Prediction of the incidence of motion sickness from the magnitude, frequency, and duration of vertical oscillation

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A method is proposed by which the incidence of motion sickness may be predicted from measurement of the motion exposure. The method is based on data from both field and laboratory studies involving large numbers of people and is applicable to marine and other environments where vertical oscillation occurs at frequencies below 0.5 Hz. The dependence of motion sickness on the frequency of oscillation requires the use of a weighting function between 0.1 and 0.5 Hz. The dependence of sickness on the duration of exposure is incorporated by the use of a cumulative measure of motion dose based on the product of root-mean-square (rms) acceleration magnitude and the square root of stimulus duration. The influence of population variables such as sex, age, and motion experience is discussed. The method enables separate predictions to be made of vomiting incidence and of feelings of illness. The prediction procedure, while not seeking to explain the underlying mechanisms of motion sickness occurrence, provides a generally applicable method which is simple to use and has an accuracy consistent with the experimental data on which it is based.

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INTRODUCTION

"Sailing on the sea shows that motion disorders the body" (Hippocrates, 5th Century B.C.) is a fundamental observation that motion sickness is caused by motion. Initial research into the causes of motion sickness resulted in descriptions of the motion conditions in which sickness is likely to occur. Further research produced quantitative information relating some motion variables to the incidence of sickness provoked. A summary of the available information was made by Allen (1974) and resulted in an International Standard (ISO, 1982). This offers a single set of boundaries for some conditions causing 10% incidence of sickness. The recent availability of data from a large field survey of seasickness among passengers on board ships at sea provides an opportunity to re-examine the previous data and formulate a more comprehensive prediction procedure.

Tyler and Bard (1947) produced an extensive review of motion sickness and concluded that, "In all cases of sickness due to the motion of ships, boats, airplanes, elevators, and swings, linear (translational) accelerations appear to constitute the principal stimuli." While motion sickness can undoubtedly be produced by various types of rotational motion, and even by visual stimulation alone, oscillatory translational acceleration has been amply demonstrated to be a potent nauseogenic stimulus. This article is restricted to situations in which there is vertical translational oscillation, accepting Tyler and Bard's conclusion in the light of subsequent research.

The underlying mechanism by which vertical translational oscillation produces sickness and the nature of the contribution of the vestibular system are not fully understood. Although current theories, such as the sensory conflict theory (Reason and Brand, 1975), provide some plausible explanations, they generate few quantitative hypotheses concerning the relevant physical variables of the stimulus that can be tested experimentally.

Information from studies of motion sickness is reviewed in order to describe the effects of the motion variables of acceleration magnitude, axis, frequency, and duration. A simple procedure is then proposed for predicting motion sickness incidence from the values of these variables.

I. LABORATORY STUDIES

Of the published laboratory studies concerned with seasickness, few have successfully manipulated one motion variable while holding the others constant. Furthermore, many are reported inadequately, have methodological flaws, or have particular situational specificities, which prevent direct comparisons between experiments. Only two series of laboratory investigations have been sufficiently comprehensive to provide information on the effects of some motion variables while also enabling useful comparisons to be made between the studies.

A. The Wesleyan University studies

A series of experiments was carried out at the Wesleyan University by Alexander, Wendt, and others (Alexander et al., 1945a,b,c, 1947). A vertical elevator (lift) was converted for use as an oscillating vertical motion device. Experiments were performed to investigate the effects of various motion parameters on the incidence of sickness among volunteer subjects who rode in the cabin. The 450 subjects used were all fit young male volunteers, generally being Naval Aviation cadets.

The control of the cabin motion was such that the acceleration could not be continuously varied. Instead, each cycle of motion consisted of a period of constant acceleration, a
period of constant velocity, a period of constant acceleration
equal to the first but in the opposite direction, and another
period of constant velocity. Although the resulting displace-
ment waveform looked approximately sinusoidal, the accele-
ration waveform had the appearance of a stepped square or
rectangular wave. An idealized reconstruction of the wave-
forms is given in Fig. 1. Variations could be made, within
limits, to the durations of the periods of constant acceleration
and constant velocity, and to the magnitudes of the ac-
celerations, thus varying the overall acceleration magni-
tudes and frequencies, which were the variables under
investigation. The motions used are described in terms of
displacement, velocity, and acceleration values, but no indi-
cation is given as to how these were measured, and no wave-
forms are presented. All the experimental exposures lasted
20 min, or were prematurely terminated by the subject vom-
iting or requesting to stop.

