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Effect of low frequency motion on the performance of a dynamic manual tracking task

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Abstract. The assessment of wind-induced motion plays an important role in the development and design of the majority of today's structures that push the limits of engineering knowledge. A vital part of the design is the prediction of wind-induced tall building motion and the assessment of its effects on occupant comfort. Little of the research that has led to the development of the various international standards for occupant comfort criteria have considered the effects of the low-frequency motion on task performance and interference with building occupants' daily activities. It has only recently become more widely recognized that it is no longer reasonable to assume that the level of motion that a tall building undergoes in a windstorm will fall below an occupants' level of perception and little is known about how this motion perception could also impact on task performance. Experimental research was conducted to evaluate the performance of individuals engaged in a manual tracking task while subjected to low level vibration in the frequency range of 0.125 Hz-0.50 Hz. The investigations were carried out under narrow-band random vibration with accelerations ranging from 2 milli-g to 30 milli-g (where 1 milli-g = 0.0098 m/s^2) and included a control condition. The frequencies and accelerations simulated are representative of the level of motion expected to occur in a tall building (heights in the range of 100 m -350 m) once every few months to once every few years. Performance of the test subjects with and without vibration was determined for 15 separate test conditions and evaluated in terms of time taken to complete a task and accuracy per trial. Overall, the performance under the vibration conditions did not vary significantly from that of the control condition, nor was there a statistically significant degradation or improvement trend in performance ability as a function of increasing frequency or acceleration.

Keywords: tall building; wind-induced motion; manual tracking task; occupant comfort.

1. Introduction

Over the past few decades there have been growing concerns of the wind-induced motion experienced in tall buildings and the effects that these motions have on the occupants that live and work in these environments. These concerns are expected to further increase as the development of high-rise structures worldwide continues to push the boundaries of engineering design, and optimization of the usage of structural material becomes more prevalent.

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The majority of the research investigating the effects that the wind-induced motion in tall buildings has on its occupants has focused on the perception and tolerance thresholds of this low-frequency motion. Past studies on these topics generally fall into three types of investigations: surveys of occupants residing in wind-excited tall buildings; motion simulator and shake table experiments testing human test subjects; and field experiments conducted in actual buildings where the motion is artificially induced. In conjunction with the perception studies, many researchers have investigated the effects of vibration on individuals, but typically these studies have been concerned with a higher range of frequencies, such as industrial and vehicular vibrations, than is encountered in our modern superstructures. A few early investigations have used devices to artificially excite tall buildings (Morris *et al.* 1979, Bouncer *et al.* 1980, Jeary *et al.* 1987) to investigate the effect of motion on manual tasks, but the excitation method only produced sinusoidal building motions which differ greatly from the random building responses normally encountered in wind-excited buildings. Irwin (1981), Irwin and Goto (1984) and Jeary *et al.* (1987) conducted a number of comprehensive tests investigating the effects of vibration on motor co-ordination tasks such as tracing lines and typing scripts; the investigation described in this paper is intended to complement those studies.

This paper reports the results from an investigation designed to ascertain the effects of the low-frequency narrow-band random vibration, above and below the perception threshold typically experienced in a tall building during a wind storm, on the performance of a manual tracking task. The tall building motion simulator at the CLP Power Wind/Wave Tunnel Facility (WWTF) at The Hong Kong University of Science and Technology (HKUST) was configured to carry out these studies. The experimental setup, test procedure, and test results and observations of the investigation are described.

2. Review of manual task performance studies

Manual tasks include any activity in which an individual is required to grasp, manipulate, or restrain an object, and it is well known that whole body vibration may interfere with such activities (Griffin 1997). An understanding of the effects of vibration on task performance may be of significant importance for individuals who are often exposed to extremely adverse vibration conditions, such as helicopter pilots or construction workers. However, it is possible that even lower levels of vibration, such as the low frequency (typically in the range of 0.10 Hz to 0.50 Hz), low acceleration (with peak magnitudes of the order of 5 milli-g to 30 milli-g) motion of a tall building in a wind storm, although not typically resulting in injury or damage to one's health, may have adverse effects on task performance. These lower levels of vibration may affect the body's senses used in the collection of information and create difficulties for the individual performing the task. Although whole body vibration may affect more complex and specific mental processes, it is thought that the mechanisms affecting performance are more greatly dependent upon levels of fatigue and arousal (Griffin 1997). A general effect of motion on performance may occur when the motion reduces motivation due to motion sickness or if the motion requires increased effort or energy output by someone subjected to the motion in order for them to perform a task.

Individuals suffering from motion sickness may experience a wide variety of sensations including headache, nausea, fatigue and disorientation (Yamada and Goto 1977). The intensity of the reaction varies with the individual and often depends on the exact nature of the motion stimulus. Often an individual may not be able to pinpoint a specific symptom, but simply have an overall uncomfortable feeling. It has also been postulated that even at levels of vibration below the threshold of perception, after exposures of several hours duration, an individual may find himself/herself unconsciously uncomfortable (Reed *et al*. 1973).

To determine whether task performance was impaired at levels of vibration below conscious perception, Jeary *et al*. (1987) conducted investigations using simulated motion in an actual tall building. Although significant performance degradation was not observed, it was hypothesized that vibration could act directly on the central nervous system by providing surplus information and disrupting cognitive skills such as memory and concentration. Often, changes in the ability to perform a task are dependent upon the task presented, including: task difficulty, and motivation and experience of participants (Jeary *et al*. 1987).

The greatest effects of whole-body vibration are on the visual input processes or the output of information through hand and/or foot movements. Detrimental visual effects of vibration were thought to be the cause of the increased length of time taken for subjects to recall letters presented on a display (Shoenberger 1974). This was observed for vibration occurring with a frequency of approximately 4.0 Hz, and was later confirmed by Griffin and Hayward (1994). It was speculated that this degradation occurs due to a change in viewing technique, from pursuit to compensatory eye movements (Huddleston 1970). Performance of specific tasks requiring precision movements may be hindered by the relative motion between a stationary object and the individual, or through the creation of balance problems. Relative motion between hand and sight will arise if the hand is either out of phase with the motion of the sight or moves more or less than the sight movement. The dynamic response of the body increases as the vibration frequency increases, resulting in a magnification of the head motion relative to the motion of the simulator (Burton *et al*. 2006) and a phase lag also occurs between the transmission of the vibration from the floor to the head (Griffin and Brett 1997).

