RESEARCH ARTICLE

Motion Sickness: Effect of the Magnitude of Roll and Pitch Oscillation

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Background: Rotational oscillation in roll and pitch can cause motion sickness, but it is not known how sickness depends on the magnitude of rotational oscillation or whether there is a difference between the two axes of motion. ***Hypothesis:*** It was hypothesized that motion sickness would increase similarly with increasing magnitudes of roll and pitch oscillation. ***Method:*** There were 120 subjects (6 groups of 20 subjects) who were exposed to 30 min of 0.2-Hz sinusoidal roll or pitch oscillation at 1 of 3 magnitudes: 1) ± 1.83°; 2) ± 3.66°; or 3) ± 7.32°. Subjects sitting in a closed cabin with their eyes open gave ratings of their illness on a 7-point illness rating scale at 1-min intervals. ***Results:*** Over the six conditions, mild nausea was reported by 17.5% of subjects. With both roll oscillation and pitch oscillation, mean illness ratings were least with ± 1.83° of rotational oscillation and greater with ± 3.66° and ± 7.32° of oscillation. At none of the three magnitudes of oscillation was there a significant difference in motion sickness caused by roll and pitch oscillation. ***Conclusions:*** With rotational oscillation about an Earth-horizontal axis, there is a trend for motion sickness to increase with increasing motion magnitude. For the conditions investigated, similar motion sickness was caused by roll and pitch oscillation.

Keywords: motion sickness, rotational oscillation, magnitude, axis, roll, pitch.

MOTION SICKNESS can be caused by oscillatory motion in any of the three translational axes [fore-and-aft (x-axis), lateral (y-axis), or vertical (z-axis)] and any of the three rotational axes [roll (r_x-axis), pitch (r_y-axis) and yaw (r_z-axis)]. People experience sickness when exposed to various combinations of these motions from braking, accelerating, and cornering in road vehicles (19) and trains (5) and when traveling in aircraft (20) and in ships (14). Although rotation about an Earth-horizontal axis (i.e., roll and pitch) has been shown to cause motion sickness, there have been few systematic studies of how the sickness depends on the characteristics of the motion (e.g., the magnitude, frequency, or axis of oscillation).

Roll oscillation through ± 8° (equivalent to 0.97 ms^{-2} r.m.s. when the magnitude of roll is represented by the lateral acceleration arising from the gravitational component, $g \cdot \sin\theta$, due to roll through an angle θ) at each of five frequencies (0.025, 0.05, 0.10, 0.20, and 0.40 Hz) has been found to produce low levels of motion sickness with no significant differences between the five frequencies (6). Pitch oscillation through ± 3.69° ($g \cdot \sin\theta = 0.45$ ms^{-2} r.m.s.) at 0.2 and 0.4 Hz has been reported to produce similar sickness at the two frequencies (2). Comparing these studies at 0.2 and 0.4 Hz, fewer subjects reached more severe illness ratings with ± 8° of roll oscillation than with ± 3.69° of pitch, suggesting either a different susceptibility to roll and pitch oscillation, or that sickness does not increase with increasing magnitude of rotational oscillation.

The sickness caused by fore-and-aft oscillation with the same acceleration at frequencies between 0.205 and 1.0 Hz decreases with increasing frequency of oscillation (e.g., 7,8). This is consistent with oscillations having the same peak velocity giving broadly similar illness ratings at frequencies between 0.2 to 0.8 Hz (10). The same study found that over this frequency range, fore-and-aft and lateral oscillation produced similar illness ratings. At lower frequencies, lateral oscillations with the same peak velocity (1.0 ms^{-1}) over the frequency range 0.0315 to 0.20 Hz resulted in greater motion sickness at the higher frequencies (4). This is consistent with oscillations having the same peak acceleration giving broadly similar illness ratings. It is also consistent with roll oscillations having the same angular displacement at frequencies from 0.025 to 0.4 Hz (and, therefore, the same equivalent lateral acceleration at each frequency) causing broadly similar sickness, as found by Howarth and Griffin (6).