B. The Human Factors Research, Inc. studies

A large research program was undertaken by Human
Factors Research, Inc. (O'Hanlon and McCauley, 1974;
McCauley et al., 1976; Guignard and McCauley, 1982) us-
ing a machine located in Santa Barbara, California. The in-
tention was to investigate the likely effects on military per-
sonnel exposed to sea motion. The motion generator was
capable of producing vertical oscillation, roll, and pitch, and
was, unlike the Wesleyan University lift, fully controllable.
Details of the construction and performance of the device
have been published elsewhere (Buckner and Heerwagen,
1969; Malone and Vickery, 1975). The moving cabin was
driven sinusoidally for most of the experiments, although
mixed sinusoids were used in the Guignard and McCauley
study. One experiment used the roll and pitch capability; the
rest of the work used only vertical motion. About 1000 sub-
jects, generally fit young males, were used and they were
exposed to motion until either they vomited or quit, or 2 h
had elapsed. The experiments examined the effects of motion
magnitude, frequency, and axis on sickness incidence. A
mathematical model was developed to fit the data, and
further statistical analysis of the data has been published by
Mauro and Smith (1983).

II. FIELD SURVEYS

Field studies of motion sickness on board ships (e.g.,
Handford et al., 1953; Nieuwenhuijzen, 1958; Kennedy et
al., 1968) have only involved one, or very few, voyages and
have generally not involved measurements of the motion
that are sufficiently comprehensive to be compared with the
laboratory data. An extensive survey of motion sickness on
board passenger ferries around the British Isles has recently
been completed (Lawther and Griffin, 1986, 1987, and
1988), involving 20 000 passengers on 114 voyages on 9 dif-
erent vessels. Voyage durations ranged from 1 h to 6 h, and
sea conditions varied from calm to very rough. As well as
measuring the incidence of seasickness among the pas-
sengers and other individual data, the motions of the vessels
were recorded continuously in all six axes throughout each
voyage. Subsequent analysis enabled the variations in sick-
ness incidence to be related to the variations in motion be-
tween voyages and between ships. A subjective illness rating
scale was developed and used in parallel with the vomiting
incidence measures. The survey also investigated population
variables, such as age, sex, regularity of travel, and the taking
of anti-seasickness tablets and alcohol.

III. THE EFFECT OF MOTION IN DIFFERENT AXES

The evidence from laboratory studies conclusively
shows that vertical translational oscillation is a sufficient
stimulus for motion sickness. Other studies using swings (e.g., Manning and Stewart, 1949), cars (e.g., Vogel et al., 1982), and rotational devices (e.g., Benson and Guedry, 1971; Leger et al., 1981) have also demonstrated the nauseogenic properties of stimulation in other axes of translation and rotation. Little information is available on the relative importance of vertical and horizontal translational oscillation. At present it is, therefore, not possible to construct a predictive model applying to all axes or all combinations of axes of stimulation.

An experiment by McCauley et al. (1976) investigated the effects of rotational oscillation both alone and combined with vertical oscillation separately for pitch and roll. Despite using high magnitudes of rotational oscillation, which also produced high lateral translational acceleration, they failed to demonstrate any significant increase in sickness occurrence over that expected purely from the vertical motion. Pitch or roll motions alone produced virtually no sickness, even though the horizontal translational acceleration caused by being above the center of rotation, combined with the resolved component of gravity due to tilting, was of sufficient magnitude to have caused about 60% sickness had it been in the vertical direction.

The field data gathered by Lawther and Griffin covered ships and sea conditions producing different motion characteristics. Although there was a degree of correlation between the magnitudes of motion in some axes, enough variation remained to demonstrate that sickness incidence correlated best with the magnitude of vertical oscillation. Multiple regression analysis of the data showed that inclusion of all axes of motion only marginally reduced the residual variance.

The prediction procedure developed in this article is intended to apply to motion sickness where the primary cause is vertical translational oscillation. This does not imply that motion occurring in other axes invalidates the procedure.

### IV. THE EFFECT OF MOTION OF DIFFERENT MAGNITUDES

The Wesleyan University studies were presented as a series of experiments, each designed to investigate a particular motion variable. However, the limitations of control of the apparatus had the result that the variables of frequency and acceleration magnitude were often confounded. Nonetheless, by pooling the results of all the experiments, some comparisons can be made.

