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Motion sickness caused by roll-compensated lateral acceleration: effects of centre-of-rotation and subject demographics.

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Abstract

The combination of low frequency lateral and roll motion experienced in tilting trains can provoke motion sickness. The incidence of sickness depends on vehicle design and subject demographics. Vehicle design affects the location of the centre-of-roll, which influences passenger perception of motion. Age and gender have large influences on susceptibility to sickness, but little is known about the effects of ethnicity and body size. This study investigated the influences of both the vertical position of the centre-of-roll and subject characteristics (ethnicity, weight, stature, and sickness susceptibility) on sickness caused by fully roll-compensated lateral oscillation. It was hypothesised that sickness would be greater when full compensation occurred at the head than when full compensation occurred at the seat. Sixty subjects experienced 0.2-Hz lateral oscillation combined with ±7.3 degrees of roll, so that the lateral acceleration was fully compensated at either the seat surface or 800 mm above the seat (i.e., average head height). Illness ratings and symptom scores were recorded every minute for 50 minutes (i.e., during a 5-minute acclimatisation period, a 30-minute exposure period, and a 15-minute recovery period). Although the mean illness ratings were greater when full compensation occurred at the head than at the seat, the difference was not statistically significant. Weight and stature were not associated with motion sickness, but illness ratings were much greater in Asian subjects than in European subjects. It is concluded that differences in susceptibility between Asians and Europeans have a greater effect on motion sickness than the height of the centre-of-rotation during roll-compensated lateral acceleration.

Keywords: motion sickness, tilting trains, low frequency motion, centre of rotation, ethnicity

1. INTRODUCTION

Motion sickness is characterised by an unpleasant combination of symptoms, including pallor, sweating, nausea and vomiting [1]. Symptoms may be caused by translational or rotational motion of the body, or by visual stimulation with no motion of the body [2].

Passengers in tilting trains and some other forms of transport experience motions that can provoke motion sickness. When travelling at speed and turning to the left or right, the resultant lateral forces can be reduced by 'tilting into the turn'. When traversing a curve in a tilting train, this is known as 'compensation', because the gravitation force arising from a roll to the left 'compensates' for a lateral centripetal force to the right, and vice versa.

Whilst the incidence of motion sickness on non-tilting trains may be low [e.g. 3, 4], reports of sickness on high-speed tilting vehicles suggest tilt compensation increases motion sickness [e.g., 4, 5, 6, 7, 8, 9]. On the Swedish X2000 tilting train, 14.5% of passengers reported sickness with 70% tilt-compensation, but there was less sickness with 55% compensation [6]. Lateral motions in the frequency range 0.25 to 0.32 Hz have been reported to be particularly provocative of sickness [9]. In Japanese passively-tilted high curve speed rail vehicles, where horizontal acceleration is greatest at frequencies less than 1 Hz, nausea was reported by 26% of passengers compared to 4% of passengers in non-tilting vehicles where acceleration is greatest at frequencies higher than 1 Hz [4]. Laboratory studies have found that fully roll-compensated lateral oscillation (i.e., 100% tilt compensation) is more provocative of motion sickness than lateral oscillation presented without the compensation, with some evidence of greatest sensitivity to acceleration around 0.2 Hz [10].

The sensory rearrangement theory states that motion sickness arises from conflict between, or within, the visual and vestibular systems [11]. Intra-sensory conflict within the vestibular system (arising from an unusual combination of stimulation of the otoliths and the semi-circular canals) will occur with combined lateral and roll motion of the head. Without lateral acceleration, roll movements of the head stimulate both the semi-circular canals and the otoliths in a way normally interpreted as head rotation. With lateral acceleration, if the head rolls so as to 'fully compensate' for the lateral acceleration, the semi-circular canals will respond to the roll without the normally expected otolithic response (because the gravitational component arising from the roll offsets the component arising from the lateral acceleration). This allows two alternative, and conflicting, interpretations of the motion based either on the response from the semi-circular canals (i.e. roll motion) or the response from the otoliths (i.e. no roll).

Previous research has investigated how motion sickness depends on the frequency, the magnitude, and the phase of combined lateral and roll oscillation when full compensation occurs at the seat surface [10, 12, 13]. In those studies, the roll motions were selected to produce the gravitational forces required to compensate the lateral acceleration at the seat, and they were therefore not of the magnitude required to compensate the lateral acceleration at the head, resulting in some otolithic stimulation even in ‘fully compensated’ conditions. The ‘centre-of-rotation’ may be defined as the position at which full-compensation occurs, but no previous experiment has investigated the motion sickness associated with roll-compensated lateral oscillation with a centre-of-rotation at head height. Passively-tilted trains tend to have a higher centre-of-rotation than actively-tilted trains [14], and it has been suggested that there is a greater incidence of sickness with passive tilting [8]. It is therefore of practical importance to understand the extent to which the centre-of-rotation influences motion sickness.

Factors that influence the motion sickness susceptibility of passengers have been investigated in various forms of transport [15, 16, 17, 18]. Females have been found more susceptible to motion sickness than males among 20,029 passengers on ships [16], 3,256 road coach passengers [17], and 923 aircraft passengers [18]. A pattern of decreasing susceptibility with increasing age has also been reported [16, 17].

