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Effects of wind-induced vibrations in tall buildings on cognitive work performance, comfort, and wellbeing of the occupants

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Abstract. Tall buildings inherently have low natural frequencies, excitable by wind loading through buffeting and vortex shedding. Such vibrations can cause discomfort or even fear in the occupants which is a design failure from vibration serviceability standpoint. Current wind-induced vibration serviceability guidelines such as ISO10137-2007, have proposed their acceptability criteria based on human *perception* of vibrations. However, recent studies suggest that such perception thresholds may not be an appropriate measure of vibration acceptability. Rather, more direct factors such as influence on work (both cognitive and physical) performance, health and wellbeing, and the emergence of mild motion sickness (sopite syndrome), should be used to assess ‘acceptability’.

This study provides experimental evidence of the effects of wind-induced vibrations on cognitive work performance, comfort, and wellbeing of the occupants. The state-of-the-art motion simulator facility, located at the University of Bath (VSimulator) was used to simulate bidirectional random vibrations, typical of tall building response due to wind loading. Under fully controlled conditions, research participants were exposed to six different motion conditions, as a cross-product of two frequencies and three peak accelerations, five of which were deemed acceptable for office buildings according to ISO-10137. Both objective and subjective psychological measurements were carried out to evaluate work performance, comfort, and wellbeing of participants subjected to these different motion characteristics. The results showed that both peak acceleration and frequency of motion had adverse effects on work performance, comfort and wellbeing of participants and showed evidence of the onset of sopite syndrome symptoms during even relatively short (~2 hour) exposures. It was concluded that even for motion conditions with peak acceleration magnitudes below the threshold of conscious perception, there were negative consequences, especially as exposure to such motions caused participants to experience sopite syndrome. The data here suggests that buildings constructed to current standards might lead to negative consequences for wellbeing and work performance even when people are not consciously aware of any motion. Current serviceability criteria might be insufficient to address acceptable levels of wind-induced vibrations in tall buildings and future design criteria could be based on how vibrations affect health, wellbeing and performance rather than simply on the perceptibility of vibrations.

1. Introduction

The advanced high-strength materials and structural systems have enabled structural engineers to design taller and lighter buildings. Such buildings are unusually flexible with lower lateral stiffness, making them particularly vulnerable to horizontal vibrations when exposed to wind loading. Wind-induced vibrations are narrow-band random with low-frequency magnitudes in the range of 0.1 to 1.0 Hz. Most tall buildings have low natural frequencies below 1 Hz which can be easily excited or resonate with wind-loading. If that happens, tall building occupants might be exposed to excessive horizontal vibrations which can negatively affect their health and wellbeing.

Research in the area of human response to wind-excited tall buildings has usually been carried out using motion simulators and real-field measurements (Kwok et al., 2009). The majority of studies so far have focused predominantly on the occupants' perception threshold of vibration to address occupant comfort, aiming to limit the maximum peak accelerations at top of tall buildings. The most recent vibration serviceability criteria, ISO 10137 (2007) used human perception thresholds to propose two frequency-dependent curves for residential and office environments, specifying the acceptable maximum accelerations at the top of a tall building with respect to its natural frequency. Recent real-field studies, however, have shown that the current serviceability criteria do not adequately address acceptability of wind-induced vibrations (Lamb and Kwok, 2017). Lamb et al. (2014) argued that other more directly relevant factors should be taken into account such as the effect of wind-induced vibrations on work performance and the incidence of mild motion sickness (sopite syndrome).

This paper investigates how wind-induced vibrations in tall buildings affect cognitive ability, wellbeing, and the severity of motion sickness and sopite syndrome symptoms. Wind-induced vibrations were simulated using a purpose-designed motion simulator facility located at the University of Bath (described in Section 2). Details of the experiments are discussed in Sections 3 and 4, and the results are discussed in Section 5.

