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Research Article

Predicting Motion Sickness Sensitivity

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Abstract

Objective: To determine the combined effectiveness of personal factors in predicting motion sickness sensitivity elicited by linear motion of a sled.

Background: Technologies that create challenging motion environments have spurred the development of mathematical models aimed at predicting motion sickness. Including personal factors may improve their predictive accuracy. History of motion sickness, age, gender, and visual dependence have been identified as potential predictors, although their individual predictive value is limited.

Method: We assessed motion sickness history, age, and gender through a questionnaire. To evaluate visual dependence, participants oriented a virtual rod parallel to the orientation of gravity while observing a tilted static frame or a disc rotating in roll. Sensitivity is expressed using a new measure that considers both the magnitude and accumulation of self-reported symptoms.

Results: Our results confirmed the predictive value of history and showed a small yet significant contribution of dynamic visual dependence, with greater dependence associated with higher sensitivity (R^2 = 25%). Recent history reported over the past 10 years was demonstrated as a better predictor than lifetime history. Age, gender, and static visual dependence did not enhance the prediction.

Conclusion: Combining multiple predictors shows little advantage for improving a prediction of sensitivity beyond history alone. Future studies could confirm the predictive value of dynamic visual dependence and seek to optimize recent history, for example, by restricting time period and motion environment.

Application: Improved prediction models may support tailoring system parameters to user sensitivity in technologies such as automated driving, head mounted displays, and simulators.

Keywords

rod-and-frame test, rod-and-disc test, MSSQ, car sickness, field dependence

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Précis: We confirmed recent motion sickness history as a significant predictor of motion sickness sensitivity elicited by linear motion. Dynamic visual dependence improved the prediction slightly, bringing the combined explained variance to 25%. Static visual dependence, age, and gender did not enhance prediction accuracy.

Introduction

The advanced automation of vehicles and an increased usage of virtual reality and simulators has proliferated motion sickness research (reviewed by Iskander et al., 2019; Rebenitsch & Owen, 2016; Saredakis et al., 2020). Motion sickness can be described as a syndrome of discomfort, induced by exposure to physical and/or visual motion stimuli (Money, 1970; Reason & Brand, 1975). For several decades, researchers have explored the causes of motion sickness and the motions that provoke it most (e.g., Diels & Howarth, 2013; Donohew & Griffin, 2004; Golding et al., 2001; McCauley et al., 1976; O'Hanlon & McCauley, 1973; Reason, 1978). These efforts have given rise to mathematical models aiming to predict motion sickness in response to a provocative stimulus, hereafter referred to as "sensitivity" (Bos & Bles, 1998; Irmak et al., 2023; ISO 2631-1, 1997; Lawther & Griffin, 1987; Oman, 1990; Wada et al., 2020). Considering that these models have largely been fit on group level data while there is large variability in sensitivity between individuals, incorporating personal predictors may help to improve model fits (e.g., Irmak, De Winkel, et al., 2021a; Irmak, Pool, et al., 2021b). The current study contributes to these efforts by investigating the predictive value of five possible personal factors.

A seemingly obvious starting point for predicting sensitivity would be to inspect one's response to similar provocative encounters in the past. Currently, the Motion Sickness Susceptibility Questionnaire (MSSQ; Golding, 2006b) could be considered the most prominent tool to do so. The MSSQ asks individuals to indicate the frequency of motion sickness experienced in various contexts (e.g., motorized transport and amusement rides) in the past, both during childhood and adulthood. This measure will be larger for persons who are more sensitive to motion sickness, although it may be confounded by the dose (e.g., acceleration and duration), amount (e.g., single time or daily), and modality (e.g., driver or passenger) of exposure to sickening environments. If exposure variations are relatively small in a study population, one could interpret this measure to provide a rough estimate of the susceptibility throughout life, and thus a predictor of sensitivity. Several studies have provided data that demonstrated moderate to strong correlations between the MSSQ and sensitivity (Golding, 1998; Lubeck et al., 2015). However, there have also been studies which reported low predictive value of the MSSQ (Nooij et al., 2021; Reuten, 2024; Ruffle et al., 2019). The MSSQ measures the product of sensitivity and exposure. Lifetime history may not account well for changes due to habituation (i.e., reduced sensitivity due to repeated exposure; Howarth & Hodder, 2008; McCauley et al., 1976; Reason, 1978). For this reason, we focus our prediction on recent motion sickness history. Nonetheless, as sensitive persons might reduce their exposure to sickening situations, it may be possible to enhance individual predictions of sensitivity by including additional predictor variables.

Two demographic variables have been reported to hold predictive value: age and gender or sex. Motion sickness is described to follow the pattern of a positively skewed (i.e., right-tailed) distribution across the life span, with a peak in late childhood (Bos et al., 2007; Gallagher & Ferrè, 2018; Golding, 2006a; Keshavarz & Golding, 2022; Turner, 1999). It is possibly a less useful predictor for those in early adulthood to late middle age. Several studies have reported that females are more sensitive to motion sickness compared to males (Bos et al., 2007; Keshavarz & Golding, 2022; Klosterhalfen et al., 2005; Lentz, 1977; Schmidt et al., 2020). However, there are also

many studies that did not confirm increased sensitivity for females (reviewed by Lawson, 2014). Age and gender/sex may explain some variance in sensitivity, although these dependencies could already have been captured by the frequency of motion sickness experienced. Is there an idiosyncratic factor that could enhance our prediction?