With vertical oscillation at four frequencies (0.22, 0.27, 0.37, and 0.53 Hz), Alexander et al. (1) found that an increase in the magnitude of motion (from 1.96 to 6.38 ms^{-2}) did not always result in an increase in the incidence of vomiting. At each frequency, the lowest magnitudes produced the least vomiting and the highest magnitudes produced more vomiting, but the intermediate magnitudes produced the greatest

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vomiting. However, other studies have found that at frequencies between 0.083 and 0.7 Hz an increase in the magnitude of oscillation (from 0.278 to 5.55 ms^{-2} r.m.s.) increased the vomiting incidence (16,18). With fore-and-aft and lateral oscillation at 0.315 Hz, increasing the magnitude of oscillation (0.28, 0.56, 0.70, 0.89, and 1.11 ms^{-2} r.m.s.) tends to increase motion sickness (11).

The vomiting incidence reported by Alexander et al. (1), McCauley et al. (16), and Lawther and Griffin (12) were used to calculate a frequency weighting for vertical oscillation by Lawther and Griffin (13) and was defined in British Standard 6841 (3) as W_f. The frequency weighting suggests a +6 dB per octave increase in sensitivity with increasing frequency from 0.1 to 0.125 Hz, equal sensitivity to acceleration between 0.125 and 0.25 Hz, and 12 dB per octave decrease in sensitivity with increasing frequency from 0.25 to 0.5 Hz.

The sickness caused by various combinations of vertical, roll, and pitch oscillation was investigated by McCauley et al. (16). The percentage of subjects vomiting from exposure to pure roll oscillation (33.3° · s^{-2} r.m.s. at 0.345 Hz) (0%) was not significantly different from the percentage vomiting from exposure to pure pitch oscillation at the same frequency and magnitude (9%). Pure vertical oscillation (0.11 ms^{-2} r.m.s. at 0.245 Hz) caused 31% to vomit—the same percentage who vomited when this vertical oscillation was combined with roll oscillation (with accelerations between 5.51 and 33.3° · s^{-2} at frequencies between 0.115 and 0.345 Hz), and almost the same as the 34% who vomited with this vertical oscillation combined with pitch oscillation at the same frequencies and magnitudes as the roll oscillation. It was concluded that vertical oscillation was the main cause of vomiting at sea.

Although the vomiting of passengers on ships has been found to correlate best with vertical (z-axis) acceleration, motion in other axes, especially lateral (y-axis) and roll (r_x-axis) may contribute to motion sickness (12). It has been reported that in subjects exposed to vertical oscillation, or roll oscillation, or combined roll and pitch oscillation, the pitch and roll oscillation generated little sickness, but when combined with vertical oscillation (even a vertical motion that produced little or no illness itself), there was greater motion sickness (21). It was suggested that the effects of roll and pitch oscillation may be masked when combined with high magnitude vertical oscillation, but they have a pronounced effect when combined with low magnitude vertical oscillation.

Although previous studies imply that roll and pitch oscillation may sometimes contribute to motion sickness, understanding of their contribution is limited by uncertainty over the effects of the magnitude and axis of these motions when presented alone. The present study was designed to investigate the effect on motion sickness of the magnitude of 0.2 Hz roll and pitch oscillation and to compare the sickness caused by roll and pitch oscillation at each magnitude. It was hypothesized that motion sickness would increase with increasing magnitude of roll and pitch oscillation and there would be no difference in illness ratings between roll and pitch oscillation at each magnitude.

METHOD

Apparatus

Oscillation of a cabin was produced using a simulator capable of ± 10° of roll or pitch. The motions were generated and monitored using an HVLab data acquisition and analysis system (version 3.81, Institute of Sound and Vibration Research, University of Southampton, Southampton, UK). An inductive accelerometer (± 12 g, 503 AD/32; S/N: AE 2653/77; Smith Industries, UK) was mounted inside the cabin at the center of rotation (at the seat surface) to measure the acceleration (i.e., the gravitational component due to roll or pitch). The accelerometer signals were recorded to confirm that each subject was exposed to the correct rotational acceleration.

Exposure Conditions

Subjects were exposed to 0.2-Hz roll or pitch oscillation at one of three magnitudes: 1) ± 1.83°, 2) ± 3.66°, or 3) ± 7.32°. The motion parameters are shown in **Table I**. Each 30-min exposure to motion was preceded by a 5-min pre-exposure period and followed by a 15-min recovery period. The beginning and end of each motion was tapered over a period of 2.5 cycles so there was a smooth transition when starting and stopping the motion.