2. VSimulator and motion simulation

VSimulator is a 3m × 4m × 2.5m self-contained motion simulator consisting of three main components: 1) a biaxial motion platform, 2) a climate-controlled test chamber, and 3) wall-projected virtual reality. The motion platform can reproduce bidirectional large-amplitude, low-frequency wind-induced vibrations on the horizontal plane, typical of medium, tall, and super tall buildings, with extremely high accuracy and low noise. The performance envelope of the VSimulator is shown in Figure 1; the green trapezoid encompasses the full range of frequency and peak acceleration magnitudes that the VSimulator is capable to simulate, i.e., peak accelerations in the range of 4 to 60 milli-g and frequencies between 0.05 to 6 Hz (1 milli-g is equivalent to 1/1000 gravitational acceleration). This covers the range of vibration magnitude criteria specified in ISO 10137 (2007) for both residential and office buildings. For more information about VSimulator, see Brownjohn and Darby (2019) and Heshmati et al. (2020).

Realistic wind-induced vibrations were simulated for two tall buildings with heights of 100m and 250m in both along-wind (parallel to wind load direction) and crosswind (perpendicular to wind load direction) directions. In the along-wind direction, the Spectral Representation Method (SRM) proposed by Deodatis (1996) was used to generate the fluctuating wind velocity time history on each storey along the tall building's height. The associated wind force time history signals were then derived based on the quasi-static assumptions (Holmes, 2007). In the crosswind direction, the quasi-static assumptions are not valid. Therefore, the wind force time history signals were derived using the generalised wind force spectrum proposed by Gu and Quan (2004) in the 1st mode of vibration. The structural responses in both directions were calculated using modal analysis and Newmark beta average constant method (Newmark,

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1959). Figure 2 shows a typical displacement response time history of a building in the along-wind direction.

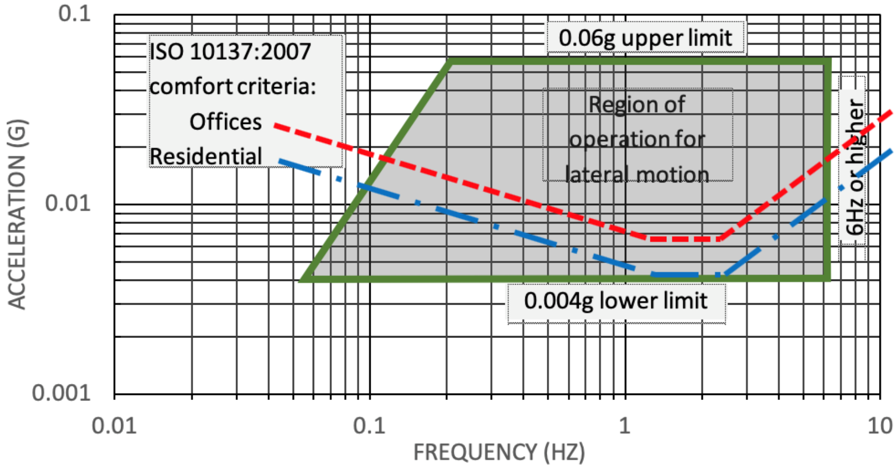

Figure 1. VSimulator's performance envelope

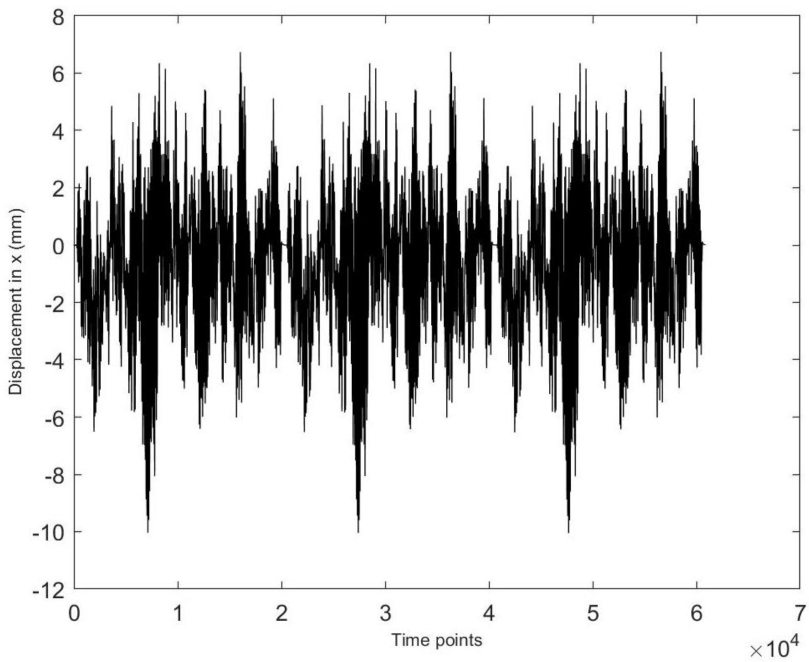

Figure 2. Displacement time history of top of a tall building in the along-wind direction