The waveforms used were nonsinusoidal in nature, but the descriptions give enough information in terms of velocities, accelerations, and repetition rates, uniquely to define each one. Reanalysis has been undertaken, based on two assumptions: that the waveform was not significantly distorted from the ideal, and that only the frequency content of the motion below 1 Hz is of interest. There is little alternative to the first assumption, since no measured waveforms are presented, and the second assumption will be seen to be justified in the light of subsequent data. A computer was used to recreate and analyze the waveforms. Spectral analysis revealed the dominant frequency in each case to be the same as the repetition rate. The spectra, at frequencies below 1 Hz, were used to determine the root-mean-square acceleration magnitudes. The results of this reanalysis are presented in Table I, together with the vomiting incidence data.

The results given in the table fall into four frequency categories and are presented graphically in Fig. 2. Although the points are somewhat scattered, a tendency towards increased sickness with increasing acceleration magnitude is discernible, at least for some of the frequencies. The scatter is not surprising, given that there are few data points for each frequency, and comparisons are being made between data from different experiments.

<table>
<thead>
<tr>
<th>Wave (code)</th>
<th>Dominant frequency (Hz)</th>
<th>Acceleration (m s⁻² rms &lt; 1 Hz)</th>
<th>Vomiting (%) of 30 subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.53</td>
<td>5.47</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>0.37</td>
<td>4.15</td>
<td>13</td>
</tr>
<tr>
<td>C</td>
<td>0.27</td>
<td>3.90</td>
<td>23</td>
</tr>
<tr>
<td>D</td>
<td>0.22</td>
<td>3.33</td>
<td>10</td>
</tr>
<tr>
<td>E</td>
<td>0.37</td>
<td>4.15</td>
<td>17</td>
</tr>
<tr>
<td>F</td>
<td>0.33</td>
<td>2.28</td>
<td>3</td>
</tr>
<tr>
<td>A'</td>
<td>0.53</td>
<td>5.47</td>
<td>7</td>
</tr>
<tr>
<td>G</td>
<td>0.37</td>
<td>3.14</td>
<td>23</td>
</tr>
<tr>
<td>H</td>
<td>0.27</td>
<td>2.31</td>
<td>20</td>
</tr>
<tr>
<td>J</td>
<td>0.23</td>
<td>1.86</td>
<td>13</td>
</tr>
<tr>
<td>H'</td>
<td>0.27</td>
<td>2.31</td>
<td>33</td>
</tr>
<tr>
<td>J'</td>
<td>0.22</td>
<td>1.86</td>
<td>17</td>
</tr>
<tr>
<td>P</td>
<td>0.27</td>
<td>1.85</td>
<td>10</td>
</tr>
<tr>
<td>Q</td>
<td>0.37</td>
<td>1.75</td>
<td>0</td>
</tr>
<tr>
<td>R</td>
<td>0.53</td>
<td>1.68</td>
<td>0</td>
</tr>
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</table>

**Fig. 2.** The effects of 20-min exposures at four frequencies (Alexander et al., 1947).
tude was explicitly manipulated as a variable independent of frequency. Ten different discrete frequency sine waves were used in the range 0.083–0.700 Hz and the results are presented in Table II. At each frequency, sickness incidence increased with increasing acceleration magnitude. Selecting the frequencies that give the most data points, the effects of acceleration magnitude may be examined for frequencies of 0.500, 0.333, and 0.167–0.200 Hz (pooled) in Fig. 3. At each of the three frequencies, vomiting incidence increased in a monotonic and approximately linear fashion with increasing acceleration magnitude.

Frequency analysis of the ship motion data from the Lawther and Griffin survey showed that the dominant frequency of vertical acceleration varied little between voyages or between vessels. The spread of the frequency spectra was small and usually centered around 0.2 Hz. Although of regular frequency, the time histories showed considerable variation in amplitude over the short term, similar to a beating effect. Root-mean-square averaging was chosen initially as the simplest way of characterizing the time-varying signal. The variation in vomiting incidence with rms acceleration magnitude for 73 trips on 4 ships which had voyages of at least 2-h duration is shown in Fig. 4. Despite the scatter in the data, there is a clear increase in vomiting incidence with increasing acceleration magnitude, and the regression line shows the best straight line fit.

