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A review on the effects of motion characteristics on motion sickness incidence

Suzanne A.E. Nooij[1]

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[1] Department Bülthoff, E–mail: suzanne.nooij@tuebingen.mpg.de

Table of Contents

1. List of abbreviations

DoF	Degrees of freedom
ISO	common short name for the International Organization for Standardization
MS	Motion sickness
MSDV	Motion sickness dose value
MSI	Motion sickness incidence
r.m.s.	Root mean squared
VI	Vomiting incidence

2. Introduction

Many forms of transport evoke symptoms of motion sickness (MS) in susceptible passengers. Symptoms include stomach awareness, palor, headache, sweating dizziness and nausea, and are caused by particular vehicle motions. The aim of this review is to summarize the literature on the relationship between motion characteristics and motion sickness. For example, which types of motions are most provocative, what is the effect of motion frequency and amplitude, and how can we predict whether a certain motion will be provocative.

This review was carried out within the framework of the CORINNE project, which investigates the relationship between vibration characteristics in helicopters and the discomfort they cause on the passengers. The ISO 2631-1[1] proposes a method of predicting motion sickness incidence from a given motion profile, but only takes into account the vertical motion. It is to be expected that the prediction will not be optimal for helicopter trajectories, as motions in other degrees of freedom may also contribute. One of the project aims, therefore is to verify whether the current ISO method is valid, or whether it can be improved by taking motion in multiple degrees of freedom into account.

In the following, we will first summarize the prediction method proposed in ISO 2631-1 and then summarize available literature on the effects of motions in other degrees of freedom. This review can then guide further research for the specific case of helicopter flight.

3. Motion sickness prediction in ISO 2631-1

The calculation of motion sickness incidence provided in ISO 2631-1 is based on extensive laboratory and field studies on sea sickness (Ohanlon and McCauley 1974; McCauley et al. 1976; Lawther and Griffin 1987; Lawther and Griffin 1988). It was recognized that, irrespective of the vehicle, motion sickness was caused by repetitive linear and angular acceleration of the head (Reason and Brandt 1975), and vertical oscillation was thought to be most important, especially for sea sickness.

The occurrence of motion sickness in these studies is expressed by the so called Motion Sickness Incidence (MSI) or Vomiting Incidence (VI). These are equivalent and refer to the amount of people who vomit within a certain exposure duration. An elaborate study was performed by McCauley and colleagues (1974, 1976), investigating how motion sickness incidence depended on frequency and amplitude of the linear acceleration, during a 2h exposure to sinusoidal vertical oscillation. They found a peak incidence at a frequency of 0.167 Hz, and a general increase in MSI with r.m.s. amplitude of the linear acceleration. Also the effect of roll and pitch motions was investigated, either in isolation or in combination with vertical oscillation, but it was concluded that heave was the most important component. In their original paper they provided a model of the data to predict the MSI based on amplitude, frequency and the duration of exposure.

[1] ISO-2631-1: Mechanical vibration and shock – Evaluation of human exposure to whole body vibration. Second edition, 1997.

Later, Lawther & Griffin (Lawther and Griffin 1986; Lawther and Griffin 1987; Lawther and Griffin 1988) collected both actual ship motion data and motion sickness reports in more than 20.000 subjects who travelled on big ferries. The r.m.s. amplitudes of motion in all 6 degrees of freedom (DoF) were positively correlated with vomiting incidence (VI) and illness ratings. Heave showed the highest correlation, followed by pitch. The finding that all motion components were correlated with VI would suggest that they all contribute to MS, but of course the components are also correlated with each other. When combined in a multiple regression model, heave proved to have the most predictive power, and adding another component to the model did only marginally increase the overall explained variance. Thus, it was concluded that heave was the most important component and that this could be used to predict MS. VI and illness ratings were positively correlated with the heave r.m.s. amplitude and also increased with the exposure duration.

Based on these findings, it was proposed to formulate a *motion dose*, solely dependent on the heave oscillation amplitude and exposure duration. The frequency dependence observed by McCauley et al (1976) was accounted for by frequency weighting of the acceleration signal, before calculating the r.m.s. value. Then the motion sickness dose value (MSDV) is calculated as follows (Lawther & Griffin 1987, 1988):

$$MSDV = \left[\int_0^T a_w(t)^2 dt \right]^2 \qquad (1)$$

Here, t represents time, T is the total duration and a_w is the frequency weighted r.m.s. value of the acceleration signal. Lawther and Griffin showed that this MSDV is linearly related to the vomiting incidence, and also to the various level of the illness ratings. This led to the following equation:

$$MSI = k \cdot MSDV \qquad (2)$$

A value for k of 0.33 is a good estimation for the percentage of people who are expected to vomit for a particular MSDV. They also recalculated the MSDV values from the McCauley (and other) data and showed a good correspondence between studies (see also Fig. 1). As the MSDV-model is simpler than the model proposed by McCauley, this is the preferred model to calculate the MSI.