3. Motion conditions vs serviceability criteria

In total, six bi-directional motion conditions were considered with different peak accelerations and building natural frequencies, as well as a control condition (no motion) as a baseline. The details of the test conditions are presented in Table 1. The peak factor – the ratio of peak acceleration to rms acceleration was taken as 3.5 in both directions, as the commonly accepted magnitude for tall buildings (Boggs and Petersen, 1997).

Table 1. Details of test conditions

#Condition	Frequency (Hz)	Acceleration (milli-g)
1	0.2	3.0
2	0.2	6.5
3	0.2	10.0
4	0.5	3.0
5	0.5	6.5
6	0.5	10.0
7	0.0	0.0

Three peak acceleration magnitudes of 3, 6.5, and 10 milli-g were chosen based on the proposed peak acceleration thresholds for tall building habitability by Kwok et al. (2015) (Table 2). 3 milli-g is below the 'perception threshold', 10 milli-g is at the 'comfort and wellbeing threshold', and 6.5 milli-g lies between these two thresholds. Two magnitudes of 0.2 and 0.5 Hz were chosen for the natural frequency of the tall building based on the empirical Equation 1 proposed by Jeary and Ellis (1983) for multi-storey buildings with a uniform plan, where the building's natural frequency (f) is inversely related to its height (H). For tall buildings with height between 100 to 250 metres, natural frequencies lie in the range of 0.2 to 0.5 Hz (Equation 1).

$$H\ (m) = \frac{46}{f\ (Hz)} \qquad \text{Equation 1}$$

Table 2. Habitability thresholds proposed by (Kwok et al., 2015)

Peak acceleration threshold (milli-g)	**Threshold level**	**Description**
5	Perception	- Perceptible acceleration to many occupants. - Unlikely to cause significant adverse occupant response or alarm. - Not frequently happening event for a long duration.
10	Comfort & wellbeing	- Perceptible acceleration limit to vast majority of occupants. - Not acceptable for occupants susceptible to motion sickness if it occurs frequently for long durations.
35-40	Fear & safety	- Some occupants lose their balance. - 40 milli-g acceptable for buildings with natural frequencies around 0.1 Hz. - 35 milli-g acceptable for buildings with natural frequencies around 0.4 Hz. - Likely to happen just in extreme wind events.

Figure 3 shows Conditions 1 to 6 on the serviceability assessment graph proposed in ISO 10137 (2007); Curve 1 and Curve 2 are associated with office and residential buildings respectively. f_0 on the x-axis represents the natural frequency of a building in Hz and A on the y-axis is the peak acceleration in m/s2. The 'perception' and 'comfort and wellbeing' thresholds proposed by Kwok et al. (2015) (Table 2) are also shown in Figure 3 as horizontal lines. As shown in the figure, all conditions were at or below the 'comfort and wellbeing' threshold, and only Condition 6 is deemed unacceptable for office buildings as it is above the limit proposed by ISO 10137 (2007).

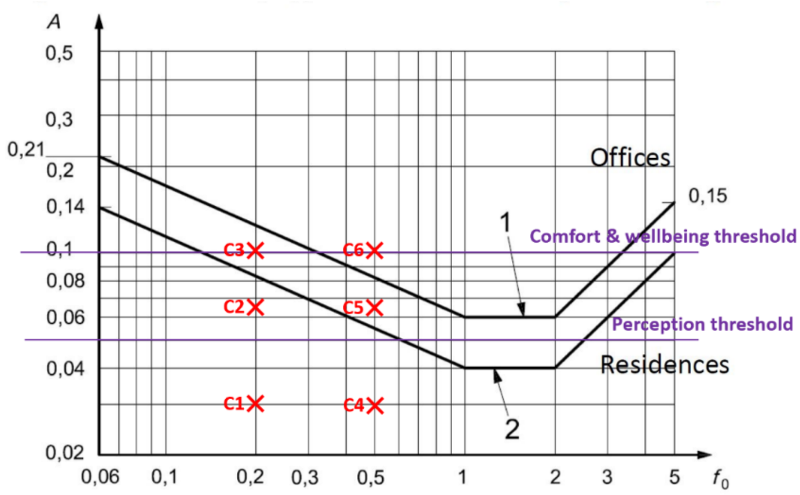

Figure 3. Motion conditions vs ISO10137 graph

4. Measurements

Both objective and subjective techniques were used to measure the human response to motion. The VSimulator Test Battery (VSTB), in the form of an automated software, was programmed in PsychoPy software v2020 (Peirce et al., 2019) to assess cognitive performance (Section 4.1), sopite syndrome (Section 4.2) and wellbeing (Section 4.3) of the subjects.

