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The effect of wind-induced vibrations in tall buildings on occupants' work performance

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ABSTRACT

This study investigated the effects of wind-induced vibrations in tall buildings on occupants' work performance. Controlled experiments were conducted using a specialized motion simulator at University of Bath (VSimulator) to simulate wind-induced vibrations. A comprehensive psychological test battery was developed to measure cognitive abilities – attention, memory, and executive function – as well as subjective work performance. Twenty-one participants completed the test battery under various motion conditions, with peak accelerations both above and below the perception threshold. Unlike previous studies, this paper shows a consistent correlation between work performance and both peak acceleration and frequency of motion. Within the tested range (0–0.1 ms^{-2}), a 0.1 ms^{-2} increase in peak acceleration was associated with an average decrease of 0.2 standard deviations in cognitive performance, 0.5 Likert-unit decrease in self-reported performance, and 0.4 Likert-unit increase in subjective effort. Furthermore, within the tested range (0–0.5 Hz), a 0.5 Hz increase in frequency was associated with an average decrease of 0.2 standard deviations in cognitive performance. This is the first controlled study of realistic tall building vibrations to show that wind-induced vibrations can potentially impair cognitive performance. The research outcome provides a foundation for future vibration serviceability studies where work performance is central to defining serviceability criteria.

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Vibration acceptability; cognitive performance; occupant comfort; peak acceleration; random vibration

Introduction

Occupants of tall buildings are frequently exposed to vibrations induced by wind loads in wind-prone regions. The number of buildings adversely affected by such vibrations is increasing as design trends shift towards lighter, more open plan, slimmer and taller buildings with lower carbon footprint. According to the Council on Tall Buildings and Urban Habitat (2018), any structure of at least 14 storeys or exceeding 50 metres in height is considered as a tall building. Wind-induced vibrations are of narrow-band random nature, with dominant frequencies typically within the range of 0.1–1.0 Hz (Kwok et al., 2015). In buildings with natural frequencies within this range, instances of resonance are common and such vibrations can induce large amplitude motions causing discomfort, or even fear, among the occupants (Lamb & Kwok, 2019). This is a critical design issue from a serviceability standpoint and can significantly impact the building performance.

Over the past five decades, researchers have investigated the effects of wind-induced vibrations on occupants. While a number of studies have focused on real-life tall building measurements (Denoon et al., 2000a; Goto, 1983; Hansen et al., 1973; Isyumov & Kilpatrick, 1996; Lamb et al., 2014; Lamb & Kwok, 2019; Lee, 1983), the majority of research utilized motion simulators, predominantly due to ease of access, better control over test parameters, and much wider measurement options not feasible in a real-life setting. The simulator-based studies predominantly examined the effects of unidirectional sinusoidal motions on perception thresholds (Burton, 2006; Chen & Robertson, 1972; Denoon et al., 2000b; Goto, 1990; Irwin, 1981; Irwin & Goto, 1984; Kanda, 1988, 1990; Khan, 1971; Michaels et al., 2013; Noguchi et al., 1993; Shioya, 1993; Tamura et al., 2006). The rationale for employing perception thresholds as a metric for assessing building performance was that maintaining motion below the perception threshold reduces the likelihood of occupants registering a formal complaint (Isyumov & Kilpatrick, 1996). Recent studies, however, have revealed that formal complaint is not a reliable metric of tall building performance (Lamb et al., 2013); occupants

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tend to tolerate discomfort even when it may have meaningful effects on their health, wellbeing, or productivity. Furthermore, evidence suggests that negative effects on occupants can occur even with sub-perception vibrations (Hammam et al., 2014).