The motion sickness caused by roll-compensated lateral oscillation is dependent on the frequency, the magnitude, and the duration of the motion, the characteristics of passengers, and the transport environment, but there is currently insufficient understanding to develop a predictive model showing the influence of all of these factors on motion sickness. One aim of the experiment reported here was to determine whether the sickness caused by roll-compensated lateral oscillation differed when full compensation was achieved at the seat surface or at the head, in order to establish whether this aspect of the design of tilting trains (i.e. the height of the ‘centre-of-rotation’), influences the motion sickness of rail passengers. It was hypothesised that sickness would be greater when full compensation occurred at the head than when full compensation occurred at the seat. The study was also designed to investigate whether three passenger characteristics that have rarely been considered (ethnic origin, stature, and body weight) influence susceptibility to motion sickness.

2. METHOD

2.1 Apparatus

Motions were produced using a simulator capable of 12 metres of lateral oscillation and up to 10 degrees of roll oscillation in the Human Factors Research Unit of the Institute of Sound and Vibration Research at the University of Southampton.

Subjects sat on a first-class train seat inside a closed simulator cabin (2.0 m high x 1.9 m wide x 1.3 m deep) with no external view. Subjects sat blindfolded in relaxed upright postures with the backrest and headrest supporting their upper-body, their hands on their laps, and feet flat on the floor. A loose lap belt was worn for safety.

Subjects wore headphones producing white noise at 65 dB(A) to mask noises of the simulator. The experimenter communicated with subjects via the headphones by interrupting the white noise. Subjects were monitored via a video camera.

2.2 Motion conditions

Two motion conditions were investigated using an independent samples (within-subjects) design. In one condition, combined lateral and roll oscillation provided full roll-compensation at the seat surface (i.e. ‘seat compensation’). In the other condition, with very similar motions, full roll- compensation occurred at head height (i.e. ‘head compensation’). The position at which there was full roll-compensation (i.e. where there is zero lateral acceleration) was defined as the ‘centre-of-rotation’.

Subjects were exposed to 0.2-Hz sinusoidal roll oscillation combined in-phase with 0.2-Hz sinusoidal lateral oscillation. When full roll-compensation was at the seat, ±7.3 degrees of roll was combined with ±1.26 ms^{-2} of lateral oscillation (i.e., the same motions employed in some previous research [10]). When full roll-compensation was at the head, ±7.3 degrees of roll was combined with ±1.41 ms^{-2} of lateral oscillation. The head was assumed to be located 800 mm above the seat surface (the median sitting eye height for British men aged 19 to 45 years is 795 mm [19]). The motions were measured throughout all exposures and found to be accurate to within 5%. The motions at the seat and at the head are shown in Table 1.

TABLE 1 ABOUT HERE

2.3 Subjects

The subjects were 60 healthy male staff and students of the University of Southampton aged between 18 and 30 years (median = 24.0, inter-quartile range, IQR = 3.0), with weights between 50 and 160 kg (median = 70.0, IQR = 14.9) and statures between 163 and 198 cm (median = 175.0, IQR = 9.8).

Subjects were assigned alternately to one of the two experimental conditions (i.e., 'seat compensation' or 'head compensation'), resulting in 30 subjects per condition. Subjects were seated in the cabin for 50 minutes, including a 5-minute acclimatisation period, a 30-minute motion period, and a 15-minute recovery period. Subjects were tested one-at-a-time and experimental sessions lasted approximately one hour.

The study was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton.

2.4 Measurement of motion sickness

The experiment utilised a 16-part motion sickness susceptibility questionnaire (MSSQ), a 7-point illness rating scale ranging from 0 ('no symptoms') to 6 ('moderate nausea and want to stop') and a symptom checklist identifying 10 common motion sickness symptoms (i.e., yawning, increased salivation, stomach awareness, bodily warmth, headache, nausea, dry mouth, cold sweating, dizziness and drowsiness) [20]. The MSSQ was completed prior to motion exposure. Subjects then entered the simulator cabin and illness ratings were recorded every minute from 5 minutes before motion started, during the 30 minutes of motion exposure, and during a 15-minute period after motion had ceased. If an illness rating of 1 ('any symptoms, however slight') or higher was given, subjects were asked to indicate the symptoms they were experiencing using the symptom checklist.

If subjects reported an illness rating of 6 before the end of the motion exposure, the motion was stopped, and a rating of 6 was assumed for the remaining motion period. The recovery period was defined as the 15-minute period commencing immediately after the cessation of motion: either after 35 minutes or after a subject reached an illness rating of 6.

At the end of the experiment, subjects completed a symptom checklist indicating which of the 10 symptoms, if any, they had experienced whilst in the cabin.

3. RESULTS

3.1 Effect of position of the centre-of-rotation

3.1.1 Population demographics

Responses to the motion sickness susceptibility questionnaire indicated that 'total susceptibility to motion sickness', M_{total} (median = 8.0, IQR = 8.8) for the sample of 60 subjects was similar to the 'normal' population [20]. Between the two motion conditions, there were no significant differences in subject age, stature, weight, or motion sickness susceptibility ($p > 0.30$; Mann-Whitney U).