Twenty-one healthy participants, 11 males and 10 females, were recruited for the test with a mean age of 27.7 years. Fifteen participants were tested individually in the VSimulator while the rest of six participants were tested in pairs. A 2D virtual reality projection on the walls provided a sense of surroundings and external views of an office environment at the top of a tall building. Indoor air quality was controlled to be within the recommended comfort range: temperature between 20°C and 22°C (ASHRAE Standard 55, 2017), relative humidity kept at around 50%, and CO2 levels kept below 1000 ppm (ASHRAE Standard 62, 2001).

Each participant was tested in all 6 motion test conditions described in Table 1. Test conditions were run in a random order to counteract the learning effect. Each test condition lasted for approximately 25 minutes during which participants carried out the VSTB on a laptop. A short break was given to the participants after running each three consecutive test conditions to avoid participants becoming tired or unwell.

4.1. Cognitive performance

Cognitive performance was measured in an objective manner. Six well-known cognitive tests were included in the VSTB associated with three main aspects of cognition: attention, memory, and executive function (Carlson et al., 2013). To contextualize the cognitive tests and link them to the actual office tasks, two simulated-office tasks were added to the VSTB. The details of the VSTB-cognitive tests are presented in Table 3. For each cognitive test, cognitive performance was measured in terms of the effort score. Effort score for each cognitive test was calculated as the ratio of response time to the accuracy of response. As a result, higher effort scores are associated with lower cognitive performance. To standardize all eight VSTB-cognitive tests, the effort scores were converted to the corresponding z-score values in units of standard deviation.

Table 3. Details of VSTB cognitive tests

Category	Test name	Test definition/description
Attention	Visual search	A set of shapes including eight pentagons and one hexagon is shown on the screen in an arbitrary format. Participants are asked to detect the hexagon among pentagons and click on it.
	RVIP	RVIP stands for Rapid Visual Information Processing in which a sequence of one-digit numbers comes up on the screen in a random order. Participants are asked to look for a particular sequence including three digits and press “space” when they find it.
Memory	Letter span memory	A random selection of 10 English letters appears on the screen for a couple of seconds. Then, a single letter comes up. Participants are asked to respond whether that letter was included in the previous random words or not.
	Corsi	A sequence of flashing squares is shown on the screen in a random order. Participants are asked to remember the sequence they observed and repeat it by clicking on the squares.
Executive function	Stroop	While there might be a mismatch between the ink colour and the word including the name of a colour, participants are asked to respond to a stimulus according to the ink colour.
	Go-No Go	Participants are asked to press “space” on the keyboard when they see ‘Go’ on the screen, and not press any key when they see ‘No Go’
Simulated-office task	Addition	A set of two 2-digit numbers comes up on the screen. Participants are asked to sum up those numbers and type the answer.
	Typing	A paragraph is shown on the screen. Participants are asked to type the paragraph.

4.2. Motion sickness and sopite syndrome

Motion sickness and sopite syndrome were measured subjectively through the Motion Sickness Assessment Questionnaire (MSAQ) proposed by Gianaros et al. (2001). MSAQ contains four subscales of motion sickness symptoms: gastrointestinal (feeling sick to stomach, queasiness, nauseous, vomit), central (lightheaded, faint-like, dizziness, disoriented, spinning-like), peripheral (feeling sweaty, clammy, hot/warm), and sopite (uneasiness, drowsiness, annoyed, tired/fatigued). The MSAQ scores for each subscale were recorded on a 7-point Likert scale (Joshi et al., 2015), where 1 and 7 were associated with the minimum and maximum severity of symptoms respectively.