Current serviceability criteria (ISO10137:2007) are based on occupants' perception threshold of motion. Two frequency-dependent curves with 1-year return period were introduced, one for office buildings and one for residential buildings, to establish acceptable peak acceleration limits relative to the building's natural frequency. This approach, however, is deemed inadequate since it does not account for the potential impact of wind-induced vibrations on occupants' work performance or wellbeing (Lamb & Kwok, 2017a). Furthermore, it cannot be assumed that perception thresholds are directly proportional to motion acceptability. Acceptable vibration levels can be defined as 'those that produce minimal or negligible adverse effects on occupant's wellbeing or work performance' (Lamb & Kwok, 2017b). In a longitudinal field study, Lamb et al. (2014) conducted an online survey to collect data from office workers in tall buildings in Wellington, New Zealand. They reported a significant reduction in work performance and an increased prevalence of mild motion sickness (sopite syndrome) symptoms, even at acceleration levels below those specified by ISO10137:2007. Lamb et al. (2016) further emphasized that, rather than relying solely on the frequency-dependent curves outlined in ISO10137:2007, it is imperative to incorporate a combination of motion factors, including acceleration, frequency, motion type, and duration of exposure, into the design criteria to better anticipate the impact of wind-induced vibrations on building occupants.

Previous studies, both in motion simulators and real field settings, investigating the effects of wind-induced vibrations on work performance in tall buildings, have not always consistently presented a coherent picture, and their findings are occasionally contradictory. In a field study conducted by Jeary et al. (1988), participants were involved in a series of cognitive tasks. They were exposed to three levels of unidirectional side-to-side sinusoidal vibrations with peak accelerations of 0, 1, and 4 milli-g (1 milli-g is equivalent to 1/1000th of gravitational acceleration, 9.80665 ms^{-2}). These vibrations were produced by vibration generators within a real 10-storey building with a natural frequency of 1.6 Hz. The authors reported no significant effect of vibrations on cognitive task performance. However, they raised the possibility that the cognitive tasks might have been too simplistic for the participants and the experiments' duration might not have been sufficient to reveal any potential effect.

Denoon et al. (2000a) conducted a field study on three airport control towers in Australia, measuring peak accelerations in two orthogonal directions ranging from 0 to 12 milli-g. Participants carried out a series of cognitive tests involving reaction time, word recognition, memory, and logical reasoning. No correlation was reported between vibrations and the occupants' cognitive performance. Denoon et al. (2000b) also carried out a motion simulator study, exposing participants to two separate unidirectional narrow-band random motion signals obtained from one of the airport towers. These motion signals had RMS (root-mean-square) accelerations of 8.15 and 0.66 milli-g and featured a dominant natural frequency of 0.39 Hz. Using the same cognitive tests as in their previous study (Denoon et al., 2000a), the authors found no correlation between these vibrations and cognitive performance. The authors however acknowledged that the cognitive tests used in these studies were simplistic and did not effectively represent real office tasks.

In a motion simulator study conducted by Burton (2006), a variety of unidirectional and bidirectional narrow-band random motions were generated. These motions included frequencies ranging from 0.125 to 0.5 Hz, peak accelerations spanning from 1 to 24 milli-g, and three peak factor magnitudes (the ratio of peak to RMS acceleration) of 1.7, 3.3, and 4.8. Participants were exposed to these vibrations while completing cognitive tests, which included reaction time, tracing, arrow sequence, attention switching, and word reasoning tests. The study did not reveal a direct relationship between these vibrations and the cognitive performance of participants. In a recent real-field study by Lamb and Kwok (2019), the impact of acceleration dose (exposure to building accelerations over time) on cognitive performance, including memory, arithmetic and vigilance tasks, was also found to be statistically non-significant.

Contrary to these findings, Lamb et al. (2014) assessed work performance through a questionnaire and reported a reduction of approximately one standard deviation in self-reported work performance score among office workers when exposed to wind-induced vibrations in comparison to a no-motion condition. Additionally, the authors noted that motion exposure had a negative impact on the Stroop test scores of the participants (Bench et al., 1993). In another field study by Lamb and Kwok (2019), work performance was measured using a self-reported work performance questionnaire and the NASA Task Load Index (Hart, 2006), a measure of task-based effort. Their findings indicated that increases in acceleration dose magnitudes were associated with decreases in both self-reported work performance and task effort scores.