Environment

Subjects sat in the closed wooden cabin (2.2 m high × 1.0 m wide × 1.0 m deep) to reduce cues to movement, such as air movement, light, and sound. They sat on a rigid seat 445 mm above the platform of the simulator such that the center of rotation was at the center of the seat surface between their ischial tuberosities. A high flat rigid vertical backrest extended 540 mm above the seat surface. The seat was rotated through an angle of 90° to obtain exposure to either roll or pitch oscillation. A loose lap belt was worn for safety reasons. Subjects wore headphones producing white noise at 85 dB(A), measured using a Knowles Electronics Mannequin for Acoustics Research (Knowles Electronics, Rolling Meadows, IL), to mask the noise of the simulator. The experimenter communicated with subjects via a

TABLE I. ROLL AND PITCH OSCILLATION PARAMETERS.

Condition ($axis_{magnitude}$)	Magnitude (degrees)	Peak velocity (degrees/second)	Gravitational acceleration at seat surface (ms^{-2})
$roll_{1.83}$	± 1.83	± 2.30	± 0.31
$roll_{3.66}$	± 3.66	± 4.60	± 0.63
$roll_{7.32}$	± 7.32	± 9.20	± 1.26
$pitch_{1.83}$	± 1.83	± 2.30	± 0.31
$pitch_{3.66}$	± 3.66	± 4.60	± 0.63
$pitch_{7.32}$	± 7.32	± 9.20	± 1.26

microphone which interrupted the white noise input to the headphones.

Subjects were told to adopt relaxed upright postures with their hands on their laps and feet separated flat on the floor with their backs in contact with the backrest. They were told to look straight ahead at all times. Subjects were under continual observation by means of closed circuit television, allowing the experimenter to check that they maintained the correct posture and kept their eyes open at all times. A fractal image (0.4 × 0.3 m) was positioned in front of subjects at approximately eye level on the internal wall of the cabin at a distance of 0.7 m.

Subjects

There were 120 fit and healthy men between the ages of 18 and 28 yr (mean age: 21.7 yr, SD: ± 3.0 yr; mean stature: 180 cm, SD: ± 7.0 cm) who participated in the experiment. Subjects were selected from the staff and student population of the University of Southampton. Prior to their first session, each subject completed a motion sickness susceptibility questionnaire (9) and a health screening questionnaire, and their height, weight, and visual acuity were determined. Visual acuity was measured with the Keystone Visual Skills Profile (Keystone View, Davenport, IA) using the Landolt C (broken ring) test. Subject near vision (at 0.41 m) and far vision (at 6 m) was determined as the last line correctly completed (e.g., completion of the last line on both cards would give a score of 20/15).

Subjects were allocated by the experimenter to 1 of 6 groups (corresponding to the 6 experimental conditions) with 20 in each group. The allocation of subjects to roll and pitch oscillation occurred with the first 30 subjects exposed to roll oscillation, the next 30 exposed to pitch oscillation, the next 30 to roll oscillation, and the last 30 to pitch oscillation. Subjects were exposed to a magnitude predetermined by cycling through the three magnitudes (i.e., 1.83°, 3.66°, 7.32°, 1.83°, 3.66°, 7.32°…).

Subjects gave their informed consent to participate in the experiment and were free to withdraw at anytime. The experiment was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton.

Illness Rating Scale

Illness was monitored from 5 min before the start of the motion until 15 min after the motion had ceased (i.e., over a period of 50 min). Subjects gave ratings of their illness every minute using a seven-point illness scale: 0 = no symptoms, 1 = any symptoms however slight; 2 = mild symptoms; 3 = mild nausea; 4 = mild to moderate nausea; 5 = moderate nausea but can continue; 6 = moderate nausea and want to stop (9).

Symptoms

Following exposure to motion, subjects completed a symptom checklist indicating which of the 10 common symptoms of motion sickness they had experienced during the exposure. The symptoms on the checklist were: yawning, increased salivation, stomach awareness, bodily warmth, headache, nausea, dry mouth, cold sweating, dizziness, and drowsiness. Each symptom was weighted equally and given a value of 1 when present. The total number of symptoms reported were added together to give a 'total symptom score' for each subject [up to a maximum score of 10 (9)].