4.3. Wellbeing
Wellbeing was evaluated using four questions associated with the level of stress, motivation, general mood, and general satisfaction. The questions were chosen based on the previous studies in the area of wind-excited tall buildings (Burton, 2006; Denoon et al., 2000; Lamb and Kwok, 2019). The scores were recorded on a 7-point Likert scale.

5. Results and discussion
Linear Mixed Models (LMMs) were the statistical tool used to analyse whether the difference in cognitive test effort scores and MSAQ and wellbeing questionnaire scores is attributed to motion exposure or not. The analysis was conducted using the 'lmer()' function of the 'lme4' package in R (Bates et al., 2014). In the analysis, the scores associated with cognitive performance, MSAQ and wellbeing questionnaire were considered as dependent variables. The independent variables were peak acceleration and frequency. Individual differences were considered as a random factor in LMMs.

The cognitive effort score was calculated as the average score of all eight VSTB cognitive tests mentioned in Table 3. The results showed that the effect of both peak acceleration and frequency on the cognitive effort score was significant as the associated p-values were less than 0.05. According to Figure 4, as peak acceleration increased from 0 to 10 milli-g, the cognitive effort score increased by 0.33 and 0.62 standard deviations for frequency levels of 0.2 and 0.5 Hz respectively. This suggests a significant drop in cognitive performance as the intensity of motion increased.

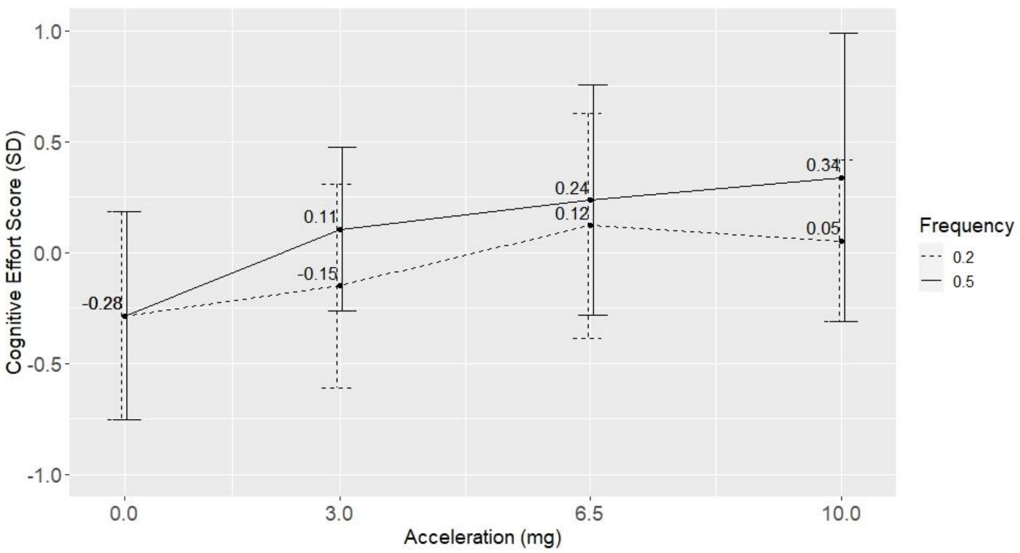

Figure 4. Effect of acceleration and frequency on cognitive effort score

The results of the MSAQ scores showed that the effect of peak acceleration on gastrointestinal, central, and sopite subscales was significant such that the increase in peak acceleration from 0 to 10 milli-g was associated with 11.4%, 24.5%, and 17.7% increase in the respective scores. The sopite score was found as the only MSAQ subscale affected by frequency while it increased from 0 to 0.5 Hz. Figure 5 shows the changes in MSAQ-sopite score with respect to peak acceleration at frequencies of 0.2 and 0.5 Hz.