As perceived verticality may be related to motion sickness (Bles et al., 1998; Bos et al., 2008), individual differences in sensitivity may be related to individual differences in orientation perception. To estimate orientation, we rely on multisensory integration of visual, proprioceptive (i.e., vestibular and somatosensory), and idiotropic (i.e., one's longitudinal bodily axis) cues (Harris, 2022; H. Mittelstaedt, 1983). It is generally assumed that sensory cues are integrated with weights proportional to the cues' reliabilities (Harris, 2022; Jacobs, 2002). However, it is not only the cues' relative reliability that determines cue weighting in sensory integration. For instance, individuals can modify their cue weighting based on experience (Pavlou et al., 2011; Van Beers et al., 2011). Moreover, there are large differences between individuals in performance on visual orientation tasks in cue-conflict situations (H. Mittelstaedt, 1983; Witkin & Asch, 1948). This indicates an idiosyncratic dependence on visual cues relative to vestibular, somatosensory, and idiotropic ones for orientation perception, which we refer to as "visual dependence" (also known as "field dependence" or "visual field dependence").

Previous studies have looked into the relationship between visual dependence and motion sickness (reviewed by J. M. Mittelstaedt, 2020). The reports in the literature about this relationship are inconsistent: some studies reported that visually dependent individuals get more motion sick than visually independent individuals (Barrett et al., 1970; Harm et al., 1998; Long et al., 1975; Yardley, 1990), while other studies reported no (linear) relationship (Keshavarz et al., 2025; Mirabile et al., 1976; Pitblado & Mirabile, 1977) or a relationship in opposite direction (Barrett & Thornton, 1968). The behavior of two patient populations who are more visual dependent than normal is also inconsistent. On the one hand, individuals with visual or benign paroxysmal positional vertigo demonstrate greater reliance on contextual visual orientation cues in comparison to healthy controls (Agarwal et al., 2012; Guerraz et al., 2001) and suffer more than average from motion sickness (Boldingh et al., 2011; J. M. Mittelstaedt, 2020; Paillard et al., 2013). On the other hand, individuals with complete loss of labyrinthine function, who are also visually dependent (Johnson et al., 1999), do not suffer from motion sickness (Irwin, 1881; James, 1883; Kellogg et al., 1964; Money, 1970). Additionally, visual dependence seems to increase with age (Agathos et al., 2015; Bugnariu & Fung, 2007), whereas sensitivity to motion sickness decreases across the lifespan. To summarize, although there are theoretical reasons to assume that visual dependence holds value for predicting sensitivity, the experimental evidence is currently inconsistent.

Studies investigating the relationship between visual dependence and motion sickness all used tests in which participants orient a visual rod parallel to the orientation of gravity in the presence of a static distractor (i.e., a tilted frame; the Rod-and-Frame test; Witkin & Asch 1948). Another test variant in which participants orient the rod in the presence of a dynamic distractor (i.e., a disc rotating in roll; Rod-and-Disc test; Hughes et al., 1972) has to our knowledge not been used. Previous work has shown a significant positive correlation between the two test variants (Guerraz et al., 1998; Hughes, 1973; Isableu et al., 1998) as well as high similarity between ratings of line orientation and motion direction across a wide range of lateral body tilts (De Vrijer et al., 2008). These findings suggest that static and dynamic distractor effects share a computational strategy, but in a prior study we observed evidence that they are based on at least partly different mechanisms (Reuten et al., 2026). This implies that that there is not a single visual dependence, raising our interest

in exploring whether there is a difference between static and dynamic visual dependence in predicting sensitivity.

The overarching goal of our study is to investigate how we could improve individual predictions of motion sickness sensitivity by answering two research questions. As factors that contribute to the prediction of motion sickness might be correlated, we first question how sensitivity and various predictors (motion sickness history, age, gender, and static and dynamic visual dependence) are interrelated. Second, we question which predictor or combination thereof is most useful for predicting sensitivity.

Methods

We (re-)analyze the data collected in three previous experiments. In each experiment, we exposed participants to multiple sessions on a sled with a provocative linear motion stimulus. Participants rated their motion sickness symptoms in each session. Before starting the first session, participants completed the MSSQ about motion sickness history, demographic questions about their age and gender, and tests of static and dynamic visual dependence.

Participants

We used the same selection criteria in all three experiments. These consisted of participants having no self-known visual, vestibular, cardiovascular or neurodegenerative disorders; using no medication that could impact alertness; having normal or corrected-to-normal vision and having experienced motion sickness in the past 10 years. The experiments complied with the tenets of the Declaration of Helsinki and were approved by TNO's Institutional Review Board (reference numbers 2022-037, 2022-046, and 2024-009). Informed consent was obtained from each participant. We could not include the results of 7 participants because of incomplete datasets for either motion sickness sensitivity (n = 6; e.g., mechanical failure of the sled) or visual dependence (n = 1; failing to meet our eligibility criterion set for a test of stereoscopic vision). Experiment 1 (Reuten et al., 2024) included 23 participants, Experiment 2 (so far unpublished data) included 26 participants, and Experiment 3 (Bos et al., 2025) included 20 participants. Our total sample size thus included 69 adult participants. In Experiments 1 and 2, we asked participants to indicate their gender (male, female, other) while in Experiment 3 they indicated biological sex (male, female, and intersex). All participants identified themselves as male or female. For simplicity, we will use the term "gender" throughout the manuscript.