Griffin and Brett (1997) demonstrated that the ability to control the head, and therefore reduce the relative motion between the head and the line of sight, was dependent on the predictability of the motion; they demonstrated that random vibrations were more detrimental to task performance than sinusoidal motion. It has also been noted that multiple axis vibrations have greater effects on task performance than single axis vibration (Griffin 1990). As the typical motion of a tall building in a wind storm is multi-axis and random in nature, the results of previous investigations using a uni-axial sinusoidal input may not appropriately demonstrate the actual effects of tall building vibration on task performance.

Much of the previous research that has been conducted on task performance has been for the aerospace, vehicular, and aircraft industries and, therefore, at both higher frequencies (> 1.0 Hz) and accelerations (> 50 milli-g) than those applicable to tall building vibration. A comprehensive review of vehicle related studies is given in a paper by McLeod and Griffin (1989). Alternatively, low frequency investigations have been carried out for the shipping industry, with the majority of the research focusing on vertical sinusoidal vibration (Wertheim 1998). Other researchers have investigated the effects that high acceleration motions could have on physical activities, including the ability to walk a straight line or up and down a set of stairs (Goto 1975). These higher levels of vibration, where peak accelerations are greater than 40 milli-g and difficulty maintaining balance becomes a priority issue, is marginally beyond the level of acceleration considered acceptable for general occupation in a tall-building.

In a series of advanced studies, Irwin and Goto (1984) conducted manual dexterity tests in the frequency range of 0.02 Hz - 10.0 Hz for five motion combinations; yaw and lateral vibration, yaw and fore-aft vibration, yaw, fore-aft and lateral vibration, and fore-aft vibration. The choice of motion magnitudes and frequencies was based on the five year return period curves for skilled task performance given in ISO-6897 (1984). Participants in the study performed tasks that closely represent typical tasks that skilled workers may need to carry out on a regular basis (threading a needle and tracing various shapes and patterns) before the vibration commenced, during the vibration, and following the conclusion of the vibration. The time taken to complete the needle threading, and the deviations from the tracing patterns were used as markers for task degradation. Overall, the time taken to complete a task was shorter at frequencies greater than 1.0 Hz and the trace lines showed greatest deviation in the frequency range 0.2 - 1.0 Hz. No differences were reported for the task performance between the five motion groups.

Although some previous research has demonstrated a lack of correlation between low frequency vibration and task performance, it has been suggested, in some cases, that the simulated tasks have been over simplified. This is a typical problem in many previous investigations, where the majority of the involved participants had little difficulty in completing the presented tasks, therefore resulting in a non-Gaussian distribution of scores (i.e., ceiling effects, see Jeary *et al*. 1987, Morris *et al*. 1979, Denoon *et al*. 2000). However, the opposite effect is also possible, where a task is so difficult that any additional difficulty caused by the vibration is insignificant (i.e., floor effects, see Griffin 1997). In order to convincingly explore the possible effects of vibration on performance, a selection of more realistic tasks is imperative.

In some extreme cases, the stress of vibration has been shown to motivate participants to improve performance above that achieved under static control conditions (Lovesey 1976, Sherwood and Griffin 1990). This perhaps ties in with the thought that differences in performance under certain stressors are more a function of an individual's personality than the stressor level itself. "Internal subjects perceive effort as an instrument of personal achievement, and "external subjects believe success and failure are outside their own influence. It has been demonstrated that "internal subjects perform significantly better than "external subjects under motion conditions (Webb *et al*. 1981).

Human response to the type wind-induced motions typically experienced in tall buildings can be broadly categorised as psychological, physiological and physical. The interaction of these mechanisms forms the sensing system that determines an individual's sensitivity to motion. Previous research, as reported in Burton *et al*. (2006), clearly demonstrated a magnification of the acceleration experienced at an individual's back and head while sitting and undergoing motion in a motion simulator. This battery of tests clearly demonstrated a measurable physical response to external motion stimuli. It was also demonstrated that the magnifications of head and back accelerations were dependent on the frequency of oscillation.

The aim of the work conducted and described herein is to investigate physical responses and their consequences at key evocative input frequencies indentified in the tests described in Burton *et al*. (2006). As previous research (Lundström and Holmund 1998) has suggested that a relaxed sitting posture increases the relaxed muscles in the back and abdominal regions, which reduce body stiffness and increases damping, the experiments described herein were conducted with standing subjects. In the standing position, it was necessary for the subjects to make appropriate physical compensations that would include control of limbs, head, neck, and balance in order to complete the assigned task to the best of their ability in each motion condition.

3. Testing methodology

Utilizing the motion simulator at the CLP Power Wind/ Wave Tunnel Facility (WWTF) at The

Hong Kong University of Science and Technology (HKUST), fourteen human test subjects were subjected to a range of low frequency, low acceleration motions. The capabilities and calibration of the motion simulator have been reported in Burton *et al*. (2003). The main objective of the study was to investigate the physical responses of the test subjects at frequencies that are typical for tall buildings. Three frequencies of horizontal bi-directional random motion were investigated, ranging from 0.125 Hz to 0.500 Hz. The oscillatory motions ranged in acceleration from 2 milli-g to 30 milli-g, each for a duration of 720 seconds. The test subjects were each exposed to five levels of acceleration (2, 4, 8, 16 and 30 milli-g) at 0.25 Hz and 0.50 Hz, whereas at the lower frequency of 0.125 Hz the subjects were exposed to only three levels of acceleration (2, 4 and 8 milli-g), the largest amplitudes reproducible by the motion simulator at this frequency. In addition to the thirteen motion conditions, each subject completed a no-motion start-up condition and an embedded control condition.

During exposure to the fifteen conditions, the test subjects performed a manual tracking and reaction time task which demanded the control of arm and hand movements. The manual task chosen for the study required the test subjects to remain in a standing position throughout the experiments and afforded the test subjects no additional or external means of support. The subjects were required to react rapidly to a stimulus that appeared at various locations on a 29 in. CRT television screen. The center of the television was 1.65 m above the floor of the simulator and it was positioned on a custom designed table 1.50 m in front of the subject. Each subject was in a standing position for all of the tests, as described in Section 3.3 below.