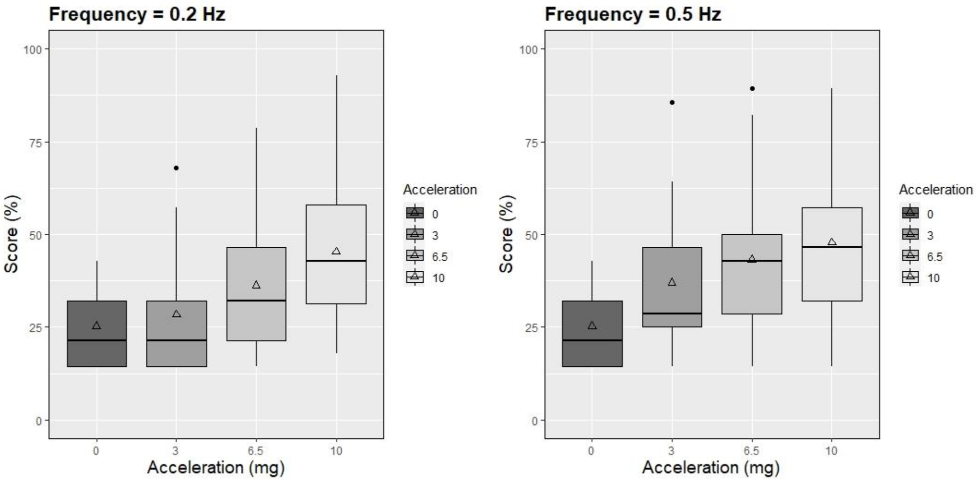

Figure 5. MSAQ-sopite score in different frequency levels

The average wellbeing score was calculated as the average score of the four questions described in Section 4.3. According to the results, the effect of peak acceleration on the average wellbeing score was found to be significant. As peak acceleration increased from 0 to 10 milli-g, the score dropped by 0.97 and 1.11 Likert units for vibration frequencies of 0.2 and 0.5 Hz respectively (Figure 6).

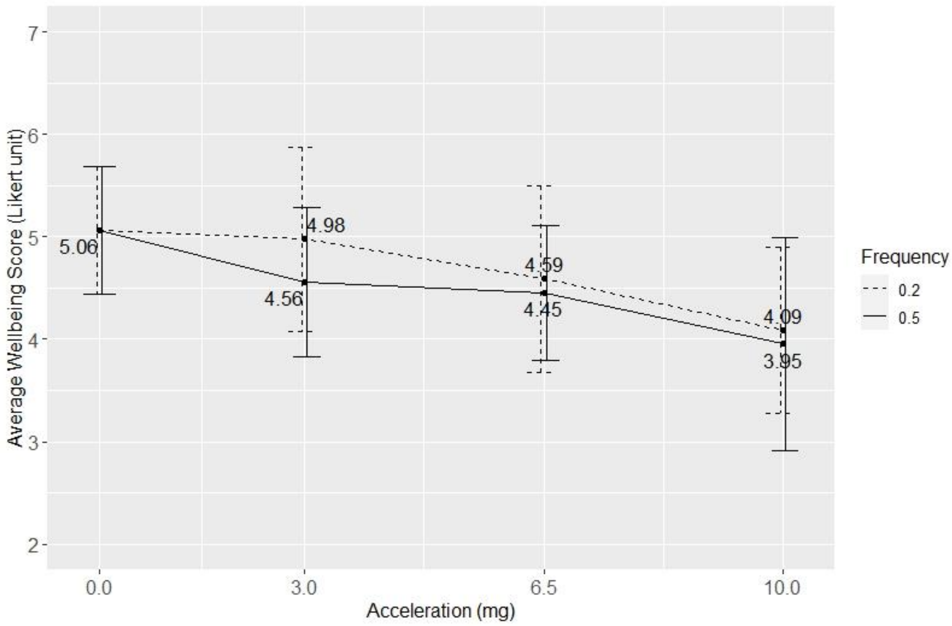

Figure 6. Effect of acceleration and frequency on average wellbeing

6. Conclusions

The results of the study show that the health status of participants is affected by motion. The score of three out of four subscales of motion sickness in the MSAQ were significantly affected by increases in peak acceleration. Central and sopite subscales were the most influenced ones. It can be concluded that participants suffered increasing symptoms of motion sickness and sopite syndrome as peak acceleration increased up to 10 milli-g. It is worth mentioning that in all motion conditions, the peak acceleration magnitude was equal to, or below, the 'comfort and wellbeing' threshold, and just one condition was not considered acceptable according to ISO 10137 (2007), as explained in Section 3. The average wellbeing score of participants also dropped significantly, confirming the effect of motion on participants' health. Cognitive effort score of participants was highly affected by increases in peak acceleration and frequency, and detrimental effects on the cognitive performance of office workers caused by horizontal motions were observed at peak accelerations below the previously proposed 'comfort and wellbeing' threshold. It is therefore concluded that there is a need to improve the vibration acceptability criteria in tall buildings as the current 'perception threshold' based criteria seem unable to account for the impact and effects of wind-induced vibrations on human occupants of tall buildings.