Statistical Methods

Nonparametric statistics were used to analyze the data. The Kruskal-Wallis test was used to investigate differences between more than two independent groups of subjects; the Mann-Whitney *U*-test was used to find differences between two independent groups of subjects. Spearman's rho was used to investigate correlations between variables. Data analysis was carried out using SPSS (version 14.0, SPSS, Chicago, IL). Results are reported as significant when $P < 0.05$, marginally significant when $0.05 < P < 0.1$, and not significant when $P > 0.1$.

RESULTS

Subject susceptibility to motion sickness reported in the motion sickness susceptibility questionnaire administered prior to motion exposure showed no significant differences in the six measures of motion sickness susceptibility: $I_{susc(yr)}$ ($\chi^2 = 1.381$, $P = 0.926$); $V_{susc(yr)}$ ($\chi^2 = 2.414$, $P = 0.789$); V_{total} ($\chi^2 = 5.985$, $P = 0.308$); M_{total} ($\chi^2 = 1.688$, $P = 0.890$); M_{land} ($\chi^2 = 3.031$, $P = 0.695$); and $M_{nonland}$ ($\chi^2 = 0.489$, $P = 0.993$). Over the 120 subjects, the median values of total susceptibility to motion sickness (M_{total}), susceptibility to motion sickness in land transport (M_{land}), and susceptibility to motion sickness in nonland transport ($M_{nonland}$) were 8.5, 5.5, and 1, respectively. For illness susceptibility in transport in the last year [$I_{susc(yr)}$], vomiting susceptibility in transport in the past year [$V_{susc(yr)}$] and total susceptibility to vomiting (V_{total}), the median values were 0.04, 0, and 0, respectively. These values are usual for this subject group [see Griffin and Howarth (9) for median values of a similar subject group].

The illness ratings reported by subjects over the six 30-min periods of motion exposure (from minute 5 to minute 35) were integrated to give 'accumulated illness ratings'. For the entire group of 120 subjects, there were significant positive correlations between accumulated illness ratings over the 30-min exposures to motion and M_{total} ($r_s = 0.482$, $P < 0.001$; Spearman), M_{land} ($r_s = 0.409$, $P < 0.001$), $M_{nonland}$ ($r_s = 0.458$, $P < 0.001$), and $I_{susc(yr)}$ ($r_s = 0.345$, $P < 0.001$). When the 6 groups of 20 subjects were analyzed separately, accumulated illness ratings arising from $pitch_{1.83}$, $pitch_{7.32}$, $roll_{1.83}$, and $roll_{7.32}$ were significantly correlated with $M_{total,}$ M_{land}, and $M_{nonland}$ ($r_s \geq 0.626$; $P \geq 0.047$; Spearman); ratings arising from $pitch_{3.66}$ were significantly correlated with M_{land} and $M_{nonland}$ ($r_s \geq 0.516$; $P \geq 0.039$; Spearman); and ratings from both $roll_{3.66}$ and $roll_{7.32}$ were significantly correlated with $I_{susc(yr)}$ ($r_s \geq 0.532$; $P \geq 0.016$; Spearman).

For each minute of the 50-min sessions, mean illness ratings were calculated over the 20 subjects exposed to the 3 magnitudes of roll oscillation and the 3 magnitudes of pitch oscillation (**Fig. 1**). Individual mean illness ratings reported during motion exposure (from minute 5 to minute 35) and total symptom scores reported following motion exposure are shown for the six conditions in **Fig. 2**.

The percentages of subjects to reach each illness rating in each of the six conditions are shown in **Fig. 3**. Over the 3 magnitudes of pitch, 13% (i.e., 8/60) of subjects did not report any illness at any time (i.e., reported 0 = no symptoms) over the 50-min session. Over the 3 magnitudes of roll, 22% (i.e., 13/60) of subjects did not report illness at any time. An illness rating of 3 (mild nausea) was reported by 18% of subjects with pitch oscillation and 23% of subjects with roll oscillation. No subjects terminated the experiment early by reporting an illness rating of 6 (moderate nausea and want to stop) with either roll or pitch oscillation.