Motion Sickness Sensitivity

Participants performed multiple sessions on the same linear sled (Figure 1) with provocative fore-aft motion in each experiment. In all experiments, participants rated their motion sickness using the Motion Illness Symptoms Classification (MISC; Bos et al., 2005; Reuten et al., 2021; Supplemental Table S1). In Experiments 1 and 3, each session lasted 15 minutes during which participants provided a MISC value every minute. In Experiment 2, each session lasted 20 minutes during which participants provided a MISC value every 25 seconds.

In Experiment 1, we exposed participants to four sessions of cosine-shaped displacements (peak acceleration 2.6 m/s^2), each lasting 9 s with 3–11 s intervals in between. In two of the four sessions, participants received an auditory or vibrotactile cue that indicated the initial direction of the upcoming displacement. In the other two sessions, they received a control cue that had no predictive value. In Experiment 2, we exposed participants to displacements with 2 s acceleration (or deceleration) profiles characterized by peak accelerations between 1 and 3 m/s^2 and jerk levels between 3 and 9 m/s^3, followed or preceded by a 0.8 m/s^2 deceleration (or acceleration) to reach standstill. The interval of standstill varied

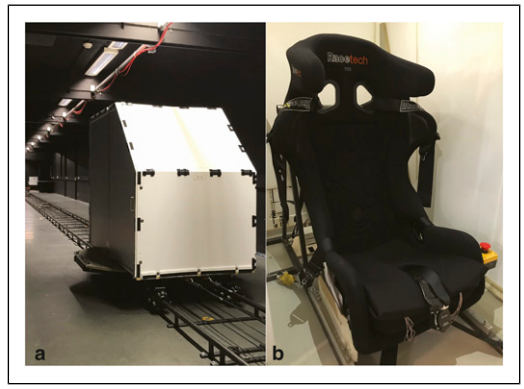

Figure 1. (a) The linear sled which was used in all experiments to provoke motion sickness. (b) Interior view of the cabin in which participants were seated. Reproduced from Reuten et al. (2023)

between 2.5 and 15 s. Participants were exposed to three sessions of a different peak acceleration but of the same jerk level. In Experiment 3, we exposed participants to four sessions of sinusoidal motion with either a peak acceleration of 2 (0.17 Hz) or 2.9 (0.1 Hz) m/s^2. We adjusted the length of the displacements to make the sessions comparable in provocativeness (as calculated using the ISO 2631-1, 1997). While participants observed the stationary interior of the cabin in Experiments 1 and 2, in Experiment 3 they observed a virtual environment that oscillated in phase with the physical motion of the sled via virtual reality goggles.

Motion Sickness History

We used the Motion Sickness Susceptibility Questionnaire (Golding, 2006b) to determine how much participants suffered from motion sickness in the past. In this questionnaire, one indicates the frequency of motion sickness experienced during motorized transport (e.g., cars, boats, or airplanes) and fun experiences (e.g., rollercoasters or swings) in the first 12 (part A) and past 10 (part B) years of their life. To maintain consistency with prior use of the questionnaire in the field, we define recent history as motion sickness reported over the past 10 years.

Visual Dependence

We used the Rod-and-Frame (Witkin & Asch, 1948) and Rod-and-Disc (Hughes et al., 1972) test to assess static and dynamic visual dependence, respectively. We applied the same test parameters in each experiment, identical to those in Reuten et al. (2026; Experiment 2). Participants performed the tests in virtual reality as also employed by Fantin et al. (2022) and Maneuvrier et al. (2021). We used an HTC Vive Pro (2018) headset with a 1080 × 1200 resolution per eye, 110° field of view, and a 90 Hz refresh rate.

Both the static and dynamic distractor were presented earth-fixed at a visual angle of 36.8° against a black background. The static distractor consisted of a white rectangle with only visible edges Figure 2a). It was tilted 28° from gravity in line with the original test parameters used by Witkin and Asch (1948). The dynamic distractor consisted of a transparent disc with an opaque pattern of 117 white dots (Figure 2b). We rotated the disc with 20°/s in roll to maximize possible distractor effects while mitigating the risk of dizziness (Dichgans et al., 1972; Reuten et al., 2026). We implemented the tests with an

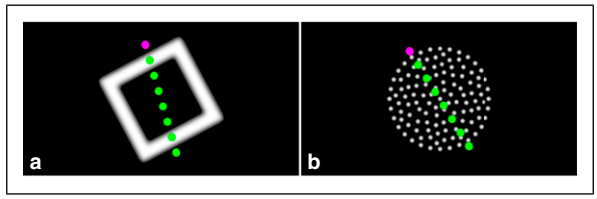

Figure 2. Example stimuli with leftward distractor images of (a) the Rod-and-Frame test and (b) the Rod-and-Disc test. Participants are tasked to orient the rod such that they think it is parallel to the orientation of gravity, perpendicular to the earth's surface. The tilted distractor image in the Rod-and-Frame test remains static (static visual dependence) while the dotted disc in the Rod-and-Disc test rotates in roll (dynamic visual dependence)

equal number of leftward and rightward distractor trials.

