angular head movement. J Neurophysiol. 1998; 80(5):2391–2404.
31. Probst T, Krafczyk S, Buchele W, Brandt T. Visual prevention from motion sickness in cars. Arch Psychiatr Nervenkr. 1982; 231(5):409–421.
32. Reason JT. Motion sickness adaptation: a neural mismatch model. J R Soc Med. 1978; 71(11):819–829.
33. Reschke MF, Somers JT, Ford G. Stroboscopic vision as a treatment for motion sickness: strobe lighting vs. shutter glasses. Aviat Space Environ Med. 2006; 77(1):2–7.
34. Rolnick A, Lubow RE. Why is the driver rarely motion sick - the role of controllability in motion sickness. Ergonomics. 1991; 34(7):867–879.
35. Santos A, McGuckin N, Nakamoto HY, Gray D, Liss S. Summary of Travel Trends: 2009 National Household Travel Survey. Washington (DC): U.S. Department of Transportation, Federal Highway Administration, 2011; Report No. FHWA-PL-ll-022.
36. Standardization IOf. Mechanical vibration and shock: Evaluation of human exposure to whole-body vibration. Part 1: General requirements. (ISO 2631–1). Geneva, Switzerland: International Organization for Standardization; 1997.
37. Stine RA. Bootstrap prediction intervals for regression. J Am Stat Assoc. 1985; 80(392):1026–1031.
38. Turner M, Griffin MJ. Motion sickness in public road transport: the effect of driver, route and vehicle. Ergonomics. 1999; 42(12):1646–1664.
39. Turner M, Griffin MJ. Motion sickness in public road transport: The relative importance of motion, vision and individual differences. Br J Psychol. 1999; 90(4):519–530.
40. Webb CM, Estrada A, Athy JR. Motion sickness prevention by an 8-Hz stroboscopic environment during air transport. Aviat Space Environ Med. 2013; 84(3):177–183.