V. THE EFFECT OF MOTION OF DIFFERENT FREQUENCIES

Because of the nonsinusoidal nature of the waveform, the Wesleyan University experiments did not succeed in varying frequency of oscillation entirely independently from rms acceleration magnitude. McCauley et al. were able to manipulate the frequency independent of amplitude, but many different amplitudes were studied at different frequencies. In order to use the maximum amount of the data available when assessing the effect of frequency, the effect of acceleration magnitude must be controlled. A convenient method of controlling for this variable is to use the linear relationships described in the previous section and produce a simple normalized sickness score by dividing each sickness incidence value by the acceleration magnitude; thus

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Acceleration (m s(^{-2}) rms)</th>
<th>Number of subjects</th>
<th>Vomiting incidence (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.083</td>
<td>0.278</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>0.083</td>
<td>0.55</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>0.167</td>
<td>0.278</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>0.167</td>
<td>0.55</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>0.167</td>
<td>1.11</td>
<td>20</td>
<td>30</td>
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<tr>
<td>0.167</td>
<td>2.22</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>0.180</td>
<td>1.70</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>0.200</td>
<td>2.34</td>
<td>35</td>
<td>71</td>
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<tr>
<td>0.250</td>
<td>1.11</td>
<td>29</td>
<td>31</td>
</tr>
<tr>
<td>0.250</td>
<td>2.22</td>
<td>54</td>
<td>63</td>
</tr>
<tr>
<td>0.250</td>
<td>3.33</td>
<td>45</td>
<td>69</td>
</tr>
<tr>
<td>0.333</td>
<td>0.55</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>0.333</td>
<td>1.11</td>
<td>26</td>
<td>15</td>
</tr>
<tr>
<td>0.333</td>
<td>2.22</td>
<td>26</td>
<td>46</td>
</tr>
<tr>
<td>0.333</td>
<td>3.33</td>
<td>32</td>
<td>50</td>
</tr>
<tr>
<td>0.417</td>
<td>3.33</td>
<td>6</td>
<td>50</td>
</tr>
<tr>
<td>0.417</td>
<td>4.44</td>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>0.500</td>
<td>1.11</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>0.500</td>
<td>2.22</td>
<td>21</td>
<td>14</td>
</tr>
<tr>
<td>0.500</td>
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<tr>
<td>0.500</td>
<td>4.44</td>
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<td>33</td>
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<tr>
<td>0.500</td>
<td>5.55</td>
<td>24</td>
<td>42</td>
</tr>
<tr>
<td>0.600</td>
<td>4.44</td>
<td>25</td>
<td>8</td>
</tr>
<tr>
<td>0.600</td>
<td>5.55</td>
<td>22</td>
<td>18</td>
</tr>
<tr>
<td>0.700</td>
<td>5.55</td>
<td>24</td>
<td>4</td>
</tr>
</tbody>
</table>

FIG. 3. The effects of 2-h exposures at three frequencies (McCauley et al., 1976).

FIG. 4. The effects of 2-h exposures on board four ships with dominant frequencies at 0.2 Hz (Lawther and Griffin, 1988).
normalized sickness score = \frac{\text{vomiting incidence}}{\text{acceleration (rms)}},

where "vomiting incidence" is the percentage of exposed persons to have vomited during the exposure period and the rms acceleration is that occurring below 1 Hz (m s\(^{-2}\)).

The Wesleyan University data have been recalculated using this procedure, and the results are shown graphically in Fig. 5. Although the data points are scattered, there is a clear trend towards decreased sickness with increased frequency.

The McCauley et al. data have been similarly treated and the results are shown in Fig. 6. Data points with zero raw sickness scores do not appear since the procedure for normalizing is not then valid. The graph supports the Wesleyan University findings, showing a steady decline in sickness with increasing frequency of oscillation, except for one data point at the lowest experimental frequency of 0.083 Hz, where sickness also decreased.

In order to compare the graphs from the two series of studies directly, however, the variable of exposure duration must also be controlled, since the Wesleyan University experiments lasted 20 min, and the McCauley et al. exposures were of 2 h. Fortunately, the sickness data are reported fully in the McCauley et al. (1976) report, and sickness incidences for 25-min durations can be calculated. The combined data from the two series of experiments, for 20- and 25-min exposure durations, are shown in Fig. 7. (Note that the sickness incidence for the stimulus at 0.083 Hz was zero over the first 25 min and hence this datum point disappears.) Considering the numerous differences between the experimental conditions used by the two research teams, the results show very good agreement. The slope of the decline in sickness with increasing frequency also appears similar to that for the 2-h duration data.

