

Auditory Induced Vection and Motion Sickness and Their Effects on Electrocardiography

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Abstract

Vection is the illusion of self-motion in the absence of actual self-motion. Visual stimulation is the most well-established inducer of vection and the same cues also induce motion sickness. Sound can also induce these percepts but has not been well explored in isolation. In the present study, we investigated whether auditory cues, in the absence of visual information, can elicit vection and motion sickness, what conditions could increase the intensity of the percepts, and how they were reflected by changes in heart rate. Participants listened to custom Shepard-Risset glissando tones, with the rate of descending sweeps manipulated to assess if presentation speed influenced the percepts. Some trials also included dorsal neck muscle vibrations, which added noise to the muscle spindle afferents about head orientation and motion. The tones induced self-reported vection relative to baseline (no sound); however, vection did not increase with faster sound speed. Neck vibrations also induced greater vection than trials without. Frequency of motion sickness also increased with sound but was not significantly affected by neck vibrations. The presence of these percepts was reflected in heart rate metrics, suggesting increased arousal and provides a physiological correlate of the subjective reports. These findings suggest that, without vision, sound can induce vection and motion sickness, particularly during conditions with unstable vestibular feedback. These results have implications for the design of artificial environments such as transportation and immersive technologies where enhancing or minimizing illusory self-motion is critical for performance.

Introduction

Vection is the illusory percept of self-motion. The typical example to illustrate vection is the train illusion: you are sat on a train at a station, and the neighboring train begins to move. For a moment, however, it feels like you are moving in the opposite direction and not the other train. This is commonly thought to be a visually induced phenomena where the information from the visual system overrides the vestibular and proprioceptive information producing vection. Whilst the factors that affect visually-induced vection are relatively well explored (Berti & Keshavarz, 2020; Palmisano et al., 2015; Warren & Rushton, 2009), there is growing interest in understanding vection induced by other sensory modalities (Sakamoto et al., 2004). This is propelled by the increased presence of artificial environments such as virtual and augmented reality (Meyer et al., 2013; Riecke et al., 2015), flight (McAnally & Martin, 2008), and space travel, where both visual and vestibular signals may be unstable or unreliable (Harm et al., 1998), leading to greater reliance on non-vision sensory modalities to identify self- or other-object motion.

Sensory modalities such as hearing and touch can induce vection by themselves (Dodge, 1923; Lackner, 1977; Murovec et al., 2021). However, the strength of the illusion tends to be much harder to induce, and when present is weaker, than in the visual domain (Keshavarz, Hettinger, Vena, et al., 2014; Murovec et al., 2021; Tanahashi et al., 2015). When the information from auditory and/or tactile modalities is congruent with the visual information, this can serve to strengthen the experience of vection more than just visual alone (tactile: (Kooijman et al., 2022); audition: (Keshavarz, Hettinger, Kennedy, et al., 2014; Murovec et al., 2021, 2022; Riecke et al., 2008; Seno et al., 2012)). The prevalent theory behind this

phenomenon is that the brain quickly weights the reliability of sensory cues when the information is incongruent, unstable, or absent (vision and vestibular: (Butler et al., 2010; Ernst & Banks, 2002; van Beers et al., 2002; Young et al., 1996); vision and audition: (Alais & Burr, 2004; Shams et al., 2005)), potentially using Bayesian-style probability (for a review, see (Knill & Pouget, 2004), (Butler et al., 2010; Fetsch et al., 2009; Gu et al., 2016)), resulting in the most stable modality/modalities determining the perception of self-motion. Examining the ways in which each sensory modality can be relied upon to provide cues for vection not only adds to our understanding of how the brain encodes self-motion, but can be used to eliminate, reduce, or amplify vection depending on the need. Difficulties in ascertaining self- or other-object motion, as well as speed and direction of motion can lead to processing errors (Britton & Arshad, 2019; Riecke et al., 2015) and difficulties balancing (Flanagan et al., 2004; Mursic & Palmisano, 2022; Tanahashi et al., 2007) which in situations of flight or space travel, could lead to disastrous consequences.

Whilst auditory-induced vection appears to be less compelling a percept and harder to elicit, there has yet to be a comprehensive exploration in the way in which auditory stimuli alone can induce vection (Riecke et al., 2023; Våljamäe, 2009). Previous studies have used real world sounds (Murovec et al., 2021; Våljamäe & Sell, 2014), manipulated whether the sounds appeared to approach or recede, or the congruency between sounds and the visual stimulus (Seno et al., 2012). These studies provided valuable insight into the perception of vection across sensory modalities. For instance, for a sound to induce vection, it had to be plausible that the sound or the situation could be moving, highlighting the role of context and congruency (Riecke et al., 2023). But there is a gap in our understanding of how audition alone can be used to perceive self-motion.

There are several ways in which the human brain encodes motion from sound. Binocular cues such as interaural timing differences (ITD) and interaural level differences (ILD) can be manipulated to induce vection, for example by physically moving a sound/speaker, generating the perception of circular/rotational vection (Larsson et al., 2004; Riecke et al., 2015; Våljamäe et al., 2004; Våljamäe & Sell, 2014). Monaural cues can also be manipulated, for example, by changing pitch and intensity which can produce the illusion of a target approaching (Seno et al., 2012), or can be used to induce Doppler effects. The Shepherd-Risset glissando tones take advantage of the Doppler effect to create a never-ending sliding tone that sounds as though it is descending (decreasing pitch frequency slide) or ascending (increasing pitch frequency slide). The tones elicit percepts of vection that have been shown to be as strong as visually-induced vection (Mursic et al., 2017) and vection intensity was related to postural instability (Mursic et al., 2017; Mursic & Palmisano, 2022), even inducing motion sickness (Mursic & Palmisano, 2020).