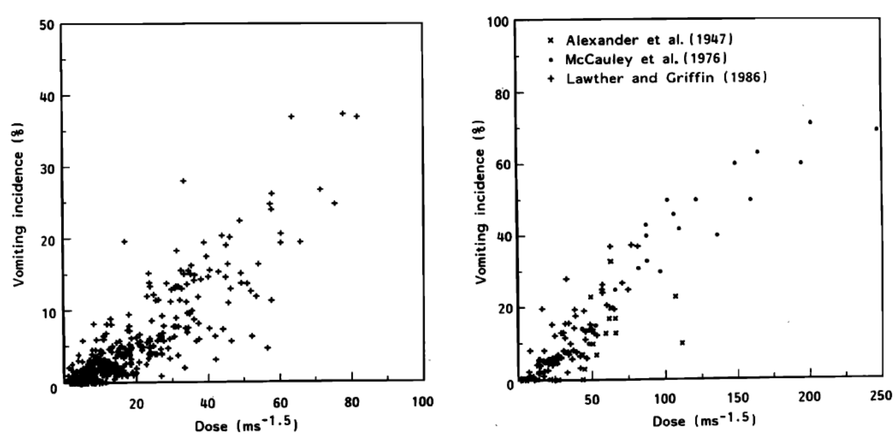

Figure 1: Graphs taken from Lawther & Griffin (1987), showing the linear relationship between MSDV and Vomiting Incidence, for several studies.

In summary, the prediction method in the ISO standard is based on extensive studies that focused on sea sickness. For ship motion, all motion components correlated with MSI, but the model was sufficiently good when only heave was included. Including more components did not lead to better predictions. However, this does not imply that these components do not contribute to MS.

4. Other motion components: horizontal oscillations

It is well-known that horizontal linear accelerations, as for example occurring in an aircraft or car, are also provocative. Turner et al. 2000 recorded airsickness and aircraft motion during short-haul flights (fixed wing). Positive correlations were found between the percentage of passengers who experienced nausea or felt ill and the magnitude of low-frequency lateral and vertical motion, although neither motion uniquely predicted airsickness. Interestingly, there was a peak in the power spectrum for lateral acceleration around 0.25 Hz, associated with the aircraft response to wind gusts. The incidence of motion sickness also varied with passenger age, gender, food consumption and activity during air travel.

Turner and Griffin also investigated the occurrence of car sickness in coaches (Turner and Griffin 1999b; Turner and Griffin 1999c; Turner and Griffin 1999a). MSDV were calculated using the frequency weighting of the British Standard, for all axes, like in their aircraft study. Here especially lateral motion was provocative, and MS increased with the overall magnitude of the MSDV. However, when passengers had a good view on the road ahead, the effect of MSDV was absent.

Applying the ISO proposed method to the prediction of MSI during horizontal motions is not always successful. Golding and colleagues (1995) compared the effect of vertical versus horizontal for-aft linear oscillation (heave vs. surge) and found that the latter was twice as provocative. In that study, a sinusoidal oscillation of 0.35 Hz was used with an amplitude of 3.6 m/s^2, but this effect was also found for other frequencies (Golding et al. 1996). This implies, as also indicated by Golding and colleagues (1996), that the MSI for horizontal oscillations is higher than that predicted by the ISO standard (based on vertical oscillations).

Although differences between the provocativeness of horizontal and vertical motions exist, the MSDV might still be applicable to horizontal motions. Griffin and Mills (2002) investigated the effect of acceleration amplitude on motion sickness during horizontal accelerations and found a positive relationship between the two variables. In addition, effects for lateral vs. for-aft motion were similar. These results provide support for the assumption that the MSDV, which predicts an increase in sickness with increasing magnitude, is also valid for horizontal motions.