In order to determine if an individual's ability to complete the task was degraded with increasing levels of vibration, a continuous record of data, including time to complete and accuracy of the task, was collected for all subjects under each of the fifteen conditions. A repeated measures design was chosen for the current study. This allowed each subject to be measured under all conditions, thereby reducing subject recruitment time, and reducing variance errors when compared to the employment of a large sample of subjects. The major disadvantage of a repeated measures design, the learning and practice effect, was overcome by randomizing the order of presentation of the motion conditions and by allowing the subjects to train at the manual task until the asymptote on the learning curve was achieved. Fatigue effects were minimized by requesting the subjects to return on different days to complete the testing.

3.1 Experimental procedure

The thirteen motion conditions, one control condition and one start-up condition were used to examine the variation in the performance for a manual tracking task as a function of frequency of oscillation and magnitude of acceleration. The order of presentation of the various motion conditions and the control condition was determined using a Latin square randomization design and at no time were the subjects informed of the experimental condition they were experiencing. The no-motion start-up condition was the first condition presented to each subject. The subjects were tested at the same time over the course of five days, thereby experiencing three conditions on each of the five days. Both the control condition and the no-motion start-up condition involved the subject standing in the simulator completing the manual tracking task with the simulator switched on, to maintain an equivalent auditory environment, but with no motion. The control condition was considered the baseline test to establish the manual tracking task ability of the subject and was used as a reference to compare the results recorded under the various motion stimuli.

One narrow-band random acceleration signal was independently scaled in frequency and acceleration amplitude to generate the desired input signals for the motion simulator. The signals were then processed so that each condition was twelve minutes in length. The data was spliced together for the higher frequencies of 0.25 Hz and 0.50 Hz, resulting in the peak acceleration being experienced more often than at the lower frequency of 0.125 Hz. To form the input signal for the bi-directional motion, an identical input signal was used in the two orthogonal directions of the motion simulator, but with an offset of ten and a half cycles between the two directions. This enabled the peaks in one direction to occur approximately at the nadirs of the opposing orthogonal direction. This is comparable to the response of a tall building that has similar natural frequencies in orthogonal directions, but where the peak component responses do not occur simultaneously.

The acceleration and the frequency of both the motion simulator and the television were monitored using two high sensitivity bi-axial accelerometers with a range of +/- 30 g. The accelerometers were used in conjunction with custom-built hardware that allowed accurate measurements of accelerations experienced in this study.

The manual task employed, a release in the PlayStation 2® series from namco®, was a first person shooter game entitled "Time Crisis 3. For all conditions, the score, task accuracy, and time taken on the trial were recorded manually. In addition to the manual record, a video recorder was mounted unobtrusively in the corner of the simulator to verify the tabulated results, thereby reducing potential human error.

3.2 Manual task selection and operation

The manual tracking task chosen for the performance testing required the selection of a task with a low learning curve and a high replay value. "Time Crisis 3 was set up in the motion simulator two weeks prior to the initialization of testing and subjects were asked to practice until they felt familiar with the game features. The premise behind the game is simple; the player's objective is to shoot down obstacles along a set path, the direction of movement is computer controlled and the speed of movement is dependent upon player shot accuracy. Although the game provides the player access to a variety of weapons (pistol, machine gun, shot gun, grenade launcher), the test subjects were restricted to using the pistol for regular game play and the machine gun for fighting a series of major battles at the end of stage one. The pistol is initially loaded with nine bullets and is reloaded using a finger control on the player's gun.

Each time a player enters a new scene, they are forced to race against a countdown timer, typically 40 s. If the time expires before the player has shot all of the targets, the player will lose one life. If a player loses four lives, they are given an option to continue and the game allows the player to continue three times, therefore allowing a total of 12 deaths before the game is automatically terminated and no further advancement in scoring can occur. As the computer controls the player's movement through various environments, the player depends on the accuracy of their shot to succeed in the game play. The player's accuracy is employed in the calculation of the accuracy score but will also affect the overall "time taken, as a decrease in accuracy will cause a corresponding increase in the time taken to complete a scene (i.e., assuming trigger speed remains unchanged).

The game is designed with three different modes of play: Arcade Mode, Crisis Mission Mode, and Rescue Mission Mode. Arcade Mode, which is similar to the original arcade game, was chosen for this investigation. The game is divided into three stages, and embedded in each stage are three areas. On average, each area in stage one took approximately four minutes to complete. Therefore, the test subjects were asked to complete stage one in the shortest time and to the best of their ability while undergoing each of the fifteen motion conditions. The maximum time allotted for subjects to complete stage one was 12 minutes. If the subject was not able to complete the stage to its entirety before the time expired, the invigilator informed the subject to stop game play and recorded the results achieved.

Competition between subjects was encouraged to help motivate the subjects to perform at their optimum and to adopt similar strategies for successful completion of the game.

3.3 Test subjects

The fourteen human test subjects, five of which claimed to be sensitive to motion sickness, that volunteered for this study were employees of The Hong Kong University of Science and Technology (HKUST). Each of the thirteen male subjects and the one female subject considered themselves "gamers" and none of the subjects had experience working in a vibrating environment. Subjects' ages ranged from 20 to 35. Subjects' age and physical characteristics are displayed below in Table 1. Prior to being exposed to the various levels of low frequency and low acceleration motion, all subjects were required to inform the investigator of any medical conditions that would render them unfit for the experiment. All subjects were unpaid volunteers, who gave verbal consent to participate in the experiment. It was assumed that throughout the experiment alertness was present for all subjects and for all trials.

Subjects were instructed to stand with both fe*et al*igned behind a yellow line marked on the floor of the simulator, which was 1.5 m from the 29 in. CRT television screen. They were directed to keep their non-shooting arm at their side, to keep both feet flat on the floor and a shoulder width apart. The lightweight gun was held in their dominant hand while they performed the manual task, as shown in Fig. 1. Subjects were instructed to be vigilant throughout the experiment.

The invigilator informed the subject when to begin the task and kept a manual record of performance data. Subject supervision was an important aspect of the testing in order to verify that the pistol was the only weapon utilized for all scenes, other than the final scene of stage one. It was also necessary to monitor the subject stance to ensure that a foot foul, i.e., stepping across the floor marker, was not made.

A research questionnaire was administered to the participants upon completion of the each condition and required subjects to self-evaluate the motion conditions and the effects that the motion had on their well being. Nausea, tiredness, annoyance, difficulty concentrating and maintaining balance, were among the effects requiring a Boolean 'yes' or 'no' response.