Typically, stimuli that induce vection are also more likely to induce motion sickness in those who are susceptible (Flanagan et al., 2004; Nooij et al., 2017; Smart Jr. et al., 2002). This has led to the question of whether the underlying neural mechanisms are similar for both vection and motion sickness (Kennedy et al., 2010; Keshavarz et al., 2015). Whilst motion sickness is an undesirable sensation, vection can assist with feelings of immersion in VR/AR and so there may be a desire to enhance vection whilst

reducing motion sickness (Hettinger et al., 2014; Riecke & Jordan, 2015). The general consensus, at least for *visually*-induced motion sickness, appears to be that while vection and motion sickness are likely to co-occur, they are not necessary for one another, suggesting different underlying mechanisms (Keshavarz et al., 2026; Keshavarz, Hecht, et al., 2014). Although less frequent than visually-induced motion sickness, auditory-induced motion sickness can also be severe (Keshavarz, Hettinger, Kennedy, et al., 2014), but it is unknown if the perception of auditory-induced vection is needed to create auditory-induced motion sickness.

The aim of the current study was to answer the following questions: Can audition reliably induce percepts of vection? If so, under what situations? And are they similar to those that induce motion sickness? We used the Shepherd-Risset glissando tones and increased the speed of the tone slides to examine if faster slides generated more or greater intensity vection/motion sickness. To decrease the reliability of proprioceptive cues, we also added vibrations to the dorsal neck muscles. This in combination with seating the participant on a stool with elevated feet served to increase the possibility that the participant could be moving – elevating the feet reduced the perception of being grounded, and the vibrations added noise to proprioceptive receptors (Riecke et al., 2008). We predicted that the faster sweeps would increase the frequency and intensity of vection, particularly when vibrations on the dorsal neck muscles were present. We predicted that frequency and intensity of motion sickness would follow a similar trend, but there would be subtle differences in the conditions that induced vection and those that induced motion sickness.

As vection and motion sickness are both subjective measures, we added a physiological measure to corroborate the percepts. Motion sickness is known to be stress-inducing, increasing heart rate (Holmes & Griffin, 2001) and decreasing heart rate variability (Ponsiglione et al., 2026). Little is known about the effect of vection on heart rate, but it has been linked to increased blood pressure, suggesting similar stress responses (Aoki et al., 2000). While there are a number of heart rate variability measures, LF/HF ratio and pNN50 are two measured that have been linked to motion sickness (Park et al., 2022; Ponsiglione et al., 2026; Shi et al., 2025) and will be the focus of the current study. Therefore, we recorded electrocardiography (ECG) during the study to serve as an easy-to-measure, objective physiological marker of changes in arousal to examine how they reflect the reported percepts.

Methods

Participants

All participants were recruited from the University of Nevada, Reno campus. Our sample comprised 41 adults (age 18–26 years old; $M = 20$ years, $SD = 1.93$ years) with 33 females and 8 males. Twenty-nine participants identified as White, 5 identified as Hispanic or Latino, 4 identified as Asian or Asian/Pacific Islander, and 3 identified as Black. All participants reported normal or corrected-to-normal vision and normal hearing and were screened for preexisting gastrointestinal, vestibular, or other underlying neurological conditions that may affect the auditory and vestibular systems. None of the participants

met our exclusion criteria. Additionally, all participants provided written informed consent prior to participating and were offered course credit for their participation. The study was approved by the University of Nevada, Reno Institutional Review Board and was conducted in line with the Declaration of Helsinki.

Stimuli

We used modified Shepard-Risset glissando tones comprising overlapping descending tone sweeps. We varied the number of seconds it took to complete a sweep so that we had a fast condition (12 sweeps/minute), and a slow condition (6 sweeps/minute). The fast and slow tones each lasted one minute and consisted of sweeps with a fundamental frequency of 262Hz across a frequency range of 16Hz-18.5kHz, sampled at 48kHz. These stimuli were generated using MATLAB (MathWorks, Natick, Massachusetts) and presented over Etymotic (Etymotic Research, Elk Grove Village, Illinois) insert earphones via Audacity (Muse Group, Limassol, Cyprus).

Equipment

Participants were blindfolded during the study to eliminate visual cues for motion and seated on a stool with their feet suspended to reduce contact-based proprioceptive and tactile cues about body position (see Fig. 1). To further worsen vestibular precision, we added a second manipulation where half of the auditory conditions included vibration stimulation of the dorsal neck muscles. This further exacerbated the motion uncertainty experienced by the participants. Dorsal neck muscles were stimulated using the NOVAFON Pro vibration device (NOVAFON, Weinstadt, Germany) at 120Hz with an amplitude of 2mm for 1-minute trials. Stimulation alternated between the left and right dorsal neck muscles to prevent irritation and fatigue. Electrocardiography (ECG) data were collected using the IX-TA 220 recorder (iWorx Systems, Dover, NH) at a sampling rate of 1kHz. Three electrodes were used: one on each clavicle and one on the right ankle. Data were recorded using LabScribe (iWorx Systems, Dover, NH) and analyzed using MATLAB.

Procedure

The experiment consisted of six blocks with blocks 3–6 presented in a randomized order. Block 1 was a baseline condition where participant resting ECG, vection, and motion sickness percepts were measured without the presentation of vibrations or auditory cues. Block 2 was a vibration baseline condition to establish the same measures under dorsal neck stimulation only (no tones). These two baseline measures were used as comparison conditions to the remaining blocks. Blocks 3–6 were the experimental auditory conditions (Fig. 2).