The virtual rod consisted of eight small discs each subtending 1.4° that were presented equidistantly along a straight line with a visual angle of 44.2°, presented in front of the static and dynamic distractors. We colored the top disc magenta and all other discs green such that the rod could unambiguously be set across the full 360° range. Participants were instructed to orient the rod parallel with gravity with the magenta disc on top. Participants could tilt the rod by pressing buttons on a handheld numpad, with the required keys marked by felt stickers and all other keys disabled. The rotation step size was 0.5° for single key presses and 33°/s when pressed and held. Further information on the experimental parameters can be found in Supplemental Table S2.

Participants performed the two visual dependence tests in counterbalanced order. Each test consisted of 24 trials with leftward and rightward distractor trials presented in alternating order. The initial starting position of the rod was pseudorandomly varied at three levels (16°, 24°, and 32°) and its direction was alternated every other trial. The two orientations of the distractor image and the two initial rod starting directions resulted in four possible trial sequences. Each participant received a different trial sequence for each test, with all sequences equally balanced across the two tests. The duration of completing both tests varied between 10 and 15 minutes.

Procedure

On the day of the first session, we informed participants about the general experimental procedure. After answering any questions, all participants provided written informed consent. We then asked participants to fill out the MSSQ and questions about their age and gender, after which we administered the TNO test of stereoscopic vision (Walraven & Janzen, 1993). This test uses random-dot stereograms of decreasing disparity to assess whether individuals can use binocular cues for depth separation. We used a disparity of 120 seconds of arc as our eligibility criterion (corresponding to 50% of trials correct). Next, we measured the participants' interpupillary distance and entered this value into the virtual reality goggles used for the visual dependence tests. We provided task instructions on performing the tests and demonstrated how to use the numpad. We explicitly instructed participants to hold the numpad in the air, without their arms resting on the table or their legs in order to avoid additional orientation cues. We furthermore asked participants to keep their head and upper body upright. Participants then started with four practice trials. After completing the tests followed by a short break, participants performed their first motion sickness session on the linear sled. Before starting, they received instructions how to use the MISC scale and to keep their eyes open and head upright. In Experiments 1 and 3, participants performed the four sessions divided across

two days. On each day, participants performed two sessions with a one-hour break in between. In Experiment 2, participants performed the three sessions on three separate days. All participants started the sessions with MISC ≤1. We stopped a session when participants scored at or above the stop-criterion, which was MISC = 6 (little nausea) in Experiments 1 and 3, and MISC = 7 (moderate nausea) in Experiment 2. Sixteen participants in Experiment 1, eight participants in Experiment 2, and six participants in Experiment 3 reached the stop-criterion in one or more sessions. The MSSQ and visual dependence tests were completed only on the first day.

Data Analysis

Motion Sickness Sensitivity. For determining sensitivity, we developed a measure which allowed us to express the sensitivity of a participant in a single value while retaining participants who reached the stop-criterion of the experiment. We consider both the magnitude and temporal development of motion sickness, for which we assume that motion sickness develops with the square root of time for up to several hours (following the ISO 2631-1, 1997). We used the highest MISC value rated in a session ($MISC_{max}$) and the first time point in minutes it was reported (t_{max}) to define the motion sickness sensitivity (MSS). For stopped sessions, the highest MISC value corresponds to the stop-criterion of the experiment.

$$MSS = \frac{MISC_{max}}{\sqrt{t_{max}}}$$

For each participant, we determined the average sensitivity by first calculating the sensitivity per session and subsequently an average across the (three or four) sessions.

Sensitivity is highest for participants reaching severe symptoms within a short timeframe (Figure 3a). Different from other sensitivity measures, which often focus on symptom magnitude exclusively, our approach supports distinguishing between participants reaching identical magnitudes at different time points. For instance, a participant who reaches $MISC_{max}$ = 6 after 9 minutes is less sensitive than one who had to abort the session because he or she reached $MISC_{max}$ = 6 after 4 minutes (Figure 3b). Figure 3c indicates the observed frequencies of $MISC_{max}$ and t_{max} combinations across Experiments 1–3.

Motion Sickness History. To determine recent motion sickness history, we calculated the raw score for part B of the MSSQ using the scoring method proposed by the developer (Golding, 2006b). We explored whether also childhood experiences (part A) are relevant by using the lifetime history, for which we summed the raw sores of part A and B. The minima and maxima for each part are 0 and 27, resulting in a maximum score for lifetime history of 54.

Visual Dependence. For determining static and dynamic visual dependence, we used the same data analysis approach as Reuten et al. (2026). We first removed trials in which the final position of the rod was equal to its initial position. We assume that these settings occurred from accidental key presses, as the initial positions involved substantial off-vertical angles (16°, 24°, and 32°), making it implausible that participants intentionally left the rod unadjusted. This procedure resulted in the removal of 0.25% of trials in Experiment 1, 0.08% of trials in Experiment 2, and 0.52% of trials in Experiment 3. We observed large variability in the distribution of final rod orientations set by our participants (Supplemental Figure S1). To avoid the need to determine an outlier criterion, we defined visual dependence in each test as half the difference between the median rod orientation for the leftward ($\tilde{x}_L$) and rightward ($\tilde{x}_R$) trials:

$$VD = \frac{\tilde{x}_L - \tilde{x}_R}{2}$$

As rod orientations left from gravity (i.e., counterclockwise) were positive in sign and those right from gravity