The increasing experimental evidence in the literature suggests that a paradigm shift is necessary for the vibration serviceability assessment of tall buildings under wind loading, moving away from the sole reliance on motion perception thresholds. Instead, it is crucial to adopt a more relevant, comprehensive, and building/use-case specific set of criteria that encompass occupants' work performance, comfort, health, and well-being (Heshmati, 2022; Heshmati et al., 2020; Lamb et al., 2016). This paper focuses on the vibration acceptability of tall building offices and specifically investigates the effects of wind-induced vibrations on the work performance of their occupants. Enabled by the world-wide unique simulation and measurement capabilities of the Bath VSimulator facility, this study improves on the state-of-the art through: (a) using a realistic bidirectional wind-induced vibration signals to run the VSimulator; (b) detailed and comprehensive control of test conditions including motion parameters, environmental parameters such as temperature, humidity, and CO_2 level, and realistic simulation of the office environment layout within VSimulator using a projected virtual reality equipment (VR); and (c) measuring work performance in a systemic way via a variety of standard objective and subjective measures/tests. The research methodology is described in the *Methodology* section, followed by a description of the data analysis in the *Data analysis* section. The *Results* section presents the research findings, which are then discussed in the *Discussion* section, followed by the *Conclusions*.

Methodology

Wind-induced vibrations were simulated using the Bath VSimulator facility (shown schematically in Figure 1), a $3 \times 4 \times 2.5$ m environmentally controlled test chamber sitting on a hydraulically controlled motion platform.

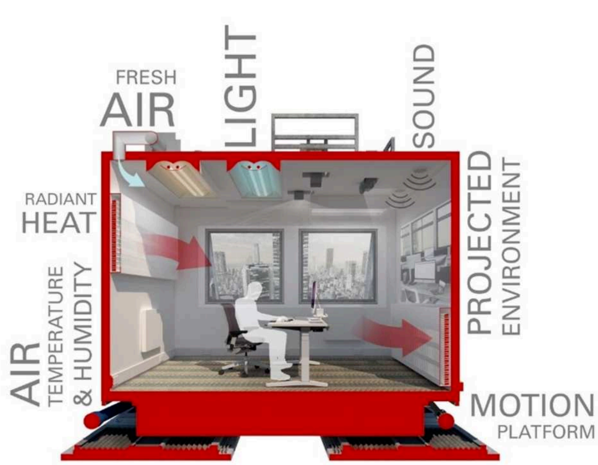

Figure 1. University of Bath motion simulator 'VSimulator'.

The facility is optimized for simulating low-frequency, large-amplitude wind-induced lateral vibrations, including peak accelerations within the range of 0.03–0.60 ms^{-2} (equivalent to 3–60 milli-g) and a range of frequencies from 0.05 to 6 Hz, encompassing the entire spectrum specified by ISO10137:2007. The key differentiating capability of this motion platform is its extremely high accuracy and smoothness while simulating the motion. This is critical since wind-induced vibrations are low-acceleration and low-frequency, and therefore, any small imperfections in motion can alert participants and compromise the test conditions. The VR within VSimulator projects images onto the walls, providing a contextualized perception of both internal and external surroundings. In this study, the monoscope VR was utilized to project a 2D view inside an office environment and an outside view on three walls of the chamber. For more information about VSimulator and its capabilities, please refer to Heshmati et al. (2020).

Wind-induced motion conditions

A set of narrow-band random bidirectional wind-induced vibrations were simulated in the form of displacement signals to drive VSimulator in the horizontal plane. A Matlab code was developed to simulate these signals in both along-wind (parallel to the wind load direction) and crosswind (perpendicular to the wind load direction) directions. This method provided explicit control over modal properties of the building and motion characteristics, including peak acceleration, frequency, and peak factor. The displacement signals in the along-wind direction were generated using the Spectral Representation Method for multi-degree-of-freedom systems (Deodatis, 1996). The fluctuating wind velocity time history for each degree of freedom within a building (building storey) was assumed as a stochastic process and simulated in accordance with the Spectral Representation Method. Subsequently, wind pressure and force time histories corresponding to each fluctuating velocity time history were derived under quasi-static assumptions (Holmes, 2001). The acceleration and displacement responses at each degree of freedom were then computed using modal analysis and the Newmark beta method (Newmark, 1959). Due to the vortex shedding effect, wake excitation, and turbulent inflow in the crosswind direction, the quasi-static assumptions, suitable for along-wind forces, were not applicable to crosswind simulations. Crosswind vibrations were simulated using the semi-empirical method (Gu & Quan, 2004), which proposes a generalized wind-force spectrum for the first vibration mode of tall buildings. The spectrum was calibrated through wind-tunnel tests on 15 building models of varied cross-sections and aspect ratios, using High-Frequency Force Balance technique to measure crosswind aerodynamic loads. Similar to the along-wind direction, the acceleration and displacement responses were computed using modal analysis and Newmark beta method.