We were concerned about the amount of time it would take to induce vection and motion sickness using sounds. While visually-induced vection typically occurs quite quickly (within seconds) (Palmisano & Riecke, 2018), motion sickness tends to require more time to accumulate reliable percepts (Palmisano & Riecke, 2018). Therefore, to increase the likelihood for vection and motion sickness events to occur, we

chose to repeat trials within a block to provide time for the percepts to accumulate. Each experimental block included five 1-minute trials where participants raised and lowered their left thumb to indicate the presence of vection which was video-recorded for analysis. In between blocks, vection intensity and motion sickness severity were reported using a 10-point Likert scale and the Fast Motion Sickness Scale (FMS), a rapid self-report scale for assessing moment to moment motion sickness (Keshavarz & Hecht, 2011). To assess for any order effects on behavioral measures, the changes in vection and motion sickness as a function of trial and block were examined. See Supplementary Materials, section 1 for details. The direction of any percepts of vection was also recorded after each trial and details are included in Supplementary Materials, section 2.

Data Processing and Analyses

Behavioral and physiological data were analyzed using R Studio and MATLAB.

Behavioral Data

Behavioral measures comprised trial-level ratings of vection intensity and motion sickness severity. Trials where no vection or motion sickness were reported were recorded with rating values of zero. For each condition, frequency measures were calculated as the proportion of trials where vection or motion sickness occurred. Trials where vection and/or motion sickness were reported were then examined to ascertain the effect of tones and vibration on intensity of the percepts. The average intensity across the trials within a condition/block was then calculated and used for further analyses.

To examine the effects of tone speed on frequency of vection and motion sickness, logistic regression models were conducted where the number of trials with reported vection or motion sickness were used as the dependent variables in separate models. The effect of only the auditory stimulation (without vibrations) on vection and motion sickness was examined separately from the auditory stimulation with the addition of vibrations to aid interpretation. Condition was used as a fixed effect (baseline, slow tones, fast tones). All pairwise comparisons were conducted using the estimated means and Holm corrections.

To examine intensity measures, analyses were limited to trials where vection or motion sickness were reported. Linear mixed-effects (LME) models were conducted with tone speed (slow, fast) and vibration (no vibration, vibration) as fixed effects. Separate models were used for vection and motion sickness intensity.

To examine relationships between vection and motion sickness measures, Spearman rank-order correlations were conducted between vection frequency, vection intensity, motion sickness frequency, and motion sickness intensity. Intensity measures were limited to trials where the corresponding perceptual experience occurred.

Bonferroni corrections were applied to control for multiple comparisons. As there were eight analyses being conducted to examine the behavioral effects (4x logistic regressions on frequency measures + 2x

LMEs on intensity), our threshold for establishing significance decreased to $p < .00625$ (alpha = 5% / 8 analyses = 0.625%). For simplicity, the same alpha was maintained for the correlational analyses and when analyzing the heart rate metrics.

ECG Data

Physiological data were processed from raw ECG signals using custom MATLAB scripts. For each trial, a 60-second ECG segment was extracted based on the timing of trial onset. Signals were visually inspected to remove segments with excessive noise and then band-pass filtered between 0.5 and 40 Hz to reduce baseline drift and high-frequency noise. Owing to poor connectivity, the ECG signal from three participants was not recorded.

R-peaks were detected using a slope-based algorithm that identified rapid upward deflections within the QRS complex and the maximum value within each segment was selected. From the subsequent R-R intervals, heart rate (HR) was calculated in beats per minute. To assess time-domain heart rate variability (HRV), the percentage of successive R-R intervals differing by more than 50ms (pNN50) was calculated. Frequency-domain HRV metrics were computed using Welch's method to estimate power spectral density for low-frequency (LF; 0.04–0.15Hz) and high-frequency (HF; 0.15–0.40Hz) components (Welch, 1967). The LF/HF ratio was calculated from these individual components to assess changes in HRV frequencies.

To examine if the physiological responses reflected the presence of perceptual experiences, LME models were conducted comparing trials where vection occurred against trials where no vection was reported (regardless of condition). Similar models were also conducted on motion sickness trials against trials with no motion sickness.

Spearman rank-order correlation tests were conducted to examine the relationship between physiology and perceptual experiences. Measures of vection and motion sickness frequency and intensity were correlated separately with measures of the average heart rate and heart rate variability from each condition/block.

Results

Perceived Vection and Motion Sickness

To assess whether the tones alone were sufficient to induce vection, a constrained logistic regression compared the baseline condition, slow tones without vibrations and fast tones without vibrations. There was a significant effect of condition ($\chi^2(2) = 113.44, p < .001$), revealing that both the slow ($M = 0.63, SD = 0.35; z = 5.15, p < .001$) and fast tones ($M = 0.65, SD = 0.38; z = 5.19, p < .001$) exhibited significantly greater vection frequency than baseline ($M = 0.00, SD = 0.00$). However, there was no significant difference between the two tone speeds ($z = 0.14, p = .990$).

To determine whether the tones induced vection with dorsal neck muscle vibrations, slow tones+vibrations and fast tones+vibrations were compared to the baseline vibration-only condition. There was a significant effect of condition ($\chi^2(2) = 54.87, p < .001$), with both slow+vibration ($M = 0.71, SD = 0.37; z = 5.98, p < .001$) and fast+vibration conditions ($M = 0.74, SD = 0.35; z = 6.68, p < .001$) showing significantly greater vection frequency relative to vibration alone ($M = 0.26, SD = 0.45$). There was no significant difference between the tone speed conditions ($z = 1.96, p = .123$; see Fig. 3A).

Next, to assess whether tones alone were sufficient to induce motion sickness, the same constrained logistic regressions were conducted but assessing effects on frequency of motion sickness. The tones were effective at inducing motion sickness ($\chi^2(2) = 35.61, p < .001$) with both slow ($M = 0.10, SD = 0.25; z = 2.22, p = .027$) and fast tones inducing motion sickness ($M = 0.17, SD = 0.35; z = 3.06, p = .002$) compared to baseline ($M = 0.00, SD = 0.00$). Interestingly, motion sickness frequency was also significantly greater when the fast tones were presented compared to the slow tones ($z = 3.82, p < .001$).