There were marginally non-significant differences in mean illness ratings between the three magnitudes of roll oscillation ($\chi^2 = 5.480$, $P = 0.065$; Kruskal-Wallis) and between the three magnitudes of pitch oscillation ($\chi^2 = 4.721$, $P = 0.094$; Kruskal-Wallis). With roll oscillation, there was a significant difference in mean illness ratings between ± 1.83° and ± 3.66° (Mann-Whitney U = 124.500, $P = 0.040$) and between ± 1.83° and ± 7.32° (Mann-Whitney U = 128.000, $P = 0.050$). With pitch oscillation, there was a significant difference in mean illness ratings between ± 1.83° and ± 7.32° (Mann-Whitney U = 117.500, $P = 0.025$). The mean illness ratings caused by roll and pitch oscillation were not significantly different at any of the three magnitudes of oscillation (Mann-Whitney U = 174.500, $P = 0.487$; Mann-Whitney U = 192.500, $P = 0.839$; Mann-Whitney U = 176.000, $P = 0.515$ for ± 1.83°, ± 3.66°, and ± 7.32°, respectively).

Subjects gave illness ratings for 15 min after the motion had ceased (i.e., from 35 to 50 min—the recovery period). During this time, in all six conditions, illness ratings decreased for all subjects who reported symptoms. **Fig. 4** shows the mean illness ratings reported by subjects during recovery from each illness rating over the six motion conditions. Subjects reporting higher illness ratings during the motion exposure took longer to recover from their symptoms than those who reported lower illness ratings.

Average illness ratings during the recovery period for each condition were $pitch_{1.83} = 0.34$; $pitch_{3.66} = 0.74$; $pitch_{7.32} = 0.36$; $roll_{1.83} = 0.3$; $roll_{3.66} = 0.62$; and $roll_{7.32} = 0.6$. There were no significant differences in the average illness ratings during the recovery period between the three magnitudes of pitch ($\chi^2 = 0.649$, $P = 0.723$; Kruskal-Wallis) or between the three magnitudes of roll ($\chi^2 = 3.006$, $P = 0.223$; Kruskal-Wallis).

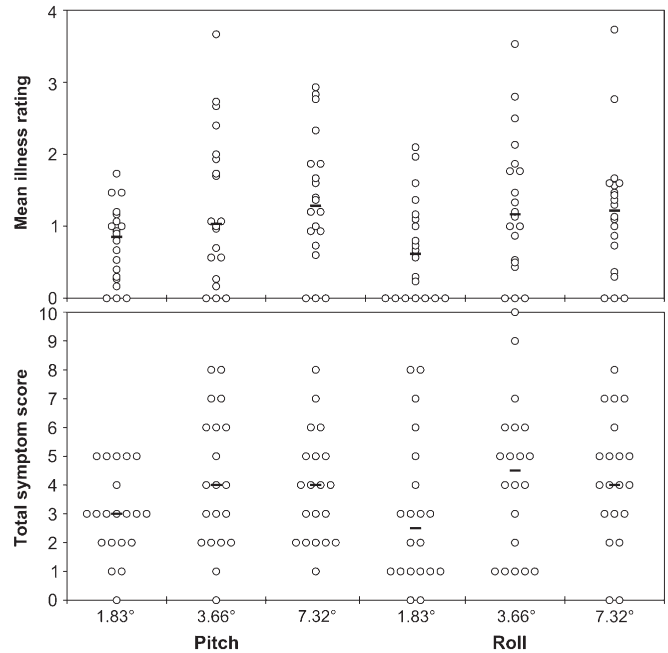

Fig. 2. Mean illness ratings reported by each subject during motion exposure (from minute 5 to minute 35) and total symptom scores reported by each subject following motion exposure over the six conditions. Each circle represents 1 subject; each line marker shows the median over the 20 subjects in each condition.