3.1.2 Illness ratings

In both conditions, illness ratings increased over the 30-minute motion exposures and decreased during the 15-minute post-motion period (Figure 1). Over the 30-minute exposures, mean illness ratings were greater with 'head compensation' (mean, *M* = 2.80, standard deviation, *SD* = 1.83) than with 'seat compensation' (*M* = 2.26, *SD* = 1.61), but the difference was not statistically significant (p = 0.23; Mann-Whitney U). Maximum illness ratings (i.e., the highest rating reported during motion) were also greater with head compensation (*M* = 3.90, *SD* = 1.92) than with seat compensation (*M* = 3.57, SD = 1.91), but the difference was also not statistically significant (p = 0.51; Mann-Whitney U). Similarly, more subjects reached the higher illness ratings with head compensation (Figure 2).

FIGURES 1 AND 2 ABOUT HERE

3.1.3 Symptom scores.

The total number of symptoms reported by each subject at the end of the study was taken as their 'total symptom score' (with a maximum of 10). The mean total symptom scores for the two conditions were similar (*M* = 5.00 and 5.03) and not significantly different (p = 0.93; Mann-Whitney U). 'Nausea' was reported by 77% of subjects experiencing 'head compensation' and by 67% of subjects experiencing 'seat compensation', with the difference not statistically significant (p = 0.39; Mann-Whitney U).

The total number of symptoms reported by each subject every minute over the duration of their motion exposure, divided by the duration of their exposure, was taken as their 'normalised cumulative total symptom score'. This measure compensates for a subject terminating exposure before the end of the planned 30-minute period. The 'normalised cumulative total symptom scores' were not significantly different between 'head compensation' (*M* = 1.72, *SD* = 1.07) and 'seat compensation' (*M* = 1.40, *SD* = 0.69, p = 0.28; Mann-Whitney U).

3.1.4 Recovery

A total of 17 subjects reported an illness rating of 6 (‘moderate nausea and want to stop’) before the end of the 30-minute exposure to motion. Eight of these experienced ‘seat compensation’ and nine experienced ‘head compensation’.

The mean illness ratings at the end of the motion period were 3.00 for ‘seat compensation’ and 3.60 for ‘head compensation’, but not significantly different (p = 0.31; Mann-Whitney U). The mean illness ratings over the 15-minute recovery period were 0.62 for ‘seat compensation’ and 0.74 for ‘head compensation’, and not significantly different (p = 0.68; Mann-Whitney U). The mean illness ratings at the end of the 15-minute recovery period were 0.29 for ‘seat compensation’ and 0.42 for ‘head compensation’ and not significantly different (p = 0.31; Mann-Whitney U). (For eight subjects, two with ‘seat compensation’ and six with ‘head compensation’, illness ratings were not obtained during recovery because they terminated the experiment, so their recovery data are not included in the analysis of mean illness ratings).

At the end of the recovery period, of the 52 subjects with recovery data, 82% of those experiencing ‘seat compensation’ reported an illness rating of 0, compared to 71% of those experiencing ‘head compensation’.

3.2 Effects of subject characteristics

3.2.1 Population demographics

The 60 subjects were grouped based on their self-reported ethnic origin. Forty subjects reported their ethnic origin as Chinese, Indian or other Asian, and were thus grouped under the heading ‘Asian’. Twenty subjects reported their ethnic origin as White British or European and were grouped under the heading ‘European’. Subject age and height were not significantly different between Asian and European subjects (p = 0.06 and 0.15, respectively; Mann-Whitney U). Subject weight was significantly greater for Europeans (M = 75.15 kg, SD = 9.16) than for Asians (M = 70.09 kg, SD = 19.89, p < 0.01; Mann-Whitney U). No significant differences were found between Asian and European subjects for any of the six measures of motion sickness susceptibility [20], $I_{\text{susc.(yr.)}}$, $V_{\text{susc.(yr.)}}$, V_{total}, M_{total}, M_{land} and M_{nland} (p > 0.35; Mann-Whitney U).

3.2.2 Illness ratings

For both the European and the Asian subjects, mean illness ratings increased over the 30-minute exposures to motion, and decreased during the 15-minute post-motion period (Figure 3). The mean illness ratings reported during the 30-minute exposures to motion were significantly greater for Asians (M = 3.01, SD = 1.74) than for Europeans (M = 1.57, SD = 1.27, $p < 0.01$; Mann-Whitney U). Likewise, maximum illness ratings were significantly greater for the Asians (M = 4.33, SD = 1.83) than for the Europeans (M = 2.55, SD = 1.47, $p < 0.001$; Mann-Whitney U). This pattern was reflected in the percentage of Asian and European subjects to reach each illness rating (Figure 4).

FIGURES 3 AND 4 ABOUT HERE

3.2.3 Symptom scores

The 'total symptom scores' reported by Asians and Europeans at the end of their exposures to motion (means of 5.20 and 4.65, respectively) were not significantly different (p = 0.25; Mann-Whitney U). However, 80% of the Asians reported 'nausea' on the symptom checklist compared to 55% of the Europeans (p = 0.045; Mann-Whitney U).

The 'normalised cumulative total symptom scores' were significantly greater for Asians (M = 1.72, SD = 0.86) than for Europeans (M = 1.24, SD = 0.92, p = 0.03; Mann-Whitney U).

3.2.4 Recovery

A total of 17 Asian subjects reported an illness rating of 6 (moderate nausea and want to stop) before the end of the 30-minute motion exposure. No European subjects reported an illness rating of 6 during the study.