When the vibrations were included, there was a marginal effect of condition on motion sickness ($\chi^2(2) = 6.58, p = .037$; not significant with Bonferroni correction), with both slow+vibration ($M = 0.15, SD = 0.29; z = 2.65, p = .008$) and fast tones+vibration ($M = 0.15, SD = 0.29; z = 2.54, p = .011$) inducing nominally more motion sickness relative to the baseline vibration-only condition ($M = 0.02, SD = 0.15$). Further, there was no significant difference between the fast and slow tone conditions when vibrations were present ($z = -0.36, p = .931$; see Fig. 3B).

Together, this suggests that the Shephard tones induced vection and motion sickness in isolation and during conditions of vestibular ambiguity induced by dorsal neck stimulation.

To test the contributions of tone speed and neck vibration on vection intensity, a LME model was conducted with speed (slow and fast tone sweeps) and presence of neck vibrations (no vibration, vibration) as fixed effects. This analysis revealed a marginal main effect of vibration ($F(1,106.64) = 5.08, p = .026$; not significant with Bonferroni correction), indicating that vection intensity was slightly greater in vibration conditions ($M = 3.55, SD = 1.70$) compared to no vibration conditions ($M = 3.22, SD = 1.55$). There was no main effect of speed ($F(1,105.25) = 0.91, p = .343$), and no interaction ($F(1,105.96) = 0.06, p = .808$; see Fig. 4A).

To test the contributions of tone speed and neck vibrations on motion sickness intensity, a similar LME model was conducted revealing no significant main effect of vibration ($F(1,20.81) = 0.71, p = .408$; slow+vibration: $M = 2.04, SD = 0.82$; fast+vibration: $M = 2.09, SD = 1.28$; slow: $M = 1.61, SD = 0.81$; fast: $M = 2.02, SD = 0.83$). There was also no main effect of speed ($F(1,22.39) = 0.62, p = .440$), and no interaction ($F(1,23.69) = 0.16, p = .696$; see Fig. 4B).

To examine the relationships between vection and motion sickness measures during the tone presentations, Spearman rank-order correlations were conducted across participants and blocks between vection frequency, vection intensity, motion sickness frequency, and motion sickness intensity. Vection frequency was positively correlated with vection intensity ($\rho(145) = .28, p < .001$), indicating that

greater frequency of vection percepts were more likely to result in stronger vection intensity (see Fig. 5A). However, this was not the case for motion sickness ($\rho(40)=.26, p=.096$; see Fig. 5B), likely due to the low number of instances of motion sickness. Across measures, greater vection frequency was significantly correlated with greater motion sickness frequency ($\rho(166)=.25, p=.001$; see Fig. 5C), but the intensities of two percepts were not related ($\rho(40)=.21, p=.192$; see Fig. 5D).

Effect of Vection and Motion Sickness on Electrocardiography

When directly comparing heart rate metrics when vection was present compared to no vection trials, there was a significant effect overall ($F(3,854) = 8.40, p<.001$; see Fig. 6 left column), due to an increase in heart rate (beats per minute) during vection ($F(1,856) = 7.31, p=.007$; absent $M = 85.20\text{bpm}$, $SD = 13.15\text{bpm}$; present $M = 87.72\text{bpm}$, $SD = 13.08\text{bpm}$), a decrease in pNN50 ($F(1,856) = 25.14, p<.001$; absent $M = 22.84$, $SD = 22.39$; present $M = 16.35$, $SD = 15.36$), but no difference in LF/HF ratio ($F(1,856) = 2.56, p=.110$; absent $M = 2.11$, $SD = 2.68$; present $M = 2.49$, $SD = 3.68$).

Similarly, when comparing heart rate metrics when motion sickness was reported compared to trials when it was not, there was a significant overall effect ($F(3,854) = 8.50, p<.001$; see Fig. 6 right column), due to higher heart rate during motion sickness ($F(1,856) = 16.75, p<.001$; absent $M = 86.09\text{bpm}$, $SD = 12.87\text{bpm}$; present $M = 91.46\text{bpm}$, $SD = 14.06\text{bpm}$), lower pNN50 ($F(1,856) = 16.98, p<.001$; absent $M = 22.84$, $SD = 19.04$; present $M = 12.12$, $SD = 12.37$) and higher LF/HF ratio ($F(1,856) = 7.45, p=.006$; absent $M = 2.23$, $SD = 3.30$; present $M = 3.15$, $SD = 3.60$), consistent with decreased HRV and increased stress response.

We then assessed the effect of the experimental conditions on heart rate metrics using LMEs, see Supplementary Materials, section 3. In summary, the presentation of the tones increased heart rate, decreased pNN50, and increased LF/HF ratio, but there was no significant effect of the neck vibrations.

Examination of the relationships between vection and motion sickness frequency and intensity and ECG measures are shown in Fig. 7. The LF/HF ratio increased with vection ($\rho(232)=.20, p=.002$) and motion sickness frequency ($\rho(232)=.21, p=.001$), and these two correlations survived Bonferroni correction. All other correlations were not significant.

Discussion

In the current study, we aimed to ascertain if vection can be reliably induced by sound. We used Shepard-Risset glissando tones that simulated a Doppler-style effect. Over half of the trials (67%) induced vection when the sounds were presented and 14% of the same trials induced motion sickness. When vection was present, the intensity was rated an average of 3/10 and motion sickness intensity was 2/10, which is not severe but was consistent. This demonstrates that even within a 1-minute presentation, sound can induce vection and motion sickness. These findings are supported by an increase in heart rate and a decrease in heart rate variability.