Table 1 Age and physical characteristics of human test subjects.

Subject #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Age	31	20	24	23	35	35	28	37	25	25	27	31	28	28
Height (m)	1.8	1.8	1.7	1.8	1.7	1.7	1.8	1.7	1.8	1.8	1.7	1.7	1.8	1.8
Weight (kg)	95	65	66	71	65	67	84	62	63	82	59	83	85	66
Susceptible to Motion Sickness	Y	Y	N	N	N	Y	N	N	N	N	Y	N	Y	N

Fig. 1 Subject performing the manual task

4. Experimental results

4.1 Test acceleration

The acceleration and frequency of the motion simulator and the television were monitored during all test conditions. The power spectral density (PSD) functions confirmed that the peak frequency of the motion simulator and the television coincided with the target frequency of the input motion. Three examples of the measured peak resultant acceleration of the motion simulator, 0.125 Hz at 8 milli-g, 0.25 Hz at 16 milli-g, and 0.50 Hz at 30 milli-g respectively are displayed in Fig. 2. The acceleration of the television was within one percent of the motion simulator acceleration. Thus, any

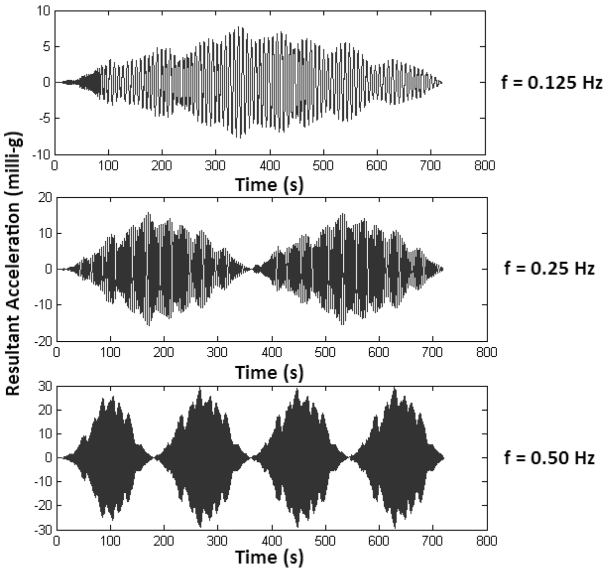

Fig. 2 Motion simulator acceleration graphs for three example signals

relative movement in the display-subject relationship, causing degradation or improvement in the performance of the manual task, was a function of subject movement alone. It was expected that at the higher frequencies of oscillation the relative movement between the subject and the television increase, similarly to the results shown in Burton *et al*. (2006) for sitting subjects but an even stronger effect for standing subjects.

4.2 Perception and effects of motion

The perception of motion of individuals undergoing the repeated measures investigation was evaluated with a Boolean 'yes' or 'no' response following the motion simulation. The cumulative percentage of individuals perceiving motion plotted against the logarithm of acceleration for each frequency approximately followed a lognormal distribution; this is consistent with previous research investigating perception thresholds (Chen and Robertson 1972, Kanda *et al*. 1990). Estimates of the parameters of the lognormal distribution for each frequency were determined graphically using probability plotting paper. Linear regression was used to analyze the relationship between the cumulative percent of individuals perceiving motion and the acceleration as plotted on the probability plotting paper. A Chi-Square goodness of fit test, statistically significant at the 5% significance level, confirmed that the sample perception data satisfied the assumption of a lognormal distribution. The threshold of motion perception for the standing subjects in this manual tracking task is shown below in Fig. 3.

The twelve minute input stimuli, with the three frequencies of motion, were analyzed for five effects; their ability to induce nausea, tiredness or annoyance, or disrupt the concentration or the maintaining of balance in participating subjects. The percentage of participants claiming to suffer effects, and become disrupted from a task, increased concurrently with the peak acceleration. Shown below in Fig. 4, grouped across all frequencies of oscillation investigated, are the percentage of subjects claiming to be affected by the motion. The percentage of subjects claiming to have difficulty maintaining balance at various levels of acceleration are also shown in Fig. 4.

4.3 Manual tracking task performance

In the initial test design, it was hypothesized that the effects of vibration stress would vary as a

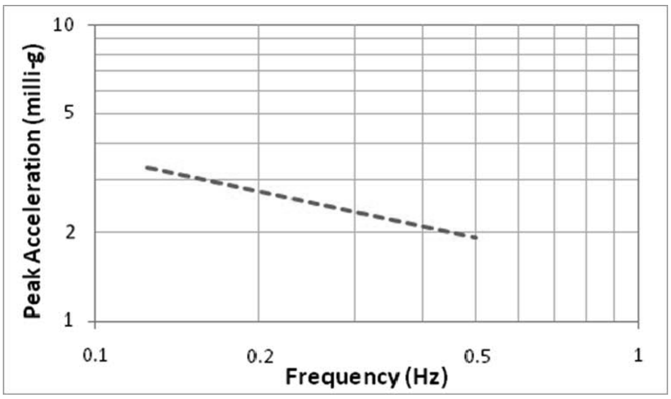

Fig. 3 Perception of motion threshold

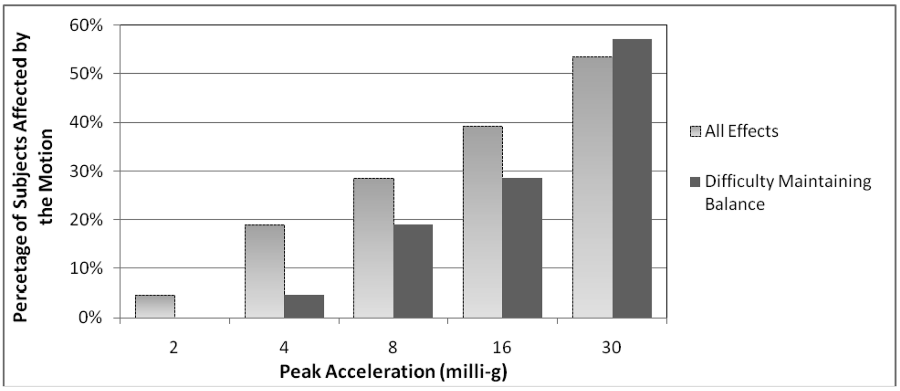

Fig. 4 Percentage of subjects affected by the motion

function of acceleration and/or frequency. For this reason, each subject's accuracy scores and time taken per trial were grouped according to conditions, which were formed as a cross-product of acceleration and frequency. Each condition was assigned a semantic label in order to minimize errors in the processing of the results. These semantic condition labels and the associated frequencies (Hz) and peak accelerations (milli-g) are outlined in Table 2.