The relation between frequency and sickness can be described by a series of straight line approximations. For use as a frequency weighting, adjusting the slopes of the lines to multiples of 6 dB/oct would be convenient. (The weighting could alternatively be defined by traditional analog filter equations.) A suggested straight line approximation to the frequency data, superimposed on the 2-h duration graph, is given in Fig. 8, together with the frequency response of an analog filter approximation to the lines (including 12-dB/oct additional bandlimiting filters). Although the decline in sensitivity with increasing frequency above 0.25 Hz pro-
duces a reasonably good fit, the data below 0.16 Hz are scanty, consisting of one experimental session at 0.083 Hz in which one subject among twenty was sick. In these circumstances, the nature, or even the existence, of the decline in sickness with decreasing frequency below 0.16 Hz is little more than a guess. In practice, this may be of little consequence, since dominant frequencies of vertical oscillation are often above 0.1 Hz in common transport environments.

Figures 9 and 10 show the relation between frequency weighted acceleration and sickness incidence obtained by applying the above weighting to the data from the Wesleyan University and the McCauley et al. studies.

Guignard and McCauley (1982) compared sickness produced by a single frequency sine wave with that produced by various combinations of two sine waves. They found no significant differences between the sickness incidences produced by exposure to the different stimuli, despite large differences in overall rms acceleration magnitude. Frequency weighting of the acceleration waveforms by the method described above produces similar weighted rms acceleration magnitudes for each of the stimuli, and is thus reasonably consistent with the experimental findings.

VI. THE EFFECT OF MOTION OF DIFFERENT DURATIONS

The effect of exposure duration cannot be examined in the Wesleyan University studies, but cumulative data over the 2 h of exposure given by McCauley et al. (1976) show that the rate of accumulation of sickness generally decreased with increasing time. The data from Lawther and Griffin covered journeys of up to 6-h duration and it was also found that sickness incidence tended to accumulate more slowly as the journey progressed.

In both laboratory and field studies, sickness incidence has been measured as a cumulative variable. The number of people to have vomited can thus only increase with increasing time and no account is taken of people who may recover during the exposure period. Adaptation to the motion, and consequent recovery from seasickness, does occur with prolonged exposures, but the effects of this phenomenon are not incorporated since the time required for significant adaptation is usually far longer than the durations considered here.

A cumulative measure of acceleration, or "dose," was used by Lawther and Griffin (1986) to examine the effect of exposure duration in the light of the previous observations. The measure was calculated using the formula

\[
\text{Vomiting incidence (\%) = } \frac{\text{Number of people who vomited}}{\text{Total number of people exposed}} \times 100
\]
where \( \alpha(t) \) is the acceleration, and \( T \) is the duration of the journey in seconds. Calculation of this value is equivalent to multiplying the rms acceleration by the square root of the durations: \( a_{\text{rms}} T^{1/2} \). [The units are those of acceleration \( \times \) (time) \( ^{1/2} \) = m s \( ^{-1.5} \).] It is a characteristic of this expression that, in order to double the dose, while the duration must increase by a factor of four, the acceleration must increase twofold. This dose measure was found to correlate well with the sickness incidence data from the shipboard surveys as the graph in Fig. 11 shows, although other cumulative measures, particularly \( a_{\text{rms}} T^{1/4} \), also produced good correlations.

**VII. THE METHOD OF SICKNESS PREDICTION**

The preceding sections have shown how the effects of the variables of acceleration magnitude, frequency, and duration may each be independently approximated by simple mathematical descriptions. These may now be combined to form a general procedure for predicting the incidence of motion sickness occurrence from the vertical acceleration waveform.

The measured acceleration waveform should be first weighted by the frequency weighting. This can be achieved by analog filtering or by digital methods. The effect in either case is to normalize the acceleration with respect to the flat portion of the weighting around 0.2 Hz. Next, the rms magnitude of the weighted waveform should be calculated by true integration over the whole period. The resulting value is then multiplied by the square root of the duration to produce the dose.

The dose value may be interpreted with reference to the experimental data. The slopes of the regression lines for the 2-h durations in Figs. 4 and 10 are both about 30% vomiting per m s \( ^{-2} \), indicating that acceleration of 1 m s \( ^{-2} \) rms would produce 30% sickness incidence. For these 2-h exposures, this corresponds to a dose of about 85 m s \( ^{-1.5} \).