Previous studies have found in isolation that both vection and motion sickness are associated with an increased stress response (Aoki et al., 2000; Holmes & Griffin, 2001; Ponsiglione et al., 2026) with motion sickness in particular causing an increase in heart rate and a decrease in heart rate variability. We find similar effects here; however, only find effects of vection on the pNN50. The pNN50 is widely theorized to reflect parasympathetic activity (Ewing et al., 1984), and the LF/HF ratio reflects the relationship between sympathetic and parasympathetic activity (Malliani et al., 1991), although note that there is debate as to the accuracy of these claims (Billman, 2011, 2013; Mietus et al., 2002). Regardless of the specific processes being reflected in these measures, the finding that vection is not reflected in the LF/HF ratio measure suggests different underlying physiological responses that are unique to each percept and work as a biological correlate separating the percepts.

When ascertaining the conditions that maximized vection and motion sickness, there was a small increase in motion sickness to the fast compared to the slow tones, but not for vection. However, the strongest driver of vection was to include the vibration on the dorsal neck muscles. The vibrations created proprioceptive ambiguity which appears to have increased reliance on the auditory input to determine self-motion, although does not appear to have consistently increased motion sickness. Together, this suggests that there are subtle differences in what induces vection compared to motion sickness. The correlation between the presence of vection and motion sickness was significant but only with a medium-to-small strength correlation ($\rho = .25$). It is worth noting that there were significantly fewer instances of motion sickness than vection, which in part is because motion sickness does not occur in everyone, limiting the sample size and therefore reducing the power in the analyses. Estimates of the proportion of the population that experience motion sickness range from 35–95% (Keshavarz, Hecht, et al., 2014) with increased susceptibility if younger, female, have high aerobic fitness, have a medical condition (particularly those with vestibular conditions and migraine), and is dependent on the menstrual cycle (Takov & Tadi, 2026). Despite the relatively few occurrences of motion sickness reported here, we still see consistent effects of motion sickness in subjective reports and in ECG measures.

The increase in auditory-induced vection with proprioceptive ambiguity suggests that it is the ambiguity that is key to inducing vection (Kuiper et al., 2019; Stróžak et al., 2025), likely related to the sensory reweighting that occurs when input from other sensory modalities (including proprioception) is unreliable or noisy. In contrast, the prevalent theory for the causes of motion sickness is based on the conflict between the sensory modalities (Keshavarz, Hecht, et al., 2014; Shupak & Gordon, 2006). It is possible that these two theories are not entirely separable – the ambiguity could cause conflict when determining self-motion, which may be why vection and motion sickness often co-occur together. In situations where vection is a desirable percept but motion sickness is not, increasing sensory ambiguity to increase the plausibility that self-motion could occur, but without conflict across the modalities, could achieve the desired effect.

There are a couple of considerations to take note of when identifying ways to improve the stability of these percepts. First, the Shepard tones themselves are slightly ambiguous in terms of the direction of the movement (Mursic et al., 2017), although participants in the current study were relatively consistent

in perceiving a downward motion (see Supplementary Materials, section 2). Improving the consistency of the direction may further increase the presence of vection and motion sickness. Second, we did not adjust the sounds for a generic or an individualized head-related transfer function (HRTF) and yet still induced vection and motion sickness. Adjusting the sounds for individualized HRTF may increase the believability of the sounds being in motion, further increasing vection and motion sickness. Third, the stool which the participants were seated on could not move. Adding the potential for the stool to move, particularly up and down, may have increased the percepts too. Alternatively, moving the sounds physically using a speaker would negate the need for a HRTF would increase the realism of the sound being in motion.

There is a question as to the functional role of vection and what we can learn from the study of the illusion of vection (Palmisano et al., 2015). Other than offering insight into how the brain encodes self- vs other object-motion (Kapralos, 2004), understanding the contexts under which vection can occur helps when trying to reduce or induce the illusion. Vection is not a fragile illusion. Every day, individuals experience vection when in unnatural situations often involving transport when the vehicle could be moving or the other object could be moving. There is then the question of what the cognitive consequences are of vection. If the person experiencing vection is a passenger, then this is likely to be inconsequential to behavior. However, if the perceiver is the driver or pilot, then effects on behavior may be more critical. For example, experiencing vection can reduce the ability to detect changes in the (visual) environment (Stróžak et al., 2019), but engagement in another task (distraction) can reduce the frequency and severity of vection (Deno, Ito, Sunaga, 2011). Vection can affect postural sway causing instability in vestibular processing (Meyer et al., 2013). However, percepts of vection were related to improved perspective taking and spatial exploration (Riecke et al., 2015) and cues that increased vection also helped with sound localization in those with superior visual imagery (Väljamäe & Sell, 2014).

In conclusion, auditory-induced vection is a reliable percept under situations of plausible self-motion, and while they are associated with motion sickness, they are not induced under identical conditions and result in different patterns of physiological responses. Further exploration is needed to systematically ascertain the parameters of the stimuli most-likely to induce vection and what the cognitive consequences are that may be unique to auditory-induced vection.

Declarations

Statements and Declarations: The authors declare that they have no conflict of interest.

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Data Availability: Data and stimuli are available on GitHub
(<https://github.com/SarahMHaigh/AuditoryInducedVectionMotionSicknessAndECG>).