During the recovery period, illness ratings decreased for both Asian and European subjects (Figure 3). The mean illness ratings at the end of the motion were 4.15 for Asians and 1.65 for Europeans, and were significantly different ($p < 0.001$; Mann-Whitney U). The mean illness ratings over the 15-minute recovery period were 0.86 for Asians and 0.39 for Europeans, but were not significantly different (p = 0.13; Mann-Whitney U). The mean illness ratings at the end of the 15-minute recovery period were 0.47 for Asians and 0.15 for Europeans, and were marginally non-significantly different (p = 0.09; Mann-Whitney U). (For eight Asian subjects, illness ratings were not measured during the recovery period due to these subjects terminating the experiment, so these data were not included in the analysis of illness ratings during the recovery period).

At the end of the recovery period, of the 52 subjects for whom recovery period data were recorded, 90% of European subjects reported an illness rating of 0, compared with 69% of Asian subjects.

3.3 Survival analysis

A Cox regression analysis was used to examine the influence of the experimental conditions, subject age, stature, weight and ethnic origin on the occurrence of the first report of illness rating 3 ('mild nausea') during the 30-minute motion period. The covariates were entered into the Cox regression model simultaneously and the results are shown in Table 2.

TABLE 2 ABOUT HERE

The Cox analysis revealed no significant influence of the experimental conditions (i.e. 'seat compensation' versus 'head compensation') on the probability of subjects reporting an illness rating of 3 ($e^{\beta} = 1.167$, $p = 0.65$). However, there was a threefold ($e^{\beta} = 3.64$) increase in the risk of reaching an illness rating of 3 for Asians compared to Europeans ($p < 0.01$). Subject age, stature, and weight did not significantly influence the likelihood of reaching an illness rating of 3.

4. DISCUSSION

4.1 Effect of the position of the centre of rotation

The motion was provocative of motion sickness in both conditions, with more than 65% of subjects across both conditions reaching an illness rating of at least 3 ('mild nausea') (Figure 2). This is consistent with previous studies that have found fully roll-compensated lateral oscillation at 0.2 Hz highly provocative of sickness [10, 12]. The mean illness ratings increased rapidly after the start of motion (i.e., at 5 minutes) and decreased rapidly after cessation of motion (i.e. at 35 minutes) with the majority of subjects fully recovering before the end of the 15-minute recovery period. Previous studies with these motions have found similar patterns, consistent with this motion being associated with a quick onset and quick recovery of motion sickness symptoms [e.g. 13].

Consistent with the hypothesis, mean illness ratings were greater when full compensation was at head height than when it was at the seat surface (Figure 1). However, analysis of both the illness ratings and the symptom scores showed that the differences in these measures of motion sickness between these two levels of compensation were not statistically significant, so the hypothesis was not substantiated. The findings suggest that any effect of increasing the height of the 'centre-of-rotation' from the level of the seat to 800 mm above the seat is small compared to other influences on motion sickness. However, the underlying model suggesting greater sickness with 100% compensation at the head than with 100% compensation at the seat has not been disproved, and it might be substantiated with greater numbers of subjects or greater control of other factors influencing sickness.

The study achieved 100% compensation at the seat and the head by combining ±7.3° of roll with each of two magnitudes of lateral acceleration (i.e., ±1.26 ms^{-2} or ±1.41 ms^{-2}, respectively) (Table 1). It would also have been possible to achieve 100% compensation at the seat and the head by combining ±1.26 ms^{-2} of lateral acceleration with each of two magnitudes of roll (i.e., ±7.3° or ±6.6°, respectively). The chosen conditions involved the same roll angle but increased translational acceleration when there was 100% compensation at the head. The increase in translational acceleration might be expected to increase sickness, but the increase in mean illness ratings was not statistically significant in this study. If instead, the experiment had been conducted with the same translational acceleration but reduced roll angle when there was 100% compensation at the head, it might be expected that the sickness would have been even less than reported in the current 'head compensation' condition [21], and therefore even less likely to be significantly greater than with 100% compensation at the seat.

With 'head compensation', the resultant lateral acceleration at the head was not exactly zero, principally due to some distortion in the translational motion. In the octave band centred on 0.2 Hz, the resultant lateral acceleration measured 800 mm above the seat was ±0.18 ms^{-2} with 'seat compensation' and ±0.07 ms^{-2} with 'head compensation'. The difference of ±0.11 ms^{-2} is probably greater than the threshold for detecting 0.2-Hz lateral oscillation, although thresholds for perceiving this type of motion are not well established and the detection of the oscillatory motion may be intermittent and not yield a clear perception of either the timing or the direction of the motion. Whether or not the difference was perceptible, the difference in otolithic stimulation between 'seat compensation' and 'head compensation' was not sufficient to cause a significant difference in sickness. The difference would be greater with greater magnitudes of oscillation and the location of the centre of rotation might then have greater influence on motion sickness.