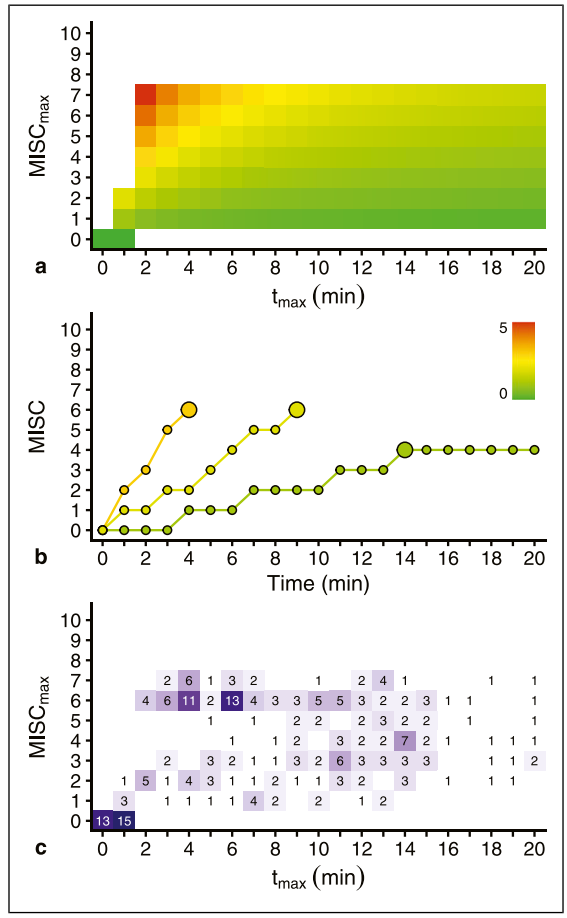

Figure 3. (a) Sensitivity increases with the maximum reported MISC score ($MISC_{max}$) and decreases with the first time point in minutes it was reported (t_{max}). (b) Example trajectories for participants with high (orange), moderate (yellow), and low (green) sensitivity. The large data point indicates the $MISC_{max}$ and t_{max} scores taken to calculate sensitivity. (c) Frequencies of $MISC_{max}$ and t_{max} rating combinations observed across Experiments 1–3

(i.e., clockwise) were negative, our definition of visual dependence (VD) corresponds to the number of degrees participants orient the rod in the direction of the distractor (i.e., frame tilt or disc rotation). Positive visual dependence scores thus reflect a strong effect of the distractor on the final rod orientation set by participants.

Statistical Analysis

To examine the interrelations among all variables (our first research question), we conduct correlational analysis. This additionally provides a basic insight into the data set and the opportunity to check for multicollinearity. To account for possible differences in the distributions of the variables between experiments, we first perform a z-score normalization per experiment. We then calculate parametric Pearson or nonparametric Spearman correlations between sensitivity, recent history, age, gender, and static and dynamic visual dependence and determine whether they differ from zero (α = 0.05). To identify predictors of sensitivity (our second research question), we use regression

analysis. We will accordingly build multilevel linear regression models of different predictor complexity and determine the best model based on the lowest Akaike Information Criterion (AIC) value (Wagenmakers & Farrell, 2004). This model offers the best balance between goodness of fit and complexity. To prevent that the outcome of our analysis depends on the order of predictor addition, we compare all possible models, ranging from those including a single predictor to all five and their various combinations. This results in a comparison of 31 possible models. To account for systematic differences between experiments, we include experiment (1, 2, or 3) as a random intercept. We standardize the predictors to facilitate interpretation of their relative contribution to the explained variance in sensitivity. To attach meaning to possible differences in AIC values, we compare models based on their Akaike weights (Wagenmakers & Farrell, 2004). Akaike weights transform AIC values into a set of normalized scores that indicate how strongly each model is supported by the data relative to the other models in the set of candidate models. The weights can be interpreted as the relative probability that each model is the best in the candidate set, in the sense that it has the lowest expected amount of information loss (i.e., smallest Kullback–Leibler discrepancy).

Results

Before answering our first research question, we investigated the data per experiment (Figure 4). Sensitivity is on average higher in Experiment 1 (μ = 2.0, 95% confidence interval [1.6, 2.4]) than in Experiment 3 (μ = 1.0, [0.7, 1.3], Figure 4a). This may be explained by a difference in the dose of the motion sickness stimulus between experiments. An additional explanation is that recent history is slightly elevated in Experiment 1 (μ = 11.1, [8.6, 13.7]) compared to Experiment 3 (μ = 7.9, [5.5, 10.2], Figure 4b). For age (Figure 4c) and visual dependence (Figure 4d and 4e), the averages between experiments are comparable. Participants reported ages between 19 and 60 years old, with the most common age group being between 20 and 25 years old (26% of participants; Supplemental Figure S2). We included about as many females (n = 38) as males (n = 31). The dynamic visual dependence test elicited larger distractor effects on average (μ = 2.5, [2.0, 3.0]) than the static visual dependence test (μ = 0.7, [0.4, 0.9]). Full descriptive statistics are included in Supplemental Table S3.

We answer our first question on how sensitivity, recent history, age, gender, and static and dynamic visual dependence are interrelated based on non-parametric correlational analyses (Table 1). From this, we observed two significant correlations. First, there is the expected positive correlation between sensitivity and recent history (ρ = 0.39 and $p < .001$). Second, there is a positive correlation between age and static visual dependence (ρ = 0.42 and $p < .001$, Supplemental Figure S3). All other correlations were non-significant (Table 1).