Preliminary analyses of participants' final scores from stage one reveals a number of outlying and extreme values, as shown in Fig. 5 represented by circles and stars respectively. The outliers and extreme values are attributable to the two most skilled competitors that volunteered for the testing. Outliers and extremes were defined as final scores, considered in each condition independently, with

Table 2 Testing conditions expressed in frequency (Hz) and peak resultant acceleration (milli-g)

Condition		Frequency (Hz)	Acceleration (milli-g)	Order of presentation
(start-up)	01	0	0	1st
	02	0.125	2	randomized using Latin-Square
	03	0.125	4	
	04	0.125	8	
	05	0.25	2	
	06	0.25	4	
	07	0.25	8	
	08	0.25	16	
	09	0.25	30	
	10	0.50	2	
	11	0.50	4	
	12	0.50	8	
	13	0.50	16	
	14	0.50	30	
(control)	15	0	0	

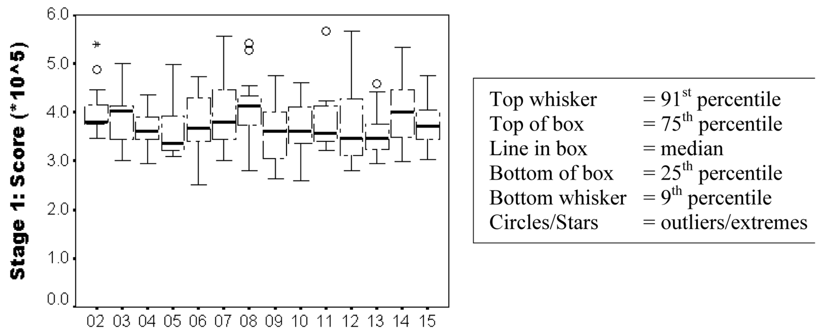

Fig. 5 Box plots of the accuracy scores from stage one

values which were greater than three or four standard deviations away from the mean respectively. Outlying and extreme values tend to skew recorded results unrealistically and may dramatically affect the data distribution and homogeneity of variance.

An initial inspection of Fig. 5 does not reveal any obvious trends with respect to the acceleration conditions, in terms of manual tracking task performance. The variability of the mean accuracy score across the conditions is expected and is due to the many factors that contribute to the calculation of the accuracy score, including the number of successful sequential shots, where on the body the shot lands (head shots are awarded more points), and time taken to complete the trial. The performance accuracy is dependent upon the subject's familiarity with the target motion and each individual is capable of achieving various degrees of performance. Due to the large variations in ability between test subjects, the accuracy score and time taken to complete each trial was normalized by dividing each subject's accuracy score and time for each individual condition by each individual's own average accuracy score and time across all fifteen conditions.

The time taken to complete the task exhibited less variability across the fifteen conditions for all fourteen subjects when compared to the accuracy score. A noticeable relationship between the time taken to complete the manual tracking task and the score achieved appeared to exist for subjects #1 and #3; that is, increasing the time spent to complete the manual task tended to increase the achieved score. This result is thought to be made possible, based on video footage of the subjects during the tests, by taking a greater amount of time to align the body with the target in order to ensure a more accurate shot. However, there is no noticeable relationship between the accuracy score and the time taken to complete the manual task for the remaining subjects, as specific instructions were given to the subjects to complete the task in the minimum amount of time.

4.3.1 Learning effect

To verify that no learning had occurred over the duration of the testing and that each subject fully grasped the concept and functionality of the game, the initial no-motion start-up condition was contrasted against the final condition presented to each subject, using a paired-samples *t*-test. A paired samples *t*-test compares the means of two variables measured under two separate conditions. It computes the differences between values of measurements made in two individual cases and tests whether the average results differ significantly from zero.

Although for some subjects there was a marginal improvement in the length of time taken to complete the task from "Day 1 to "Day 5 using pair samples *t*-test, it was determined that there was no statistically significant learning effect present. Hence, having each subject practice until the

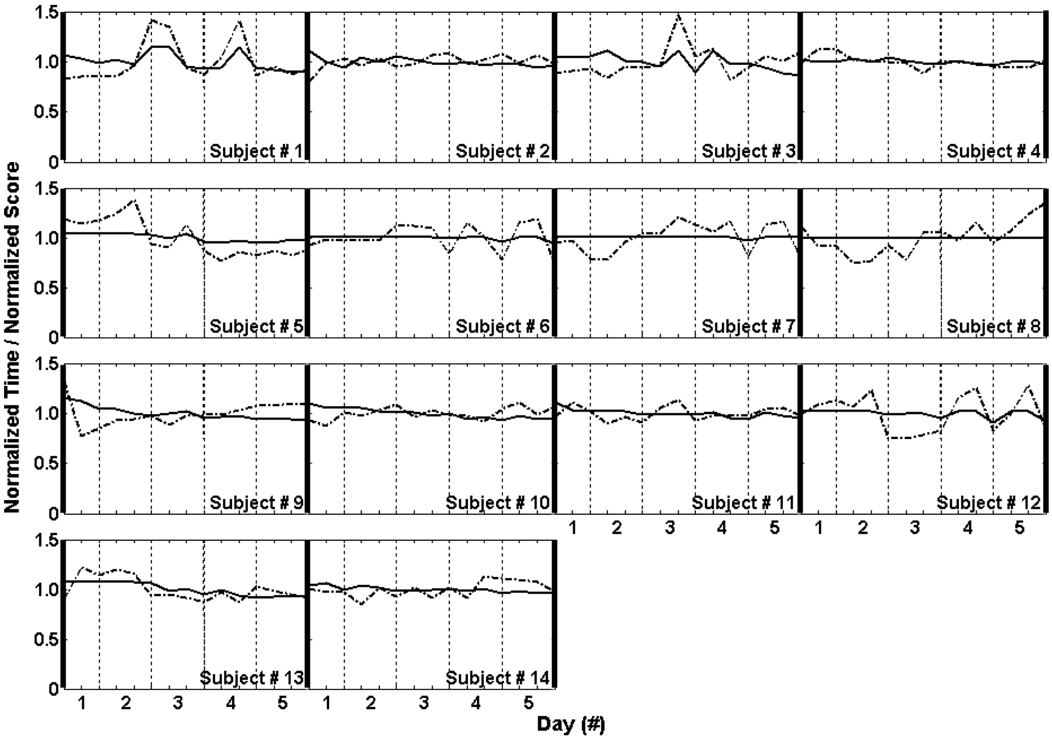

Fig. 6 Accuracy score and time taken for stage one; displayed for each subject based upon the order in which conditions were presented: -·-·-·-·- score, ——— time

asymptote on the learning curve was achieved was an effective method to eliminate any practice effects.