The relationship between dose value and sickness incidence can be examined by pooling all the experimental data onto one graph. Figure 12 shows the frequency weighted data from the Wesleyan University studies and the McCauley et al. experiments converted to dose values and combined with survey data on one ship from Lawther and Griffin (1986). A simple linear approximation to the data is given by the formula

\[
\text{vomiting incidence (\%) } = K \times \text{dose},
\]

where \( K \) is a constant. The value of \( K = \frac{1}{3} \) (i.e., 30/85) appears a suitable fit to the data, and the line with this gradient is almost identical to the linear regression line. Sickness incidence is thus directly calculated from the dose value by multiplying by \( K \).

When obtaining a prediction of sickness incidence from the acceleration dose, it is important to acknowledge the nature of the data from which the procedure has been developed since this defines the scope of application. The data covered durations from 20 min to 6 h, and sickness incidence up to about 70%, with motion frequencies mostly between 0.1 and 0.5 Hz. The use of the estimation procedure when parameters are outside these ranges is not supported by sufficient data.

**VIII. COMPARISON WITH ALTERNATIVE METHOD**

A mathematical model was produced by O'Hanlon and McCauley (1974) to relate vomiting incidence to acceleration magnitude and frequency, based on the results of their first experiments. The results from later experiments were
absorbed into the model by McCauley et al. (1976) and the variable of stimulus duration (up to 120 min) was also incorporated. The relation between acceleration and vomiting incidence was described by a cumulative normal distribution function of the logarithm of the rms acceleration magnitude. The equation for this function is given as

$$\text{MSI (vomiting incidence)} = \Phi(\ln a) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\ln a} \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right) dx,$$

where $a$ represents acceleration, and $\sigma$ and $\mu$ are parameters with values determined empirically from the data. The value of $\mu$ is given as a quadratic function of the logarithm of frequency, with a maximum at about 0.17 Hz. The effect of stimulus duration is evaluated by a further cumulative normal distribution of the logarithm of time, with the same form as the equation given above. Values of $\mu$ and $\sigma$ for the duration equation were also obtained empirically, and all the values necessary are presented in the report by McCauley et al.

Estimates of vomiting incidence are not easily obtainable from the model described above because of the complicated mathematics involved. However, the equations have been evaluated using a computer and direct comparisons can thus be made between this model and the procedure proposed in this article. Figure 13 shows the predicted vomiting incidence for magnitudes of acceleration up to 2.5 m s$^{-2}$ for 60-min exposure at 0.2 Hz evaluated using both procedures. Figure 14 shows the predicted vomiting incidence for durations of exposure up to 6 h for 1 m s$^{-2}$ rms at 0.2 Hz. (The McCauley et al. prediction line is shown dotted above 120 min since no experimental exposures exceeded this duration.) Figure 15 shows the predicted vomiting incidence for frequencies of oscillation over the range 0.01–1 Hz for 60-min duration at 1 m s$^{-2}$ rms. (Data only exist, however, between 0.083–0.7 Hz.)

The graphs show overall agreement in predictions, and the disparities appear small when compared against the general scatter of the data upon which these procedures are based. While the McCauley et al. model is evidently a good mathematical description of their results, the equations used represent a precision which may be unwarranted for general use, where a simple calculation procedure has a distinct advantage.

IX. SYMPTOMS

The above descriptions of the experimental data and prediction procedure have used the terms "motion sickness," "seasickness," and "sickness incidence." Where any quantitative data are involved, all these terms are synonymous with vomiting incidence. It is this symptom of motion sickness that was used in the experimental studies, and the prediction procedure thus strictly predicts the percentage of people who will vomit at some time during the period of exposure to the motion. There are many other symptoms of motion sickness but these are less easy to define and measure. The Wesleyan University studies used an illness category defined as "nausea or profuse sweating" in addition to the two categories of vomiting and not vomiting. By scoring this intermediate category as half the score for vomiting, a sickness index was defined. The results showed similar variations to the vomiting data, with slightly decreased scatter, and it appeared that, for any group of people who vomited, about 50%–100% as many again exhibited nausea or profuse sweating.