We answer our second question on which predictor or combination of recent history, age, gender, and visual dependence is most useful for predicting sensitivity by comparing the AIC values of all possible multilevel linear regression models. For a model with only recent history as a predictor, AIC = 177.4 (Akaike weight: 0.047). The prediction improves by adding other personal predictors. Table 2 shows the top six of best-fitting models based on their low AIC values (full list in Supplemental Table S4). Consistent with the significant correlation between recent history and sensitivity (Table 1), recent history is included as a predictor in all six models. The best model with the lowest AIC value includes recent history and dynamic visual dependence as predictors (AIC = 173.8, Akaike weight: 0.288). Recent history explains the most variance in sensitivity: β = 0.41, t = 4.2, $p < .001$; dynamic visual dependence contributes with $\beta = 0.23$, $t = 2.4$, p = .021 (Figure 5). They collectively explain 25% of the variance in sensitivity. An analysis

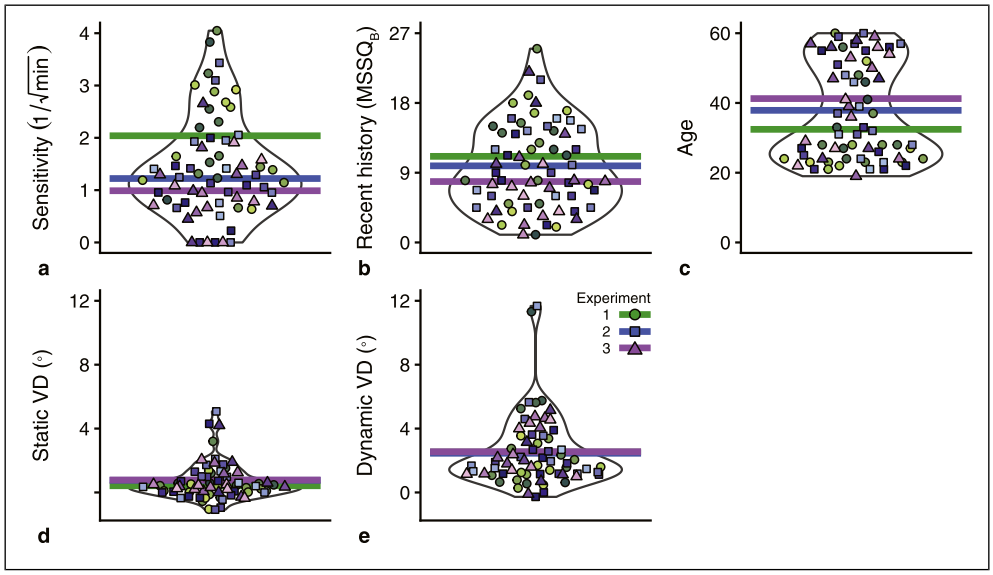

Figure 4. Distribution of (a) sensitivity, (b) recent history, (c) age, (d) static visual dependence (VD), and (e) dynamic visual dependence. Each data point represents a different individual from one of the three experiments (different symbols). The width of the violin is a mirrored kernel density estimate based on the number of observations. The thick horizontal lines in each panel indicate the average across participants for each experiment. $MSSQ_B$ = Motion Sickness Susceptibility Questionnaire part B (Golding, 2006b)

of the Akaike weights indicates that the model with recent history and dynamic visual dependence is about two times more likely to be the best model than the next-best model, which included static visual dependence as an additional predictor. It is also about six times more likely to be the best model compared to a model including only recent history. Note that the six best models all include recent history and dynamic visual dependency as predictors. The relationship between sensitivity, age, gender, and static visual dependence is shown in Supplemental Figure S4.

Recent Versus Lifetime History

We argued in the introduction why we focus the prediction on recent rather than lifetime motion sickness history. Some readers may, however, be concerned that recent history provides an unreliable predictor. It can be biased by situational factors (e.g., recent travel patterns and negativity bias), whereas lifetime history captures underlying tendencies less affected by temporary circumstances. Additionally, it is more common for studies to use lifetime estimates rather than those of the past 10 years. For these reasons, we explored whether lifetime history yielded a better predictor of sensitivity compared to recent history. We extended the candidate set with models in which we replaced recent by lifetime history, amounting to 47 possible models that included one to all five predictors. The results indicate that the best model including lifetime history (AIC = 179.5; Supplemental Table S5) performed poorer than the best model including recent history (AIC = 173.8). The model including recent history is 17 times more likely to be the best model than the model including lifetime history. Although adding more history reduced the quality of the predictions, it did not change our finding that dynamic visual dependence is included as a predictor in the best models.

Discussion

Here we (re-)analyzed the data collected from three studies to investigate how we could

Table 1. Matrix of Spearman's rho correlations based on variables standardized within each experiment. For the predictor gender, we coded females as 1 and males as 0. ***$p < .001$

	Recent history	Age	Gender	Static VD	Dynamic VD
Sensitivity	0.39***	0.11	0.09	0.17	0.18
Recent history		−0.00	0.19	0.02	0.06
Age			−0.06	*0.42***	0.12
Gender				0.18	0.08
Static VD					0.20

improve individual predictions of motion sickness triggered by linear motion of a sled. We introduced a new measure to quantify how sensitive a participant responded to a certain sickening motion stimulus. We refer to this measure as motion sickness sensitivity (MSS), or sensitivity for brevity. We analyzed five potential predictors of this sensitivity: recent motion sickness history, age, gender, and static and dynamic visual dependence. We assessed recent history, age and gender using questionnaires, and visual dependence using line orientation estimates. First, we investigated how all variables were interrelated. We observed two significant positive correlations: between sensitivity and recent history and between age and static visual dependence. Our second research question focused on investigating whether the five predictors could predict sensitivity. The results showed that a model including recent history and dynamic visual dependence as predictors provided the best fit, collectively explaining 25% of the variance in sensitivity.