Graphically demonstrated in Fig. 6, in the order in which the conditions were presented to the subject, is each subject's accuracy score and time taken to complete each trial. The vertical grid lines represent the points of separation for each of the five days of testing. Therefore, moving from left to right, the first grid line represents the end of "Day" 1 of testing; the second line corresponds to the end of "Day 2", and so forth.

4.3.2 Manual task performance

As every subject was tested under each condition, a General Linear Model (GLM) for Repeated Measures statistical test was employed in the analysis of the final results. The 'p' value (the observed level of significance) was specified at the 5% significance level ($p<0.05$) as suggested by researchers in the field of behavioural sciences (Keppel 1991).

The GLM tool for analysis is only valid if the data follows a normal distribution; therefore two tests were carried out to ensure that the assumption was not invalid. The normal quantile-quantile (Q-Q) plots compare the distribution of a given variable to a normal distribution. The obtained scores (on the x-axis) are plotted against the expected scores (on the y-axis) resulting in data points represented by squares in Fig. 7. The expected scores represent the values that would be obtained if the testing results followed a normal distribution. If the scores are normally distributed then the plot of the observed values versus the expected values will result in a straight line. The straight line

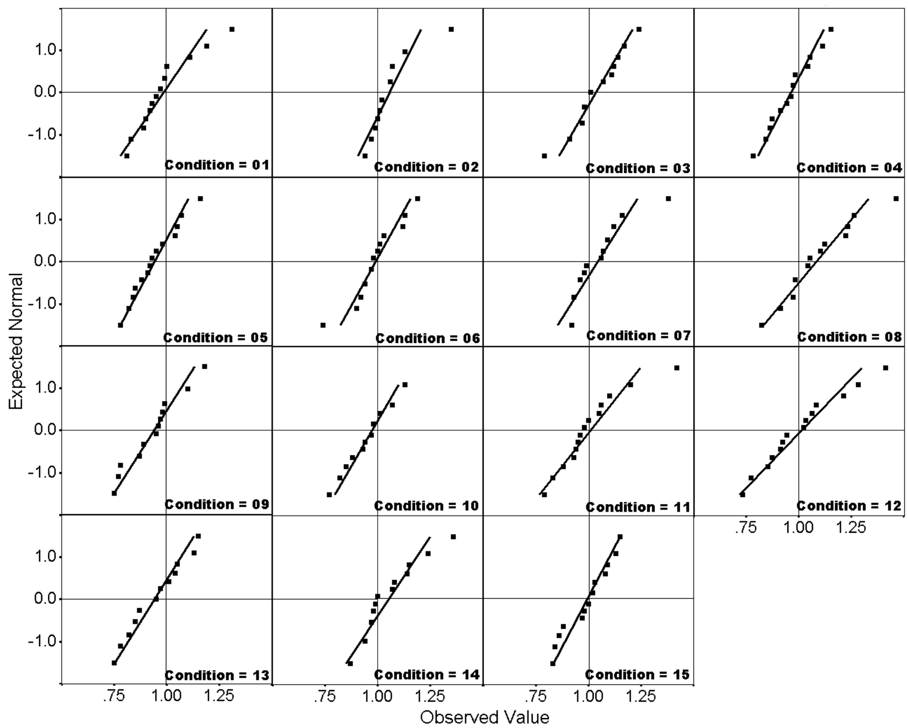

Fig. 7 Normal Q-Q plot of testing conditions

displayed in Fig. 7 represents the desired location of normally distributed data, any values deviating from this straight line are considered to not follow a normal distribution.

From Fig. 7, it can be observed that the results from each of the fifteen conditions are reasonably aligned with the straight line representing normally distributed data. In addition to the normal Q-Q plots, the Wilks-Shapiro statistic, which takes into account skewness and kurtosis of the data, demonstrated that all of the conditions (except condition 02) were found to satisfy the test of normality. One outlying value in condition 02 skews the data substantially therefore forcing a non-normal distribution. To enhance the statistical reliability of the results, the data was trimmed such that the largest and smallest data point from each of the fifteen conditions was eliminated. The Wilks-Shapiro test of normality was satisfied subsequent to the trimming of the extreme value data points.

The accuracy score and time taken to complete each trial, normalized to each subject's average, are shown in Figs. 8 and 9 for stage one. The graphs are divided into four sections, the first of which displays the recorded results from the control condition, followed by the results recorded under 0.125 Hz, 0.25 Hz, and 0.50 Hz respectively. The trimmed arithmetic mean values, individual subject's data, and plus or minus one standard deviation from the mean are represented by circles, crosses and error bars respectively in Figs. 8 and 9.

Initial inspection of Figs. 8 and 9 reveals little in terms of data trends resulting from increased acceleration within each frequency. To quantitatively measure the variation in performance, the GLM was used to determine whether any trend existed within each frequency group across the range of tested accelerations. The accuracy scores and time taken to complete each trial were re-