In tilting railway vehicles, passengers experience lateral, vertical, and roll motions that are influenced by track geometry, vehicle suspension, and tilt mechanisms [7]. The location of the centre-of-rotation associated with track cant will typically be lower than that associated with a carbody tilting mechanism. This study investigated the simplified situation where roll motion is used to compensate for lateral acceleration, with two alternative centres-of-rotation, but the difference in location was not selected to compare differences between track cant and carbody tilt. Reductions of lateral acceleration arising from the cant of the track and carbody tilt increase acceleration in a direction normal to the floor of the vehicle (i.e., in the *z*-axis of the seat passenger). If motion sickness increases when there is increased compensation, increases in these 'vertical' accelerations will be associated with increases in motion sickness [5, 7, 22]. In this laboratory study the vertical acceleration was ±0.16 ms^{-2} and ±0.18 ms^{-2} in the seat compensation and head compensation conditions, respectively. Over the 30-minute exposure to motion, the motion sickness dose values corresponding to these accelerations are approximately 4.8 and 5.4 $ms^{-1.5}$, respectively, which would be expected to result in about two persons vomiting according to both BS 6841 [23] and ISO 2631-1 [24]. In fact, 26% and 30% of subjects in the 'seat compensation' and 'head compensation' conditions, respectively, stopped their exposures within 30 minutes, presumably because they feared imminent vomiting.

The position of the centre-of-rotation differs between different designs of tilting train, with higher centres of rotation in some Japanese passive tilting mechanisms than some European active tilting mechanisms [14]. Although greater incidence of motion sickness has been reported in passively-tilted trains than actively-tilted trains [8], the current findings suggest differences in the height of the centre-of-rotation may not be sufficient to explain differences in sickness.

The position of the centre-of-rotation can also be expected to influence responses other than motion sickness (e.g., passenger comfort and stability), with greater vibration discomfort as the distance between the seat surface and the centre-of-rotation increases [25]. With low frequencies of roll combined with lateral acceleration, the influence of the position of the centre-of-rotation on the physical comfort and stability of passengers has not been systematically investigated. The present study of motion sickness may assist the consideration of alternative designs but contributes only a part of the required information.

4.2 Ethnicity

There were no significant effects on motion sickness of subject age, weight, or stature but a highly significant effect of ethnic origin. Asians reported higher illness ratings and more motion sickness symptoms than Europeans and had significantly increased risk of reaching an illness rating of 3 ('mild nausea').

An apparent 'hyper-susceptibility' to motion sickness in Asian subjects has been documented previously. With visually-induced sickness in a rotating optokinetic drum, Chinese subjects reported significantly greater sickness than European-American or African-American subjects [26]. A follow-up study with American-born subjects with Asian parents, European-American, and African-American subjects found similar results, suggesting environmental factors associated with living in Asia were not sufficient to explain the findings [27]. When exposed to constant velocity rotation in yaw while making pitch movements of the head, Chinese subjects were reported to have significantly shorter 'rotation tolerance times' than Caucasian subjects, although motion sickness susceptibility scores reported by the Chinese subjects before testing "did not reflect their higher susceptibility during the subsequent test" [28, p. 1054], and there were no significant differences in susceptibility scores between Caucasians and Chinese subjects. This may suggest the Chinese subjects were less aware of their increased susceptibility to provocative motion stimuli relative to the Caucasians, consistent with the present study where no significant differences were found between the susceptibility scores of Europeans and Asians. Likewise, with 'pseudorotation' in a vection drum, rotation tolerance time was significantly less in Chinese subjects than in White subjects [29].

Although the visual motion stimuli used in the above studies may have caused sickness in a fundamentally different way from the combined lateral and roll oscillation used in the present study, there is a similar pattern of greater susceptibility to motion sickness in Asian compared to European subjects, suggesting genetic influences are responsible. In mono-zygotic and di-zygotic twins, approximately 53% of the variation in sickness susceptibility in a study sample has been attributed to genetic factors [30]. Genetic influences were greatest during childhood and decreased as age increased. The study was limited to females, assumed common environmental factors across pairs of twins, and was susceptible to questionnaire response bias, but nevertheless suggests a basis for understanding the role of genetic factors in motion sickness susceptibility.

The alpha 2-adrenergic receptor genes may be associated with motion sickness susceptibility [31], with allelic variations in this gene in the Chinese population accounting for the observed pattern of increased susceptibility [32]. Motion sickness research supported by advances in genetic screening may help to explain the hyper-susceptibility to motion sickness in Asians or, conversely, the reduced susceptibility in Europeans.

The language used in motion sickness susceptibility questionnaires, instructions sheets, and any verbal instructions given by experimenters may be a barrier to understanding differences between subjects with different languages. In the present study, all participants were deemed sufficiently proficient to study at degree level in the English language, having proven their ability by passing English language exams, and not all the subjects classified as 'European' were native-English speakers. Care was taken to ensure that subjects understood the instructions before entering the simulator cabin and it seems unlikely that language differences were the main cause of the observed differences between Asians and Europeans.

The findings have implications for the selection of subjects in motion sickness research, the design of motion sickness susceptibility questionnaires, and the development of anti-motion sickness measures. When constructing a sample population for motion sickness research, differences in susceptibility between ethnic groups require consideration so as to minimise bias, especially when using experimental designs with independent groups. In motion sickness susceptibility questionnaires, Asians may tend to underestimate their susceptibility to motion sickness relative to Europeans. However, the findings suggest that the need to understand and control the causes of motion sickness, including the motions in tilting trains, may be greater in Asian than in European populations.

5. CONCLUSIONS

With fully roll-compensated 0.2-Hz lateral oscillation, no significant differences in motion sickness were found with full compensation of lateral forces at the seat surface or 800 mm above the seat surface (i.e. at the average sitting eye height). Subject age, weight, and stature did not have a significant effect on motion sickness, but Asian subjects reported significantly greater motion sickness symptoms than Europeans, consistent with previous reports of ethnic differences in motion sickness susceptibility. It is concluded that differences in susceptibility between Asians and Europeans have a greater effect on motion sickness than the height of the centre-of-rotation during roll-compensated lateral acceleration.