In total, five motion characteristics were considered to generate the signals: peak acceleration, frequency, duration, peak factor, and direction. The latter two parameters were constant in all tests, i.e. bidirectional motion and peak factor of 3.5, typical for tall buildings (Boggs & Petersen, 1997). Kwok et al. (2015) proposed that peak accelerations of 5 and 10 milli-g represent the 'perception' and 'comfort and wellbeing' thresholds, respectively. For the tests described in this paper, three peak accelerations were used: 3 milli-g (below perception threshold), 6.5 milli-g (perceptible, but below comfort and wellbeing threshold), and 10 milli-g (exceeding comfort and wellbeing threshold). Larger peak accelerations were not used due to their infrequent occurrence in real buildings. Two frequencies of 0.2 and 0.5 Hz were used, representing the natural frequencies of two tall buildings with respective heights of 250 metres and 100 metres, based on the empirical formula proposed by Jeary and Ellis (1983). Figure 2 displays a typical bidirectional simulated vibration response, with a peak acceleration magnitude of 6.5 milli-g, a peak factor of 3.5, and a frequency of 0.2 Hz. Motion signals in both directions were simulated for a duration of 496 s.

Only the first mode of vibration (0.2 Hz, for acceleration signals shown in Figure 2(a and b)) is used to simulate the building's response. Figure 3 shows the corresponding one-sided amplitude spectrums in both along-wind and crosswind directions, with a single peak at 0.2 Hz. Wind-gust wavelengths generally exceed a tall building's height, so the nearly uniform pressure field excites primarily the first mode while weakly affecting higher modes with alternating sign mode shapes along the height (Boggs & Dragovich, 2006).

VSimulator setup

The internal space of VSimulator chamber was set up to represent an open-plan office environment with an outside view from a tall building storey (Figure 4). The virtual time of day was set to 9:00 am for morning tests, and 3:00 pm for afternoon tests. All other controllable indoor air quality parameters were kept constant at the recommended comfort standards: temperature was maintained between the range of 20°C and 22°C (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE], 2017), relative humidity was held at approximately 50%, and CO_2 levels were maintained below 1000 ppm (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE], 2001). Workstations were arranged such that one or two participants were seated in the same direction, each equipped with a desk, a laptop, a mouse, an LED light, and an office wheelchair (Figure 4). The workstations were positioned to expose participants to along-wind and crosswind vibrations in the fore-aft and side-to-side directions, respectively.

Participants

The number of participants (sample size) was calculated using power analysis in G*Power (Faul et al., 2007). The power calculation showed that 21 participants were sufficient to explore effects down to $f = 0.12$ with $\alpha = .05$ and power = .80. Twenty-one participants, with a mean age of 27.7 years and a standard deviation of 9.4, participated in the tests. 52.4% of participants were female ($N = 11$), and 47.6% were male ($N = 10$). Before the test day, participants were provided with a short training video to familiarize themselves with the test protocol.

Work performance measurement

Work performance was assessed through three methods: (1) a series of cognitive tests to measure participants' cognitive performance, (2) a self-reported performance questionnaire measuring participants' perception of their performance, and (3) a subjective effort questionnaire to measure workload. A test battery, including all these cognitive tests and questionnaires, was developed using PsychoPy v2020 (Peirce et al., 2019), in the form of a visual interactive computer application.