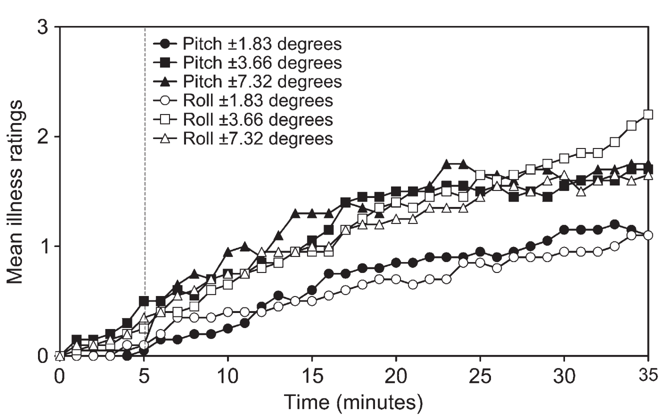

Fig. 1. Mean illness ratings reported by the subjects at each minute during the six conditions (with exposure to motion between 5 and 35 min).

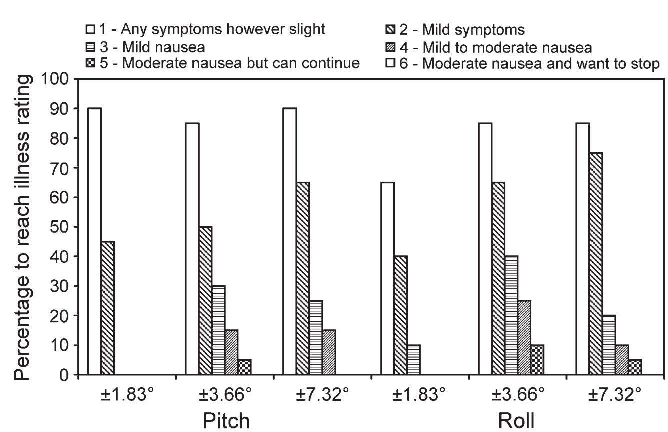

Fig. 3. Percentage of subjects to reach each illness rating during exposure to pitch oscillation and roll oscillation.

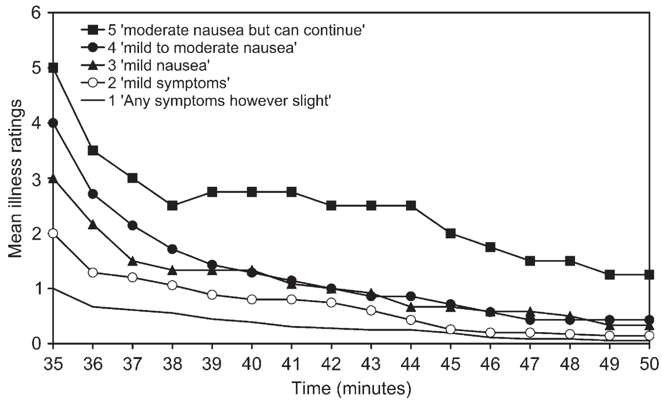

Fig. 4. Mean illness ratings reported by subjects during recovery from each illness rating over the six motion conditions.

The numbers of subjects who reported an illness rating of 0 at the end of the recovery period (at minute 50) were: $pitch_{1.83} = 18$; $pitch_{3.66} = 13$; $pitch_{7.32} = 19$; $roll_{1.83} = 20$; $roll_{3.66} = 16$; and $roll_{7.32} = 17$. Of the 17 subjects who reported a rating of 1 or greater at the end of the recovery, 10 had been exposed to pitch oscillation (2, 7, and 1 for $pitch_{1.83}$, $pitch_{3.66}$, and $pitch_{7.32}$, respectively) and 7 had been exposed to roll oscillation (0, 4, and 3 for conditions $roll_{1.83}$, $roll_{3.66}$, and $roll_{7.32}$, respectively). The highest illness rating at the end of the recovery period was 2 (mild symptoms), reported by two subjects: one after $roll_{3.66}$ and one after $pitch_{7.32}$.

Total symptom scores (i.e., the total number of symptoms reported by subjects after exposure to motion) were 60 after $pitch_{1.83}$; 83 after $pitch_{3.66}$; 78 after $pitch_{7.32}$; 60 after $roll_{1.83}$; 86 after $roll_{3.66}$; and 84 after $roll_{7.32}$. There were no significant differences in the total number of symptoms reported by subjects between the three conditions of roll ($\chi^2 = 3.751$, $P = 0.153$; Kruskal-Wallis) or three conditions of pitch ($\chi^2 = 2.804$, $P = 0.246$; Kruskal-Wallis). Within each of the six conditions, there was a significant positive correlation between the total number of symptoms reported by subjects and their mean illness ratings over the 30 min of oscillation ($r_s \leq 0.874$, $P < 0.001$; Spearman).