Prior studies identified age and gender as personal predictors of sensitivity. Their limited contribution in our study is surprising. A possible reason is that our sample did not include children and elderly, whereas the strongest age-related differences in sensitivity are typically found at the extremes of the life span: immunity for babies, hypersusceptibility for children and young adolescents, and reduced sensitivity for older adults (Bos et al., 2007; Gahlinger, 2006; Keshavarz & Golding, 2022; J. M. Mittelstaedt, 2020). The age distribution of our sample thus limited the possibility to confirm patterns previously reported in the literature. The correlations between sensitivity and recent history with age we found were small and far from significant. Very large sample sizes may be needed to detect more subtle differences in sensitivity for individuals closer in adult age. We partially replicated a positive association between age and visual dependence (Agathos et al., 2015; Bugnariu & Fung, 2007): older participants based their verticality judgments

Table 2. We compared the AIC values of all 31 possible multilevel linear regression models to determine the best model for predicting sensitivity. This table shows the six best-fitting models based on their low AIC values. The best model (top row) includes recent motion sickness history and dynamic visual dependence (VD) as predictors (β), which were consistently included in all six models

Recent history	Age	Gender	Static VD	Dynamic VD	AIC	Akaike weight
0.41				0.23	173.8	0.288
0.41			0.06	0.22	175.3	0.134
0.41	0.06			0.22	175.4	0.129
0.40		0.04		0.23	175.6	0.118
0.40	0.07	0.05		0.22	177.1	0.054
0.41	0.04		0.05	0.22	177.2	0.053

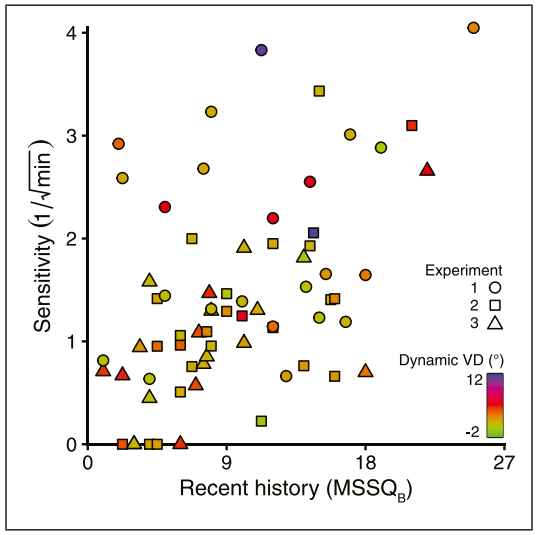

Figure 5. The relationship between recent motion sickness history ($MSSQ_B$) and motion sickness sensitivity (MSS). Each data point represents a different individual from one of the three experiments (indicated by symbols), with their color indicating the dynamic visual dependence (VD)

significantly more on the static (but not dynamic) visual distractor compared to younger participants. Regarding gender or sex, there is some evidence suggesting that an increased susceptibility of females is more pronounced for history than sensitivity (reviewed by J. M. Mittelstaedt, 2020). In our study, recent history and sensitivity showed a significant but only moderate association (ρ = 0.39). Nevertheless, gender is unlikely to account for much of the variance in their association. The correlation between gender and recent history was comparably small as the one between gender and sensitivity (ρ = 0.19 and ρ = 0.09, respectively), with a 95% confidence interval for their difference including zero [−0.16, 0.36]. Our findings are consistent with Lawson (2014), who reported that of the 56 studies he reviewed, half did not report differences between males and females in motion sickness. Overall, our findings suggest that age and gender offer little value for predicting individual sensitivity within an adult sample. In contrast, recent history (the motion sickness reported over the last 10 years) seems to be a more comprehensive marker of sensitivity, encompassing other personal factors that extend beyond age and gender such as habituation.

Motion sickness history and dynamic visual dependence significantly predicted sensitivity, but the variance they explained was limited to 25%. How should we interpret this result? Are history and dynamic visual dependence weak predictors of sensitivity, or are we unable to measure sensitivity reliably? We determined our measure as an average of the sensitivity reported across multiple sessions. If it is able to capture motion sickness reliably, it should yield similar results between sessions expected to induce comparable levels of motion sickness. Hence, we calculated correlations per experiment between the sessions we judged to be most similar in terms of the used intervention (see Supplementary Information, section H, for details). The results indicate significant and strong positive correlations in all experiments, ranging from 0.7 to 0.8 (all $p < .001$). This indicates that our measure MSS obtained in a single session can explain about twice the amount of variance in motion sickness in another session (i.e., $r \geq 0.7$; $R^2 \geq 49\%$) compared to recent history and dynamic visual dependence jointly (i.e., R^2 =

25%). We therefore conclude that the limited amount of variance explained by these latter predictors is not the result of an unreliable measurement of sensitivity. MSS thus provides a reproducible summary of individual differences in the magnitude and temporal development of motion sickness in a single value. Although more sensitive individuals will reach a given sickness level faster, this follows from their greater sensitivity under the assumed square root relationship between sickness and time (ISO 2631-1, 1997). Therefore, MSS is theoretically time independent and the choice of an experimental stop-criterion should not have a systematic effect.