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Figures



Figure 1

Image of the experimental setup. Participants were seated on a stool with their feet suspended off the floor. During recordings, participants wore insert headphones which presented the Shepard tones and were blindfolded to eliminate visual cues. Permission was ascertained to use the photo taken for dissemination purposes

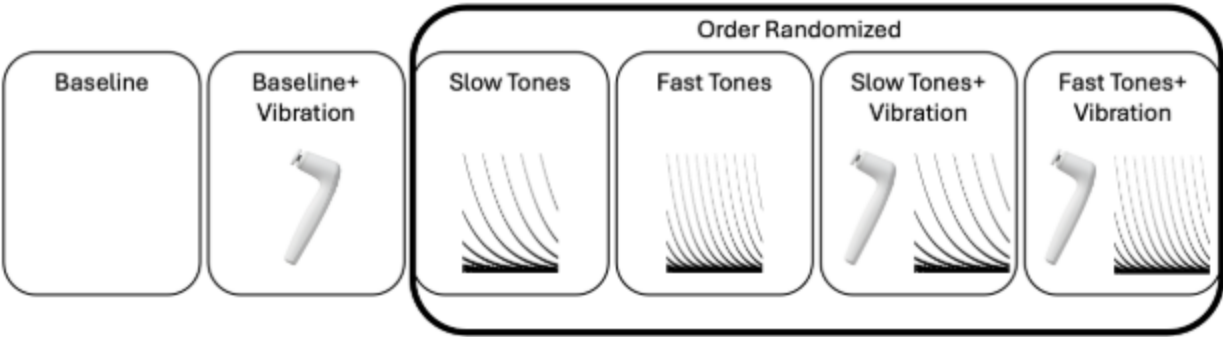


Figure 2

Illustration of the different conditions. Baseline and vibration tolerance measures were collected at the beginning of the study and served as control measures without auditory stimuli. The remaining four experimental conditions contained modified 1 minute Shepard-Risset glissando tones with or without dorsal neck vibration stimulation. The spectrograms depict the characteristics of the auditory stimuli over time (x-axes). Note the descending tone sweeps overlap to create a continuous sound. Fast conditions consist of more tone sweeps with steeper slopes generating the perception of a faster tone descent compared to slow conditions

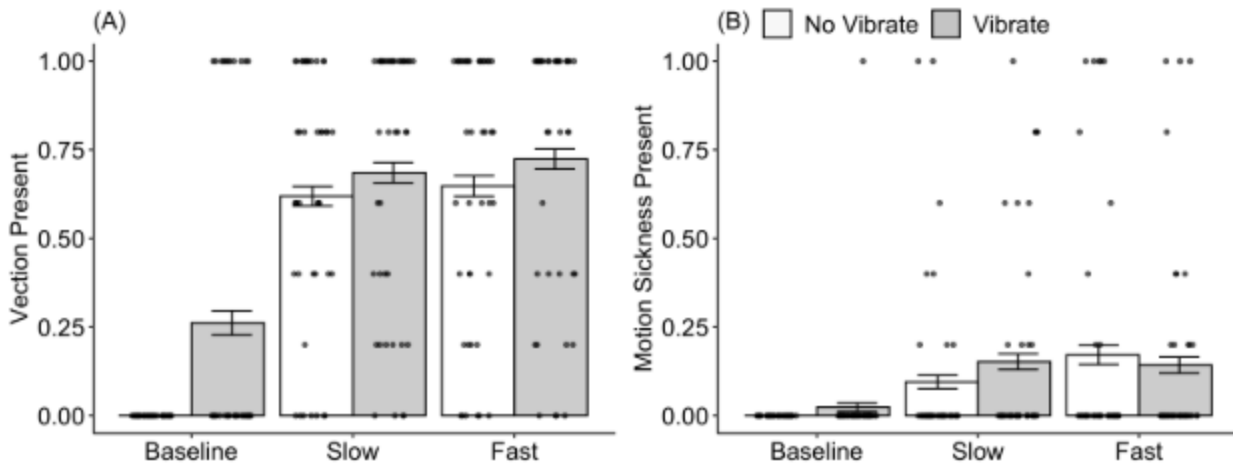


Figure 3

(A) Frequency of the perception of vection being reported and (B) frequency of participants feeling motion sick for the baseline, slow, and fast tone conditions, shown separately for the conditions without neck vibrations (white) and with neck vibrations (grey). Error bars show one standard error

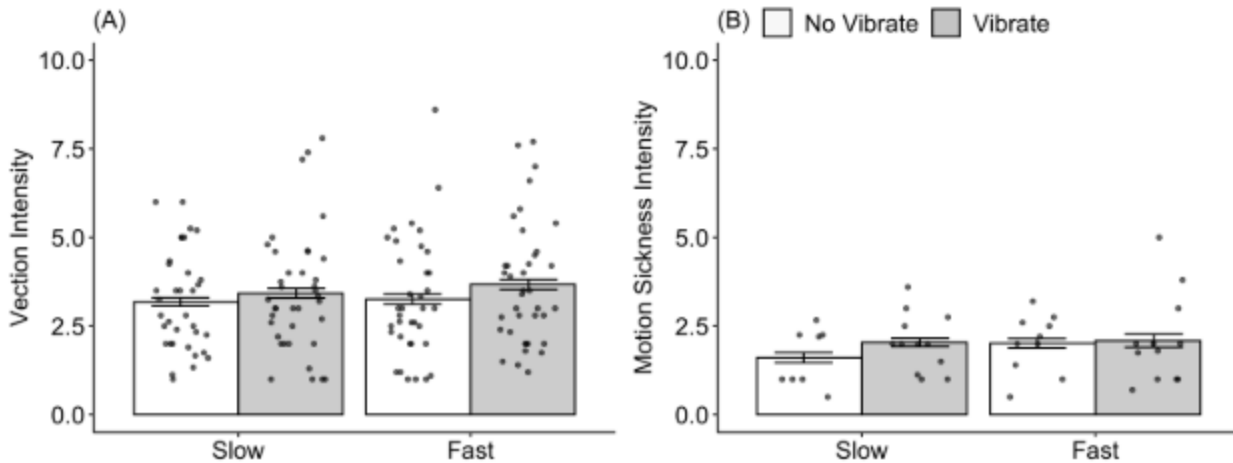


Figure 4

(A) Intensity of the vection and (B) of the motion sickness for the slow and fast sweep conditions, shown separately for the conditions without neck vibrations (white) and with neck vibrations (grey). Error bars show one standard error