References

ASHRAE Standard 55. (2017). Standard 55–2017 thermal environmental conditions for human occupancy. In *Ashrae: Atlanta, GA, USA*.

ASHRAE Standard 62. (2001). Standard 62–2001 Ventilation for acceptable indoor air quality, Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers. In: Inc.

Bates D, Mächler M, Bolker B and Walker S (2014). Fitting linear mixed-effects models using lme4. *arXiv preprint arXiv:1406.5823*.

Boggs D and Petersen C P (1997). Acceleration indexes for human comfort in tall buildings–Peak or RMS. *CTBUH monograph*, 1-21.

Brownjohn J M W and Darby A (2019). *Human factors simulation for motion and serviceability in the built environment* 13th UK Conference on Wind Engineering Leeds.

Burton M D (2006). *Effects of low frequency wind-induced building motion on occupant comfort* PhD thesis The Hong Kong University of Science and Technology.

Carlson S M, Zelazo P D, and Faja S (2013). Executive function.

Denoon R, Roberts R, Letchford C and Kwok K C (2000). *Effects of wind-induced tall building motion on cognitive performance* (RESEARCH REPORT-UNIVERSITY OF SYDNEY DEPARTMENT OF CIVIL ENGINEERING R, Issue.

Deodatis G (1996). Simulation of ergodic multivariate stochastic processes. *Journal of engineering mechanics*, *122*(8), 778-787.

Gianaros P J, Muth E R, Mordkoff J T, Levine M E and Stern R M (2001). A questionnaire for the assessment of the multiple dimensions of motion sickness. *Aviation, Space, and Environmental Medicine*, *72*(2), 115.

Gu M and Quan Y (2004). Across-wind loads of typical tall buildings. *Journal of Wind Engineering and Industrial Aerodynamics*, *92*(13), 1147-1165.

Journal of Physics: Conference Series **2647** (2024) 252032 doi:10.1088/1742-6596/2647/25/252032

Heshmati K, Shahabpoor E, Darby A and Walker I (2020). Moving from Human Perception to Acceptability: A Paradigm Shift in Vibration Serviceability Assessment of Tall Buildings. *Structures Congress, 2020.*

Holmes J D (2007). *Wind Loading Of Structures*. CRC press.

ISO 10137 (2007). Bases for design of structures–Serviceability of buildings and walkways against vibration. In: *International Organization for Standardization Geneva*.

Jeary A and Ellis B (1983). On predicting the response of tall buildings to wind excitation. *Journal of Wind Engineering and Industrial Aerodynamics*, *13*(1-3), 173-182.

Joshi A, Kale S, Chandel S and Pal D K (2015). Likert scale: Explored and explained. *British Journal of Applied Science & Technology*, *7*(4), 396.

Kwok K C, Burton M D and Abdelrazaq A K (2015). Wind-induced motion of tall buildings: designing for habitability.

Kwok K C, Hitchcock P A and Burton M D (2009). Perception of vibration and occupant comfort in wind-excited tall buildings. *Journal of Wind Engineering and Industrial Aerodynamics*, *97*(7-8), 368-380.

Lamb S and Kwok K C (2017). The fundamental human response to wind-induced building motion. *Journal of Wind Engineering and Industrial Aerodynamics*, *165*, 79-85.

Lamb S and Kwok K C (2019). The effects of motion sickness and sopite syndrome on office workers in an 18-month field study of tall buildings. *Journal of Wind Engineering and Industrial Aerodynamics*, *186*, 105-122.

Lamb S, Kwok K C and Walton D (2014). A longitudinal field study of the effects of wind-induced building motion on occupant wellbeing and work performance. *Journal of Wind Engineering and Industrial Aerodynamics*, *133*, 39-51.

Newmark N M (1959). A method of computation for structural dynamics. *Journal of The Engineering Mechanics Division*, *85*(3), 67-94.

Peirce J, Gray J R, Simpson S, MacAskill M, Höchenberger R, Sogo H, Kastman E and Lindeløv J K (2019). PsychoPy2: Experiments in behavior made easy. *Behavior research methods*, *51*(1), 195-203.