We observed that two participants demonstrated noticeably larger dynamic visual dependence (i.e., the blue circle and square data point in Figure 5) than our other participants. We questioned if their data could account for the significant contribution of dynamic visual dependence as a predictor of sensitivity. To that end, we repeated the analysis without these participants (Supplemental Table S6). The results indicated that a regression model with only recent history ($\beta = 0.43$, $t = 4.4$, $p < .001$) as a predictor was the best model (AIC = 167.7). The second-best model with a marginally worse fit included both recent history ($\beta = 0.42$, $t = 4.3$, $p < .001$) and dynamic visual dependence ($\beta = 0.15$, $t = 1.1$, $p = .280$) as predictors (AIC = 168.4). However, the relative likelihood of the best-scoring model was reduced from 0.288 to 0.193. The likelihood for the first model being the best model is limited: it is 1.5 times more likely to be the best model than the second model also including dynamic visual dependence. When taking into account that dynamic visual dependence was consistently included as a predictor in the six best-fitting models (Table 2), we consider it worthwhile for future studies to elaborate on its value as a personal factor. Examining its contribution to predicting motion sickness induced by visual stimulation, such as virtual reality, could be a relevant use case. Discriminatory power might increase by creating more immersion (e.g., larger field of view) or by removing orientation cues (e.g., performing the test standing). Based on the current results, we conclude that dynamic visual dependence provides a small contribution to the prediction of sensitivity in addition to motion sickness history.

In a prior study, we found that static and dynamic distractor effects reflect different components of visual dependence (Reuten et al., 2026). This is in line with our current findings showing that dynamic but not static visual dependence contributed to predicting sensitivity, consistent with recent work by Keshavarz et al. (2025). Although both static and dynamic tests involve orientation estimation, they presumably differ in the complexity of the underlying neural processing. With the dynamic distractor, optokinetic flow in roll must be integrated with static sensory cues on self-motion, while the static distractor effect is based on a relatively simple weighted addition of static cues. As stated previously, several authors have argued that the brain uses optimal integration schemes to combine multisensory information. That is, sensory cues are weighed proportional to the inverse of their variance meaning that noisy cues receive smaller weights (Ernst & Bülthoff, 2004; Fetsch et al., 2010; Van Beers et al., 2011). There is some evidence that individuals demonstrating greater ability to reweigh sensory cues in cue-conflict situations are less sensitive to motion sickness (Chung & Barnett-Cowan, 2023; Dida et al., 2021; Nooij et al., 2007; Tal et al., 2010; Weech et al., 2020). We speculate that it may be worthwhile to elaborate on (dynamic) visual dependence as a personal factor for sensitivity in the context of sensory reweighting.

Recent history constitutes a relatively general predictor. It encompasses the frequency of motion sickness experienced for various forms of transport and amusement rides in the past. This suggests that our findings may generalize to motion sickness induced by inertial linear accelerations different from those in the present study. Consistent with this interpretation, Souman

et al. (2026) reported a similar frequency dependency for longitudinal, lateral, and vertical periodic accelerations. Nevertheless, generality may come at the expense of predictive specificity. The predictive value of history might be improved by narrowing it to categories considered relevant to the motion sickness stimulus. Such an analysis was not feasible in our study as our sample size was too small (due to unavailable raw data and non-exposures to motion environments). Another approach for improving the prediction may be shortening the time span taken to define recent history. In our sample, the most common age group was between 20 and 25 years old (26% of the participants), resulting in substantial overlap between child- and adulthood exposures. This may contribute to explaining a near-perfect correlation between recent and lifetime history ($\rho = 0.95$). Nevertheless, recent history demonstrated a better predictor than lifetime history. Therefore, we think it is possible that the greater predictive value of recent history may become more pronounced in samples with older participants. On the whole, increasing the specificity of history involves a trade-off with reliability. Restricting history reduces the number of experiences contributing to the measure and introduces greater risk for measurement error.

Our study introduced a new measure of motion sickness sensitivity (MSS) to assess the combined predictive value of personal factors. However, combining factors generally provided limited improvement in predicting sensitivity. Motion sickness history emerged as the strongest predictor, with a small but meaningful contribution from dynamic visual dependence. These findings suggest that the history may already capture much of the variance in sensitivity that can be explained by other predictors considered here. Restricting history to the frequency of motion sickness experienced over the past 10 years improved the prediction. Predictive value could potentially be optimized by focusing the history to motion environments relevant to the exposure for a shorter time period.

Key Points

- Motion sickness history predicted motion sickness sensitivity better than any other personal factor examined.
- Dynamic visual dependence improved the prediction slightly, whereas static visual dependence, age, and gender did not.
- Recent motion sickness history reported over the past 10 years emerged as a better predictor than lifetime history.

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Ethics Considerations

The experimental protocols were in accordance with the ethical standards laid down in the 2013 Declaration of Helsinki and received ethical approval from TNO's internal review board. Participant provided written informed consent prior to participating in the study.

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The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data Availability Statement

The visual dependence test software application used in the experiments is available on https://ci.

tno.nl/gitlab/anna.reuten-tno/visual-dependence-tests. Data can be accessed via https://osf.io/bgkqc/overview. Both are licensed under CC-BY Attribution-NonCommercial 4.0 International.

Supplemental Material

Supplemental material for this article is available online.

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