Cognitive tests

Cognition encompasses the human capacity to process and remember information, as well as metacognitive abilities such as the ability to consciously switch between tasks. In this context, cognitive performance was considered as an objective measure of core workplace skills in an office environment. Manual task dexterity/performance was not considered in these experiments. This study addresses concerns in the literature regarding the simplicity of generic cognitive tests by adopting a comprehensive approach to measure three key cognitive domains – attention, memory, and executive function, defined as the ability to control and coordinate cognitive processes to achieve goals (Carlson et al., 2013). Six established cognitive tests, two for each domain, were selected from the literature,

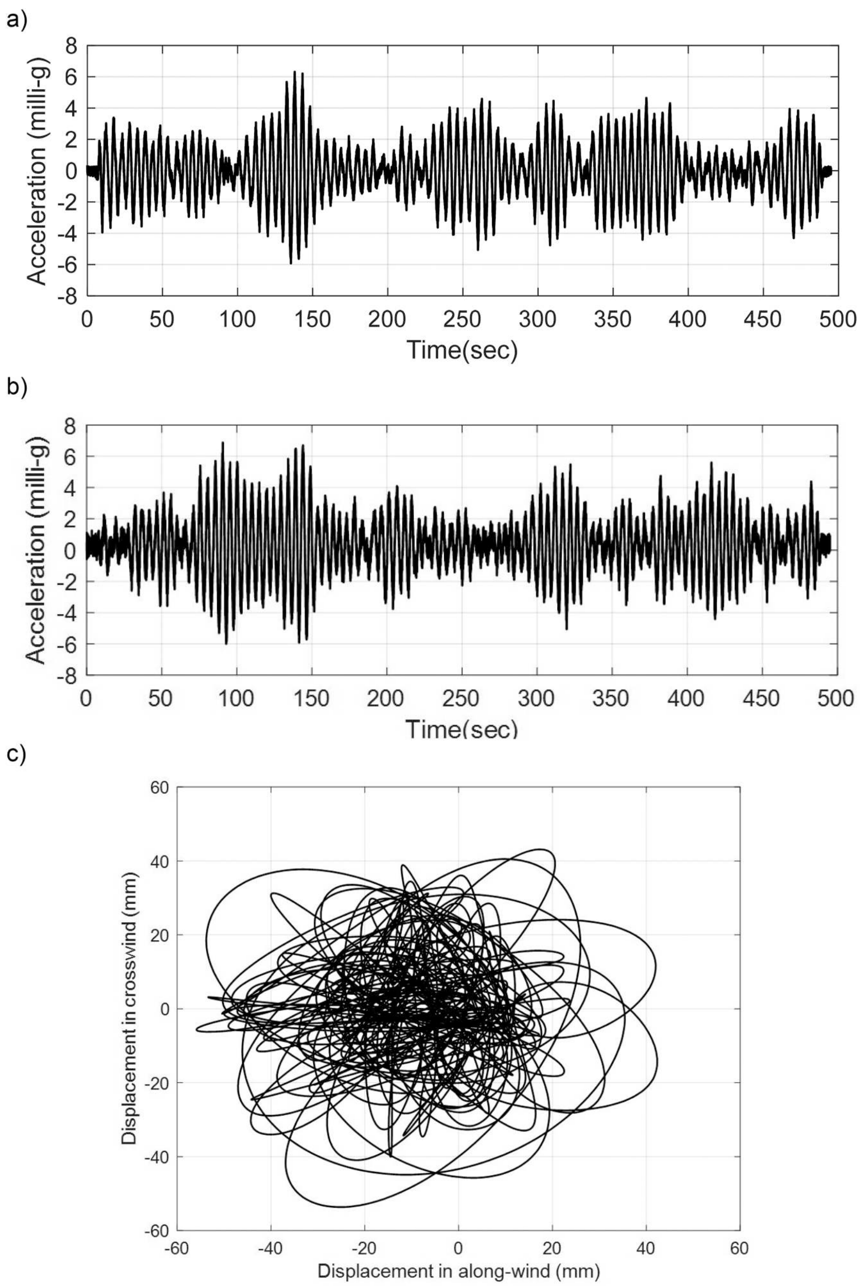

Figure 2. Typical simulated response with frequency of 0.2 Hz, peak acceleration of 6.5 milli-g and a peak factor of 3.5. (a) Along-wind acceleration time history; (b) crosswind acceleration time history; (c) bidirectional displacement.

along with two tests simulating real-life office tasks: addition and typing. The description of the selected cognitive tests and their measured parameters are presented in Table 1.