The questionnaire used by Lawther and Griffin asked for a subjective rating of feelings of illness in four categories: "I felt all right"; "I felt slightly unwell"; "I felt quite ill"; and "I felt absolutely dreadful." Using a simple linear weighting of 0, 1, 2, and 3 for each category, respectively, and taking an overall weighted average, an illness rating scale was defined having a range of 0 (denoting everyone feeling "all right") to
3 (denoting everyone feeling “absolutely dreadful”). Testing of the scale versus the motion data revealed the weighting factors to be reasonable approximations (Lawther and Griffin, 1986). It was found that there were many people on ships who did not vomit but who, nevertheless, felt ill to some degree. The illness rating data generally gave slightly higher correlations with motion variables than vomiting incidence, although the two measures were naturally highly correlated with each other. Figure 16 shows a graph of illness rating against acceleration for the same motion data as the vomiting incidence graph in Fig. 4. Comparison of the two graphs yields the following approximations:

- Illness rating = 1.5 × a (for 2-h exposures),
- Illness rating = 0.05 × vomiting incidence,
- Illness rating = F × dose,

where F = 0.02. These expressions apply up to an illness rating of 1 and vomiting incidence greater than zero and up to about 30%. Predictions of subjective feelings of illness may thus be made from the rms acceleration, vomiting incidence, or the dose value.

**X. POPULATION VARIABLES**

The values of sickness incidence predicted by the procedure apply for populations and circumstances similar to those of the experimental data. The laboratory studies used fit young men enclosed in small cabins, and the field studies surveyed members of the public traveling as passengers on sea-going ferries. The resulting close agreement is encouraging.

There is some evidence of effects of population variables on sickness occurrence. It has been frequently reported that females are more susceptible than males, and this result was confirmed in the ship survey data, where the incidences of seasickness in males and females were significantly different, in the approximate ratio of 3:5, respectively. The sickness incidence among males on ships was thus slightly lower than would be predicted by the laboratory data. There is an effect of age, however, that shows a slight decrease in susceptibility with increasing age. It is possible that use of only young men in the laboratory studies produced higher sickness rates than would be expected from a more balanced age group.

Where the effects of population variables, such as sex and age, can be quantified, modified values of K could be used to estimate sickness susceptibility for specific populations. There is also some evidence that regular travelers by sea are less likely to become seasick, and there are possible other effects, such as the taking of antiseasickness tablets or alcohol, which could result in further modifications of the value of K to increase the accuracy of predictions for specific groups with known population variables.

**XI. CONCLUSIONS**

The comparison of experimental data from three separate series of studies of motion sickness caused by vertical oscillation has revealed a high degree of agreement. Examination of the effects of the principal motion variables has shown that they can be approximated by simple mathematical relationships that can then be combined into a general prediction procedure.

The data on the effects of different axes of motion suggest that, where there is sufficient vertical oscillation to cause sickness, additional motion in other axes need not necessarily be considered.

The effect of rms acceleration magnitude on sickness incidence has been approximated by a linear relationship over the range for which there are data. Using this linearity with magnitude to produce a normalized sickness index, the effect of oscillation frequency has been determined. The region of apparently greatest sensitivity to acceleration, from 0.1–0.25 Hz, and the sharp decline in sensitivity at high frequencies have been described by straight line approximations that can be used to produce a frequency weighting.

The effect of stimulus duration has been approximated by a formula using the square root of the duration, and a cumulative measure of motion dose has been defined. Sickness has been treated only as a cumulative variable, since adaptation and recovery are unlikely to occur within the durations considered. Predictions of sickness incidence for longer durations would need to take account of the effects of adaptation to the motion.

The prediction procedure involves calculation of the motion dose and multiplication by a factor K to obtain the prediction of vomiting incidence. The factor K may be adjusted for specific populations.

Vomiting incidence is a measure of the percentage of people who attain the usual end point of the motion sickness syndrome. There appears to be a large proportion of people who may suffer from seasickness to some degree but who may not actually reach the point of vomiting. A simple subjective well-being scale has been described, and its approximate relation to vomiting incidence given.

The aim of this article has been to produce a motion sickness prediction procedure that is easily applied to a specific range of environments. Approximations have been.
made for simplicity, and are justified by the amount of natural scatter in the data. The mathematical descriptions of the effects of the variables are not intended to reflect the underlying mechanisms that cause motion sickness, but are merely a pragmatic approach to a problem with a clearly defined scope. It is to be hoped that additional experimental data will enable the procedure to be extended so as to broaden its application. Such data may also provide an insight into the underlying mechanisms of motion sickness.


Hippocrates (5th Century, B.C.). Aphorisms 4 XIV.