DISCUSSION

The greatest magnitude of oscillation at 0.2 Hz used in this study (± 7.32°) is similar to the ± 8° of roll previously studied at 0.025, 0.05, 0.10, 0.20, and 0.40 Hz (6). Mean illness ratings reported after 30 min of motion exposure were 1.65 with 0.2-Hz roll oscillation at ± 7.32° (current study), and 1.1 with 0.2-Hz roll oscillation at ± 8° (6). No subjects terminated the experiment by reporting illness rating 6 in this study; only one subject terminated the experiment in the study by Howarth and Griffin after 28 min of exposure to 0.2-Hz roll oscillation at ± 8°. In both studies, a low level of sickness was found even though this angle of roll approaches the limit for seated subjects being able to retain themselves in a seated position without making undue effort (22). This confirms previous observations that, when presented alone, neither roll nor pitch oscillation are highly nauseogenic.

Mean illness ratings reported by subjects were least with a magnitude of ± 1.83° and greater at ± 3.66° and ± 7.32° for both pitch and roll oscillation. However, while there were significant differences between the lowest and highest magnitudes of roll and pitch oscillation, there was no increase in sickness when the magnitude of roll or pitch increased from ± 3.66° to ± 7.32°. This suggests either the mechanisms involved in the causation of sickness are nonlinear or that subjects developed a voluntary or involuntary response that, to some extent, became protective at the higher magnitudes.

Similar to the present study of illness caused by roll and pitch oscillation, Alexander et al. (1) found that with vertical oscillations, an increase in the magnitude of motion did not always increase the incidence of vomiting. Several other studies involving vertical oscillation have found increased sickness with increased magnitudes of oscillation. At frequencies between 0.083 and 0.7 Hz, greater magnitudes of vertical oscillation increase the incidence of vomiting (16). Studies in ships also show increased sickness when passengers are exposed to greater motions (e.g., 12,15). The results of these studies were used to develop the 'motion sickness dose value', in which the vomiting incidence increases in proportion to the magnitude of vertical oscillation.

Experimental evidence of increased sickness with increased magnitudes of non-vertical oscillation is less clear. Both lateral and fore-and-aft oscillations at 0.315 Hz tend to produce greater illness ratings with greater magnitudes of oscillation (11). However, the evidence (as shown in **Fig. 5**) is not overwhelming. With fore-and-aft oscillation there was an increase in mean illness ratings from 0.28 ms^{-2} to 0.89 ms^{-2} r.m.s. and a decrease in mean illness ratings from 0.89 ms^{-2} to 1.11 ms^{-2} r.m.s. With lateral oscillation there was an increase in mean illness ratings as the magnitude increased from 0.28 ms^{-2}

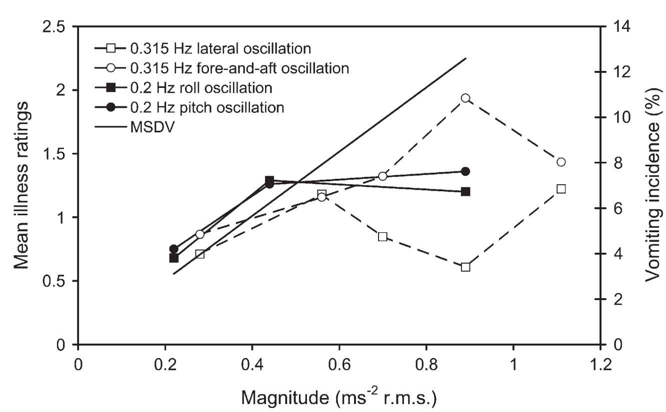

Fig. 5. Mean illness ratings reported by subjects during roll and pitch oscillation at 0.2 Hz (current study, where the magnitude of roll and pitch is given by the gravitational acceleration at the seat – g · Sinθ, as shown in Table I) and during lateral and fore-and-aft oscillation at 0.315 Hz (10,11). The motion sickness dose value shows the predicted vomiting incidence for 30-min exposures to 0.2-Hz vertical oscillation after a period of 30 min.

to 0.56 ms^{-2} r.m.s., but there was a decrease from 0.56 ms^{-2} to 0.89 ms^{-2} r.m.s. and an increase from 0.89 ms^{-2} to 1.11 ms^{-2} r.m.s.