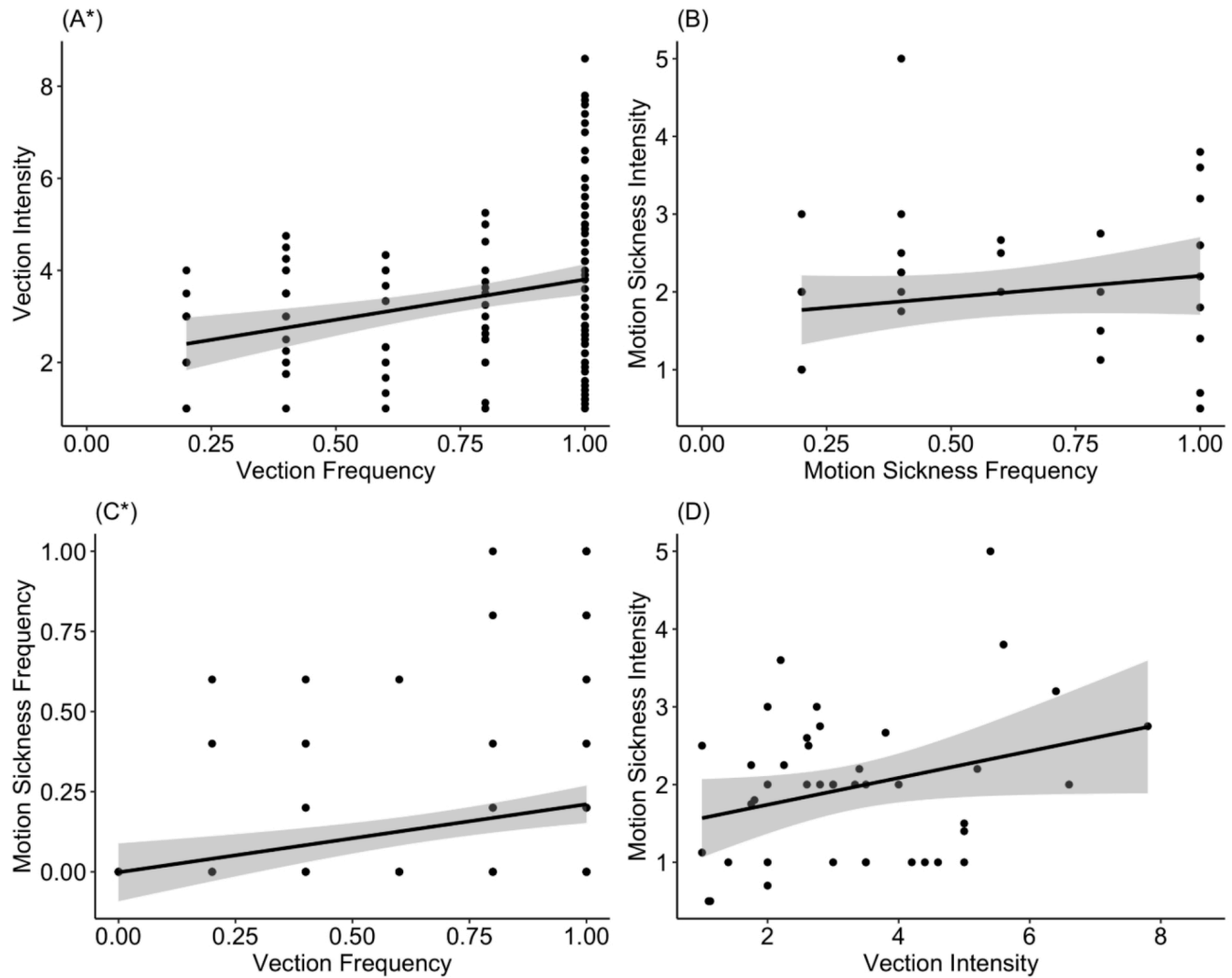


Figure 5

Relationships between behavioral measures. Asterisk shows significant relationships. Grey indicates 95% confidence intervals around the regression line. (A) Shows a significant relationship between vection frequency and intensity across participants for all conditions; (B) however, there was no significant relationship between motion sickness frequency and intensity. (C) Vection and motion sickness frequency were significantly correlated, but (D) the intensity of the experience was not related across percepts