One possible explanation for the differences between horizontal and vertical motions, then, is the applied frequency weighting in the MSDV. The frequency dependency is clearly different for each motion component. For fore-aft oscillations, provocativeness also peaks around 0.2 Hz (Golding et al. 1996; Golding et al. 1997; Golding et al. 2001), although the peak is less sharp than the one found for vertical motions. Golding and colleagues investigated fore-aft oscillations and found an increase of 2-3 dB/octave for frequencies below 0.2 Hz, and a decrease of 3-4 dB/octave for frequencies above 0.2Hz. For vertical oscillations this was around 6 and 12 dB/octave respectively. For lateral oscillations the weighting is again different. A study by Donohew and Griffin (Donohew and Griffin 2004) showed that the MS severity was relatively independent of frequency below the 0.25 Hz, but decreased with -12 dB/octave for frequencies above 0.25 Hz. Including the appropriate weighting functions in the calculation of the MSDV is expected to improve the accurateness of the MSI model.

5. Other motion components : Roll or pitch motion

In the calculation of the MSDV the angular motions of the vehicle are often ignored. Support for this choice is provided by studies of Griffin and colleagues, investigating the effects of pure sinusoidal roll or pitch motion on motion sickness. Motion sickness levels were overall very low, and no effect of rotation frequency was found between 0.02 and 4 Hz for a roll tilt of 8 deg (Howarth and Griffin 2003). Albeit low, MS levels rose with tilt amplitude for tilts between 1.8 and 7.3 deg at 0.2 Hz (Joseph and Griffin 2008). However, there is evidence for an interaction between the different motion components. Wertheim et al. 1998 showed that pitch, roll and heave motions that are in itself not provocative, can cause motion sickness when combined. As will also be discussed in the next paragraph, it shows the overall MSI cannot be calculated as a linear addition of all of its components.

6. Tilt compensation and tilting trains

Accelerations in the horizontal plane cause a tilt of the total gravito-inertial acceleration vector (GIA) that is acting on the body. The GIA is the acceleration due to gravity plus the acceleration due to motion. For example, when going through a turn in a car, the passenger is tilted to the outer side of the curve (due to the centrifugal force) whereas the driver anticipates the curve by leaning inward. In this way the driver compensates for the inertial (lateral) acceleration and aligns himself with the GIA. This is referred to as *tilt compensation*, where the GIA tilt caused by the horizontal inertial acceleration is compensated for by tilting the body. This might, under particular circumstances, be beneficial for motion sickness.

Golding and colleagues (Golding et al. 2003) started to investigate the effect of tilt compensation on motion sickness and exposed subjects to for-aft oscillation. The GIA tilt was either compensated by active head tilt performed by the subject (analogous to the car-driver in the example above), or by an active suspension system, that is, tilt of the chair. They found that only the active head motion was successful in alleviating sickness, and an active suspension system was not. In accordance with the latter result, Donohew and Griffin (2009) found that horizontal oscillations with full GIA tilt compensation lead to higher MS levels than uncompensated GIA tilt. As roll in itself is hardly provocative (see Howarth & Griffin 2003), it shows that there appears to be an interaction between roll and lateral oscillation, and the overall sickness cannot be predicted based on its components.

In a later study (Donohew and Griffin 2010) these authors investigated the effect of percentage of compensation, and found that partial compensation was better than no or full compensation (50% at oscillations of 0.2 Hz, 0.25% at 0.1 Hz). Again, this shows that the overall MSI cannot be predicted as a linear combination of the effects of its components.

Tilt compensation is also applied in tilting trains to minimize the lateral forces acting on the train passengers and allow higher traveling speeds in curves. However, as also may be expected based on the results above, motion sickness is an unwanted side effect. Cohen et al. 2011 Investigated how this tilt could be optimized and compared the effects of different mechanisms. A purely reactive mechanism, (producing somewhat delayed tilt with lower accelerations) was more nauseogenic than a predictive mechanism (reaching the desired tilt velocity faster). They conclude that the delay in tilt is responsible for the increase in motion sickness often observed in tilting trains.

7. Concluding remarks

The current method for predicting the occurrence of motion sickness based on vehicle motion is primarily based on studies investigating sea sickness, where vertical motion is considered the main contributor. This review showed that the same method may be useful for the prediction of horizontal motions as well, when different frequency weightings are used. Having said that, it is also clear that predicting motion sickness incidence in complex, multidimensional motions is hard, as the overall incidence is not a linear sum of the separate parts. Investigating vehicle specific combinations of motions may lead to vehicle specific adaptations of the prediction method.

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