The mean illness ratings obtained in the present study with 0.2-Hz roll and pitch oscillation with a high backrest (but no headrest) are compared with those obtained by Griffin and Mills (11) with 0.315-Hz fore-and-aft and lateral oscillation with a low backrest in Fig. 5. The comparison assumes that the roll and pitch oscillation can be represented by the acceleration arising from the gravitational component ($g \cdot \sin\theta$). There are broadly similar mean illness ratings for all four conditions. Fig. 5 also shows the percentage of vomiting incidence predicted by the motion sickness dose value for 30-min exposures to vertical oscillation. The absence of any subject reaching rating 6 in the current study suggests that roll and pitch oscillation causes less sickness than an equivalent magnitude of vertical oscillation.

There were no significant differences in either illness ratings or symptoms between pitch and roll oscillation at any of the three magnitudes investigated. This is consistent with no significant difference in the vomiting incidence caused by roll and pitch 0.345-Hz oscillation at $33.3° \cdot s^{-2}$ r.m.s. (16). It is also consistent with similar illness ratings produced by fore-and-aft and lateral oscillation in studies of the effects of oscillation magnitude (11) and oscillation frequency (10).

Responses to the motion sickness susceptibility questionnaire showed that the variables M_{total}, $I_{susc(yr)}$, M_{land}, and $M_{nonland}$ were positively correlated with illness ratings reported during motion exposure. M_{total} was determined by subjects ever experiencing each of eight symptoms (feel hot or sweaty, headaches, change of skin color, mouth watering, drowsy, dizzy, nausea, vomiting) for each mode of transport (car, bus, coach, train, small boat, ship, and airplane), for avoidance of each mode of transport, and for self-rated susceptibility to motion sickness. M_{total} was divided into two categories: susceptibility to motion sickness in land transport (M_{land}) and susceptibility to motion sickness in nonland transport ($M_{nonland}$). Illness susceptibility in transport in the past year [$I_{susc(yr)}$] was the illness frequency in the past year for each mode of transport, taking into account the frequency of travel in each form of transport. The positive correlations found between M_{total}, $I_{susc(yr)}$, M_{land}, and $M_{nonland}$ show that subjects' past experiences of motion sickness in transport were associated with the sickness experienced when exposed to the motions in this study. The correlations also suggest that the symptoms caused by the rotational oscillations in this study were in some way relevant to those caused by both land transport and nonland transport. Although the correlations between the illness ratings in the experiment and the measures of susceptibility provided before the experiment were statistically significant, the variability in the illness ratings cannot be explained by these measures of susceptibility alone.

The results of the present and previous studies suggest that although the probability of motion sickness and the severity of symptoms tend to increase with increasing magnitudes of oscillation, the increase is not always evident or strong. This could reflect the characteristics of the complex processes involved in the development of sickness or it could reflect the development of protective strategies people employ when motion becomes more severe. Most studies of sickness in transport and in laboratories have employed conditions in which subjects have some control of their postures (e.g., movement of their upper body and orientation of their head) and so they may be able to modify their responses by adjusting their posture. The presence of a backrest has been found to be sufficient to reduce sickness (17), so it would not be surprising if, when the magnitude of motion begins to cause discomfort or sickness, subjects try to reduce discomfort or sickness by adjusting their posture. It is likely to be easier to move with or move against fore-and-aft, lateral, roll, and pitch oscillation than vertical oscillation. It may, therefore, be appropriate to apply greater control of posture, or to monitor posture and body movements in studies of motion sickness caused by oscillatory motion.

Conclusions

Motion sickness caused by 0.2-Hz roll and pitch oscillation is dependant on the magnitude of the motion, with a trend for illness ratings to increase with increasing magnitude. The lowest magnitude of both roll and pitch oscillation caused the least sickness and the intermediate and higher magnitudes caused greater sickness. There were no significant differences in either illness ratings or symptoms caused by pitch and roll oscillation at the magnitudes studied.

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