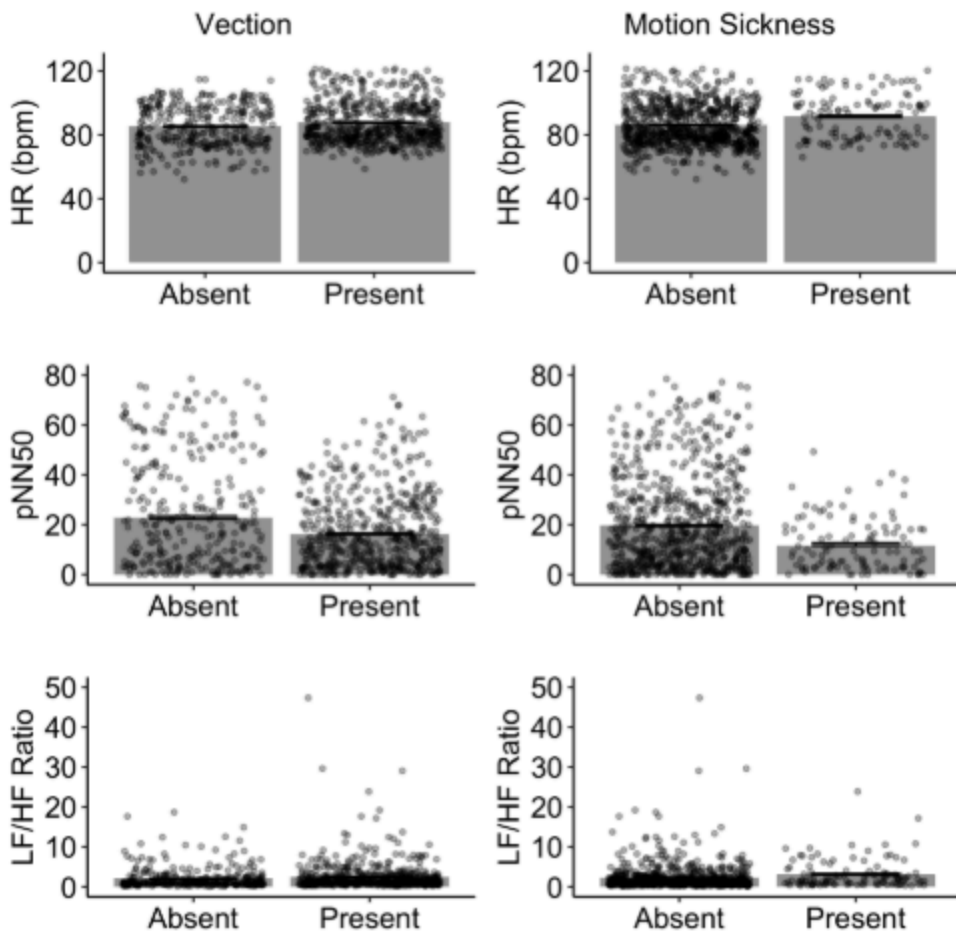


Figure 6

Left column: Effect of vection percept on heart rate, pNN50 and LF/HF ratio. Right column: Effect of motion sickness on heart rate, pNN50, and LF/HF ratio. Error bars show one standard error

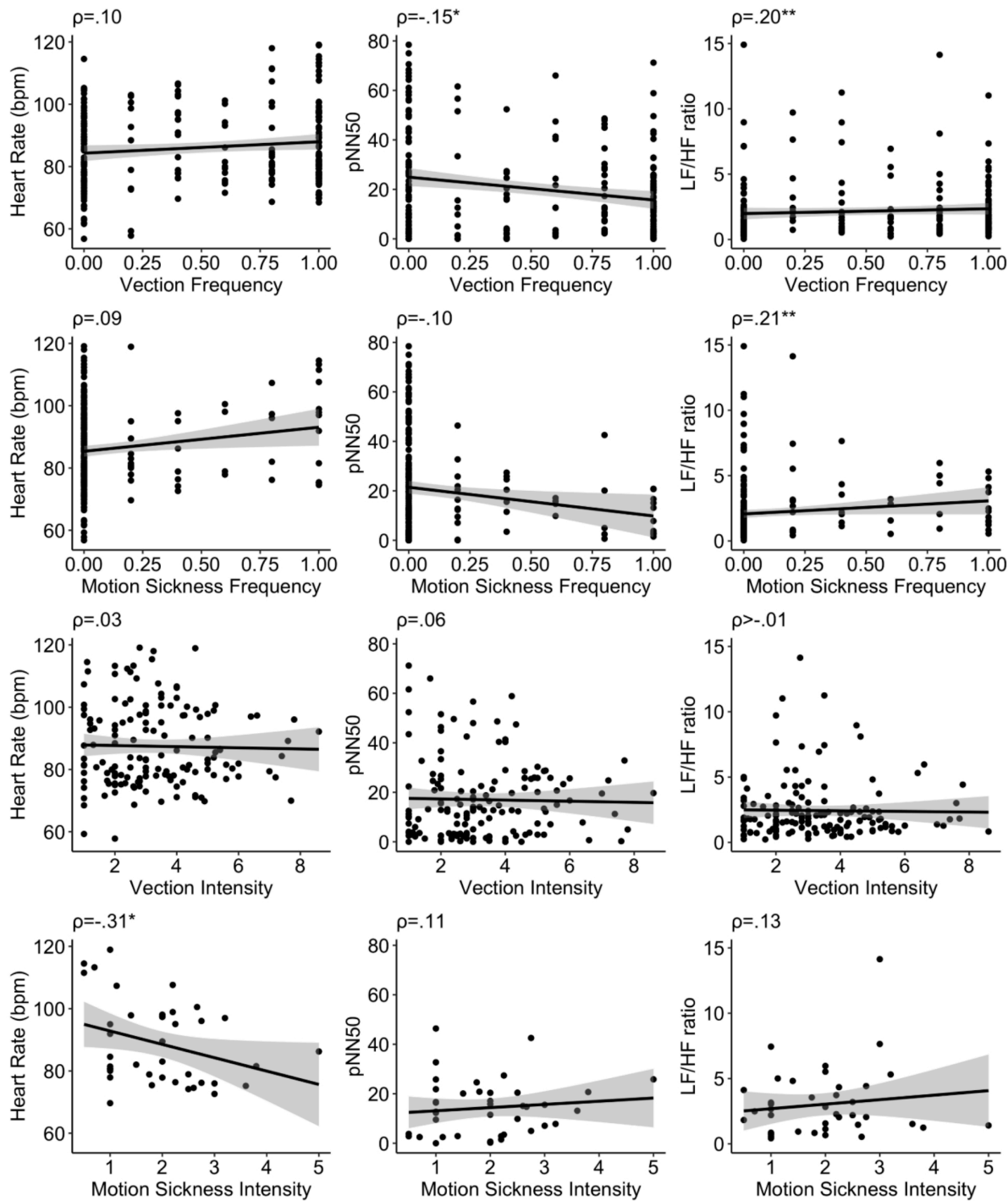


Figure 7

Relationships between ECG measures (heart rate, pHH50 and low frequency/high frequency ratio) and behavioral measures (vection and motion sickness frequency and intensity). Spearman's rho (ρ) coefficients shown. $^{**}p < .00624$, $^*p < .05$

Supplementary Files

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- [SupplementalMaterials.docx](#)