In Table 1, 'accuracy' represents the percentage of correct answers, while 'speed' is the average response time in seconds. Cognitive performance for each test was assessed using a 'cognitive score', calculated as the ratio of response time to accuracy. Higher scores indicate lower cognitive performance, as they reflect slower and/or less accurate responses.

Self-reported performance

Self-reported performance was assessed using a questionnaire adopted from Lamb and Kwok (2019) and Lamb et al. (2014), rated on a 7-point Likert scale (Joshi et al., 2015), where 1 and 7 represented the lowest and highest perceived performance, respectively.

Subjective effort

A subjective effort was assessed using the NASA Task Load Index (NASA-TLX) questionnaire, a multidimensional scale designed to measure workload (Hart, 2006). NASA-TLX includes six dimensions:

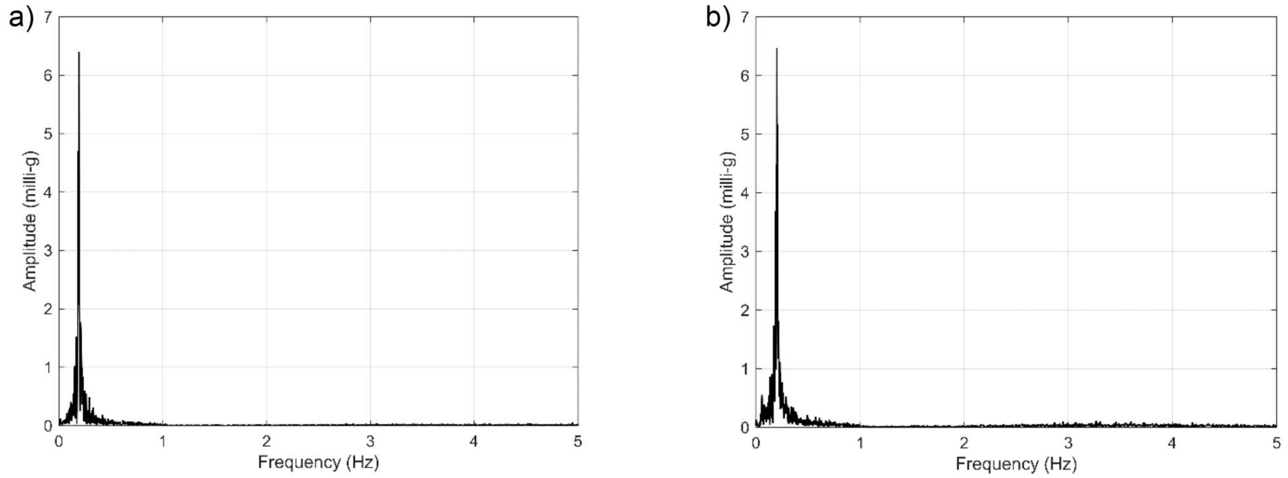

Figure 3. One-sided amplitude spectra of the simulated acceleration response with dominant frequency of 0.2 Hz, peak acceleration of 6.5 milli-g and a peak factor of 3.5: (a) along-wind acceleration; (b) crosswind acceleration.

mental demand, physical demand, temporal demand, performance, effort, and frustration level, providing insight into the level of effort exerted by participants while performing a task. In this study, participants rated each of the six dimensions on a 7-point Likert scale. The subjective effort score was computed as the average score across all six dimensions. A higher effort score indicates a greater level of effort required to complete the tests.