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Table 1

Motion quantities for each experimental condition

Condition	Frequency (Hz)	Earth-lateral displacement (± m)	Earth-lateral acceleration (± ms^{-2})	Roll displacement (± degrees)	% compensation at seat surface	% compensation at head height
1: Seat compensation	0.20	0.80	1.26	7.30	100	112
2: Head compensation	0.20	0.89	1.41	7.30	88	100

Table 2

Results of Cox regression analysis

Predictor variable	**Reference**	**Exp (β)**	**Significance level**
Compensation at the head	Compensation at the seat	1.167	0.654
Age	-	1.056	0.462
Height	-	0.964	0.257
Weight	-	1.009	0.503
Asian ethnicity	European ethnicity	3.636	0.003

LIST OF NOTATION

Measures of motion sickness susceptibility, from:

Griffin, M.J., and Howarth, H.V.C. Motion sickness history questionnaire. Institute of Sound and Vibration Research, University of Southampton, England. 2000 Technical Report No: 283.

$I_{susc.(yr.)}$: Illness susceptibility in transport in past year

$V_{susc.(yr.)}$: Vomiting susceptibility in transport in past year

V_{total}: Total susceptibility to vomiting

M_{total}: Total susceptibility to motion sickness

M_{land} : Susceptibility to motion sickness in land transport

M_{nland} : Susceptibility to motion sickness in non-land transport

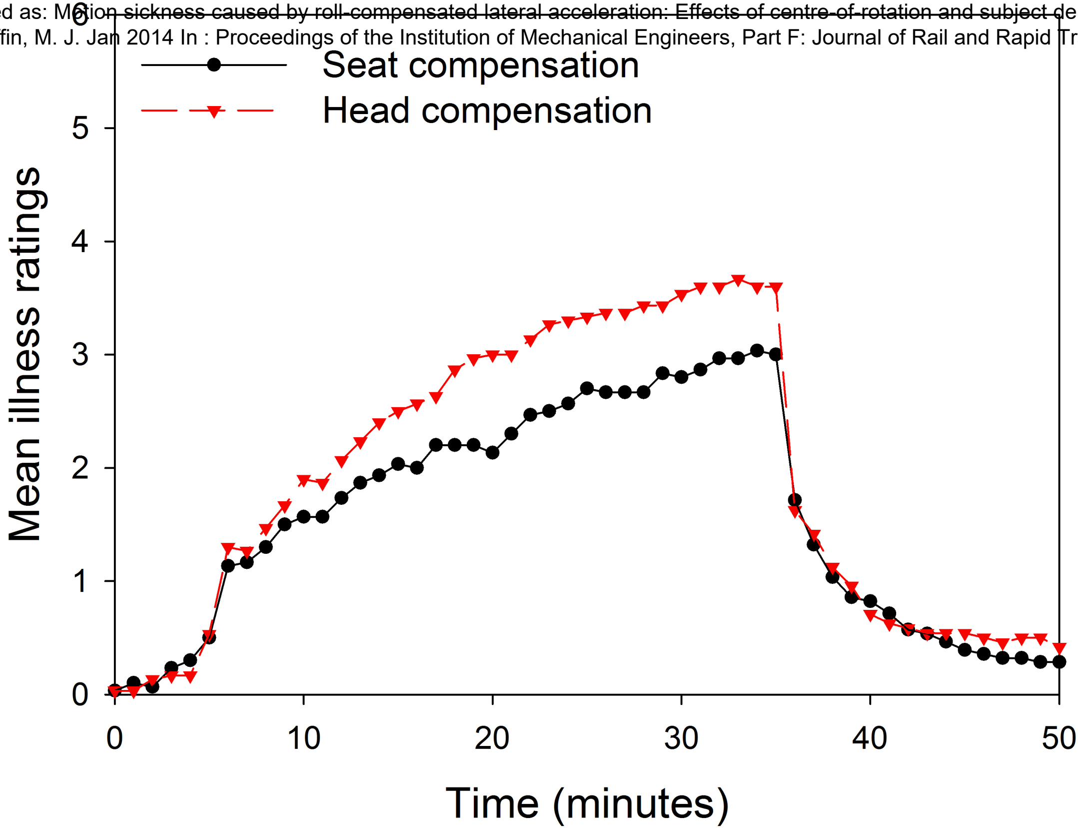
FIGURE CAPTIONS

Figure 1. Mean illness ratings reported each minute for seat compensation and head compensation. Exposure to roll-compensated lateral oscillation occurred between 5 and 35 minutes.

Figure 2. The percentage of subjects to reach each illness rating with seat compensation and head compensation.

Figure 3. Mean illness ratings reported each minute by 20 European and 40 Asian subjects. Exposure to roll-compensated lateral oscillation occurred between 5 and 35 minutes.

Figure 4. The percentage of European and Asian subjects to reach each illness rating.