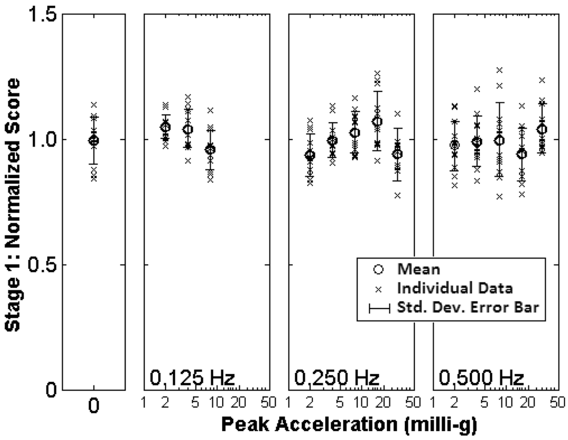

Fig. 8 Normalized final accuracy score

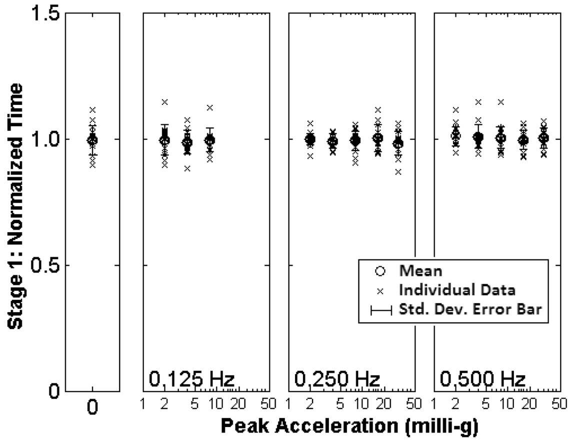

Fig. 9 Normalized time taken to complete

normalized to the average score and time within each frequency grouping. Therefore, all the recorded score and time data from 0.125 Hz was normalized to the subject's average score and time calculated from conditions 15, 02, 03, and 04, and data from 0.25 Hz and 0.50 Hz were normalized to averages determined from conditions 15, 05, 06, 07, 08 and 09 and conditions 15, 10, 11, 12, 13 and 14 respectively.

Within each of the three low frequency groups considered in this study, the GLM analysis determined that there was no statistically significant performance degradation or improvement observed for increasing levels of acceleration. Further analysis was completed on acceleration grouped data to determine whether the performance was affected more significantly at a specific frequency. The sample data in each acceleration group was normalized by the average score and time of all frequencies at the matched level of acceleration. The varying frequencies of oscillation appeared to have no significant effect on the manual task performance.

Although no linear trend in the performance scores was established, there is a possibility that some or all motion conditions resulted in performance scores significantly worse than those recorded in the control condition. Therefore, the accuracy score achieved in stage one for the control condition was contrasted against the accuracy score of all individual motion conditions with three levels of frequency (0.125, 0.25, and 0.50 Hz) and six levels of acceleration (0, 2, 4, 8, 16, 30 milli-g), using a paired samples *t*-test. To complete the contrast, the data from each condition was normalized to the average values, for each subject, calculated from the 13 motion conditions and the control condition. The paired samples *t*-test is often employed when measuring variations in results obtained during a testing condition and a control condition. Known to be one of the most common experimental designs, the pre-post study consists of two measurements taken on the same subject, one during a control condition and the second following the introduction of a stimulus. It is understood that if the stimulus has no effect on the subject, then the average difference between the results, in this case the accuracy scores, measured under the two conditions is zero.

Accuracy scores varied between the control condition and the stimulus conditions, but the variations were inconsistent across all subjects. Several subjects exhibited performance improvement with the introduction of the vibration stimulus; however, several others either showed evidence of performance degradation or maintained their level of performance. This performance improvement and degradation was even variable in individual subjects from day to day. This variation in performance amongst subjects resulted in an overall non-significant difference between the mean performance in any of the vibration conditions and the no-motion control condition.

5. Discussion of results

5.1 Perception and effects of motion discussion

Thresholds for the detection of discrete bi-directional narrow-band random vibration in the low frequency range found in the present experiment lie within the range reported by other authors (Chen and Robertson 1972, Goto 1975). It has been previously noted, for a sinusoidal motion stimulus, that the threshold of perception of low levels of vibration is reduced for standing individuals, when compared to sitting individuals (Chen and Robertson 1972, Goto 1975). This may potentially be attributed to the contrasting biodynamic reactions and transmissibility factors of the standing versus sitting human body to a vibration stimulus. Previous research (Lundstrm and Holmund 1998) has suggested that a relaxed sitting posture increases the number of relaxed muscles in the back and abdominal regions, which reduce body stiffness and increase body damping. Given similar input stimuli, if the relaxed subject in the seated position exhibits greater damping than the stiffer standing subject, it is reasonable to assume that the level of vibration magnification, when compared to the stimulus, experienced at a subject's head is lower for the seated subject. Given the limited number of test subjects involved in this study and the step change in the accelerations presented, the threshold of motion perception of these standing subjects was not contrasted against previous research involving seated or supine subjects.

The experiment demonstrated that the threshold for detection of discrete movements in the bi-directional plane decreased as the frequency of oscillation increased. This positive slope suggests that the detection process of low frequency acceleration is dependent upon a combination of acceleration and the rate of change of acceleration or jerk of the motion stimulus, as suggested in earlier research (Benson *et al*. 1986).

Previous research (Burton *et al*. 2005) has shown that at higher accelerations in the frequency range between 0.25 - 0.50 Hz reports of nauseogenic symptoms in test subjects are as high as 50%. In this investigation, only one of the fourteen test subject reported nausea, and this report was for the 30 milli-g acceleration at 0.50 Hz. The indication is that the length of time spent at the elevated acceleration in this test was not ample enough to induce nausea. This is further proved positive by the fact that approximately 80% of the 40% of the individuals that experienced nausea in the Burton *et al*. (2005) reported tests, left the motion simulator after experiencing the motion for longer than 30 minutes. The nauseogenic effect of low frequency motion has been previously noted to increase as a function of exposure time and acceleration intensity (Golding 1992)

Although the individuals in this study were less likely to experience nauseogenic symptoms that were to distract them from the task, over 50% of the participants subjected to peak accelerations of 30 milli-g had difficulty maintaining balance. This fact could have a greater implication on the ability of the average individual to complete a manual task. In this instance the participants are young and fit and it is hypothesized that they have been able to compensate for their difficulty in maintaining balance to overcome the potential degradation in performance.

5.2 Manual tracking task performance discussion

Previous research (Griffin 1990) has shown that the effects of vibration on task performance are likely to be dependent upon the task presented, including such factors as its difficulty and the motivation and experience of the subjects. The characteristics of the task and the type of vibration combine to determine the effects of a motion stimulus on performance, where a certain vibration may affect one type of manual task but have little effect on another. It has also been speculated (McLeod and Griffin 1989) that the actual effects of vibration on task performance are dependent upon the workload imposed on the subject performing the task and that it may be possible for subjects to compensate for minimal vibration effects by increasing their effort and thereby showing no overall performance degradation. It is thought (Lovesey 1976) that the stress of vibration, in some situations, may even motivate some subjects to improve their performance above that achieved under static control conditions.