Seat compensation
Head compensation
Mean illness ratings
Time (minutes)
0
1
2
3
4
5
6
0
10
20
30
40
50

Published as: Motion sickness caused by roll-compensated lateral acceleration: Effects of centre-of-rotation and subject demographics
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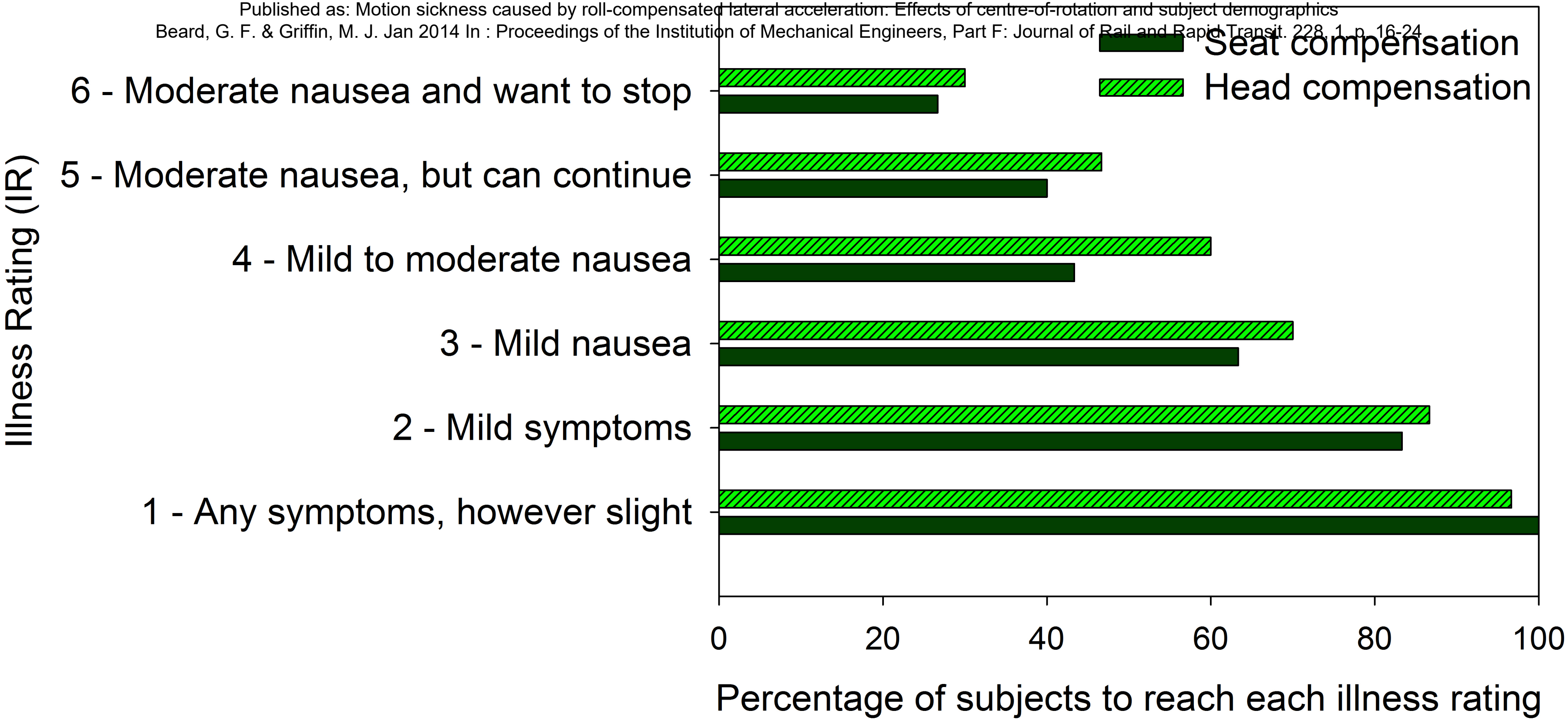
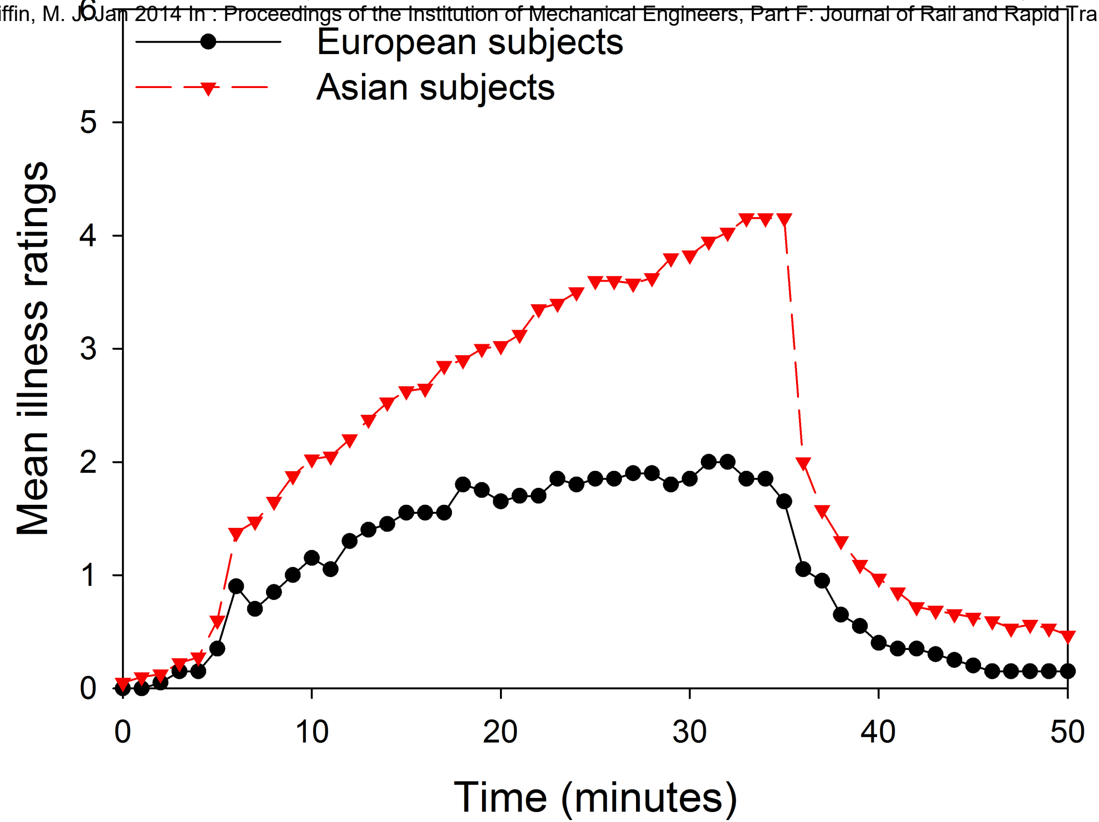
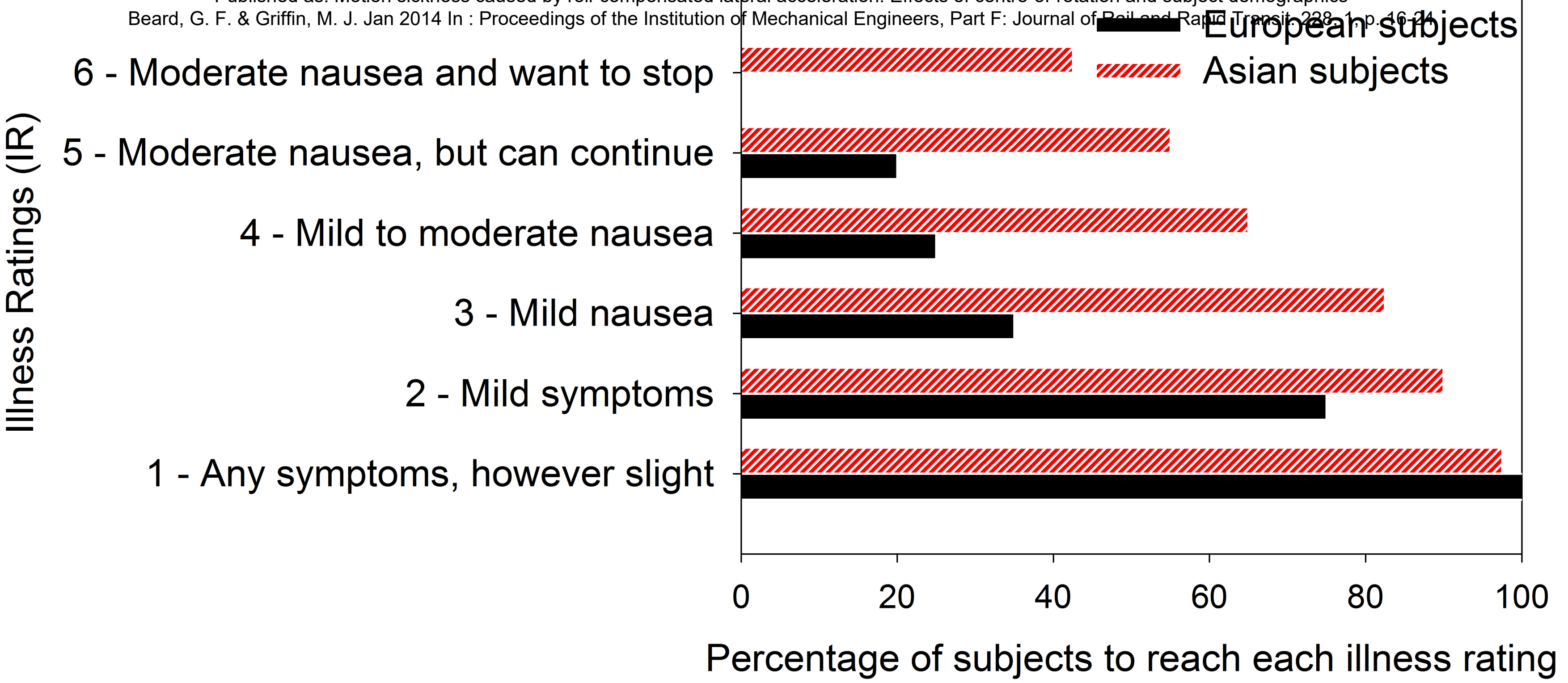



European subjects
Asian subjects
Mean illness ratings
Time (minutes)
0
1
2
3
4
5
6
0
10
20
30
40
50


European subjects
Asian subjects
6 - Moderate nausea and want to stop
5 - Moderate nausea, but can continue
4 - Mild to moderate nausea
3 - Mild nausea
2 - Mild symptoms
1 - Any symptoms, however slight
Illness Ratings (IR)
0
20
40
60
80
100
Percentage of subjects to reach each illness rating