In the current study, it is reasonable to assume that the manual tracking task implemented generated enough interest that, in general, the subjects were able to compensate for the levels of motion presented. It is understood by the authors that all of the performance measurements made in this investigation are task specific and may not necessarily represent the complexity nor the subject interest level for the wide range of manual tasks performed in actual tall buildings. In order to cover a broader range of the effect of movement on manual tasks, it would be necessary to implement tasks of a more specific nature with increased complexity. It is reasonable to presume that the physical effects on the manual task implemented in this research programme would be more significant than that of a typical point-and-click computer task an individual may perform in an office environment.

Specific effects of motion on task performance may be limited to biomechanical factors where the effects of a motion stimulus on co-ordinated control may be expected to depend on the amount of support given to the controlling limb. There is evidence (Shoenberger 1974) that indicates that the human body amplifies input vibrations at certain frequencies, most notably at the body's resonant frequencies (frequencies outside the range of the tests reported herein). These biomechanical effects may largely be responsible for any decrements in the performance of manual tasks. However, in the current study, although a number of subjects expressed difficulty in maintaining balance at the higher levels of acceleration, no performance degradation was noted. Similar results were found for a series of motor coordination and tracking tasks completed during ship movements at sea (Wertheim 1998). It was concluded that low levels of vibration may interfere to some extent with fine motor control involving visual clarity and accuracy but not necessarily with specific tasks characterized by other biomechanical factors. The fact that no performance degradation was demonstrated in this study is most probably attributable to the implementation of the broader manual task, requiring limited fine motor control, for which the subject was able to compensate for motion effects. However, it is likely that there is an upper limit to the level of vibration for which a subject is able to compensate. This upper limit is likely to be well in excess of accelerations experienced in tall buildings in wind storms.

The duration of the manual tracking task employed is likely to have an effect on the performance results. It is understood that general performance degradation may result from motion induced fatigue (Wertheim 1998) caused by the continuous muscular effort used in maintaining balance. It has also been noted (Kjellberg and Wikström 1985), albeit for higher frequencies, that with increasing exposure duration the body tends to become stiffer. This increased stiffness may result in a higher transmissibility factor producing greater levels of vibration at the controlling limb and thereby reducing performance. Clarke (1979) investigated the effects of long duration motion at vehicular frequencies of oscillation on task proficiency, implementing tasks such as; audio vigilance, visual search, tracking and writing. He observed that although the results showed a clear decrease in performance with time, the trends were the same without vibration present. Therefore, he concluded that the effect of duration on performance was independent of whole body vibration. Although this test was conducted for higher frequencies and accelerations, Denoon (2000) reported similar findings for the lower frequencies typically associated with modern tall buildings. This hypothesis is in conflict with that of El Falou *et al*. (2003), albeit for vehicular motion, where it was noted that the experimental durations used in previous research, and their own, was not significant enough to observe the expected degradation in task proficiency as a result of the motion stimulus.

A more complex manual task and an increased level of vibration could potentially result in a shorter time period until an individual reached the point of motion induced fatigue. The duration of the motion stimulus implemented in this study, 720 seconds, may have been too short to highlight any longer term effects that a low level of vibration may have on manual task performance. Therefore, as the type of motion simulated in these tests may be applicable to a wind environment strongly influenced by shorter duration wind events, it is not appropriate to infer similar results for areas affected by longer duration synoptic type winds. It is not possible to extrapolate the results collected from this investigation into exposure durations for a typical eight hour work day, nor was the study performed with this in mind. Further investigative studies are recommended to determine the effects of longer duration low frequency motion on manual task performance.

The findings of this experiment provide the basis for an understanding of how low levels of vibration, typical of a tall building in a short duration wind storm (such as a thunderstorm), affect the performance of and individuals on a manual task and identify a direction for future studies that could lead to a procedure for providing more accurate and useful guidance for tall building designers worldwide.

The authors acknowledge that physiological effects, such as motion sickness, are also likely to be important for manual task performance. However, the main aim of the current study was to focus on the physical effects only, rather than physical and physiological. The authors are continuing their work in this field in collaboration with research colleagues with expertise in medical research and specifically in physiological and neurological effects and, extending from the experience gained from the tests conducted for the current paper, they are currently conducting further experiments that aim to study causes and effects of various motion conditions that cause “discomfort.

6. Conclusions

The conditions investigated in the experiment reported herein highlight results from a manual tracking task performed by standing subjects under low-frequency low acceleration motion typical of a tall building in a short duration wind storm, such as a thunderstorm event. The motion simulated was both above and below the perception threshold. The test results showed that there was no statistically significant trend, either performance degradation or improvement, in individual ability under any of the vibration conditions when compared to the static condition.

For the low frequency and acceleration range investigated herein, this study suggests that there is no strong increase or decrease in performance ability due to relatively coarse physical effects as a function of increasing frequency or acceleration. The test results suggest that accelerations in excess of the maximum acceleration investigated in this study, or accelerations for longer durations that distract subjects from the task at hand, are required to induce performance disruption, either through the amplification of the body's motion at resonant frequencies or through stability issues at high accelerations, or through exhaustion in long duration events.

In an environment where an occupant is required to perform manual tasks during exposure to low frequency and low acceleration vibration of a short duration, it is hypothesized that a compensation effect may occur and mitigate any performance impairment due to the physical effects of motion if the individual has interest in the task. In practice, there is likely to be a greater tendency for individuals to shift positions and move more freely about a room when suffering from feelings of motion discomfort, although individuals may feel less inclined to shift their position if they are having difficulty maintaining their balance.

The authors recognize that the difficulties encountered when translating motion effects derived from simulator investigations into motion effects in tall buildings are great, as the environmental conditions in the motion simulator are such that fear is not accurately represented. Given that the environmental factors in the simulator, and the variability amongst the subjects results was great, it is acknowledged that the results of this study form a basis for further work to be conducted in this area and do not form absolute conclusions on the ability of individuals to complete coarse manual tasks in tall buildings subjected to wind-induced motion.

It is recommended that further testing be carried out considering higher levels of acceleration and longer duration motion. For this testing it would be prudent to consider using a manual task measure that has stricter time control limits, thus discouraging the ability of any of the participants to reach the ceiling threshold of performance in the allocated time.

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