Test procedure

The experiments were conducted over seven months. Each participant completed two test sessions over a full day: the morning session focused on the effects of peak acceleration and frequency of motion on work performance, and the afternoon session examined the impact of motion duration. In the morning session, all 21 participants went through seven test conditions shown in Table 2.

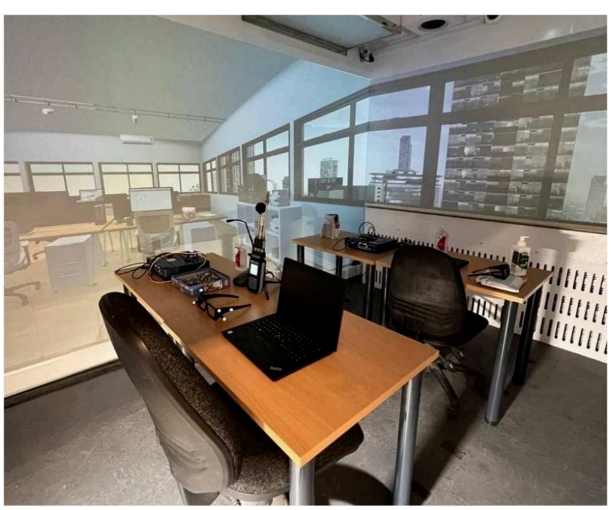

Figure 4. VSimulator internal layout simulating an office environment with workstations.

The control condition 7 (no motion) serves as the baseline for each participant. In each condition, participants carried out the test battery over a period of approximately 25 min. To simulate motions over this period, the motion signals generated with a duration of 496 s (as shown in Figure 2) were repeated as necessary. To minimize the effects of expectancy, learning effects, and fatigue, the order of conditions was randomized for each participant. Furthermore, the contents of the cognitive tests (Table 1) were randomly generated each time that they run, i.e. in each condition. After running three consecutive conditions, participants were given a break during which they were required to leave the VSimulator chamber.

In the afternoon session, participants were split into two groups: 11 participants were exposed to sub-perceptible motion (Condition 8 in Table 3), and 10 participants were tested in the control condition (Condition 9 in Table 3). Participants were not informed of which motion condition they experienced.

In Conditions 8 and 9, participants were tested over a period of 140 min, during which they completed the test battery twice: once at the beginning and once at the end of the session. Between these two tests, for approximately 90–110 min depending on participants' speed, they were engaged in typical office-based tasks in-line with their daily real-life work. For participants in Condition 8, the 496-second motion signals were repeated approximately 17 times to cover the entire 140-mimute test period. The key aim of the afternoon session was to investigate the effects of duration of the sub-perceptible motion (with peak acceleration of 3 milli-g) on work

Table 1. Details of the cognitive tests included in the test battery.

Cognition aspect	Test name	Measure	Description
Attention	Visual search	Speed	A set of eight pentagons and one hexagon was shown on the screen in an arbitrary position. Participants were asked to find and click on the hexagon.
	RVIP	Speed Accuracy	RVIP stands for Rapid Visual Information Processing in which a sequence of one-digit numbers appeared on the screen in a random order. Participants were asked to look for a specified sequence of three digits and press 'space' when they find it.
Memory	Letter span memory	Speed Accuracy	A random selection of 10 English letters appeared on the screen for a few seconds. Then, a single letter appeared. Participants were asked to respond whether that letter was included in the previous group of random letters or not.
	Corsi	Speed Accuracy	A sequence of flashing squares was shown on the screen in a random order. Participants were asked to remember the sequence they observed and repeat it by clicking on the squares.
Executive function	Stroop	Speed Accuracy	The words 'Red', 'Blue', and 'Green' appeared on the screen in a random order, and with a randomly assigned font colour (i.e. not necessarily the same as the word). Participants were asked to respond to the stimulus according to the font colour, not the word itself.
	Go-No Go	Speed Accuracy	Participants were asked to press space bar key on the keyboard when they saw 'Go' on the screen, and not press any keys when they saw 'No Go'
Real-life office tasks	Addition	Speed Accuracy	A set of two 2-digit numbers appeared on the screen. Participants were asked to sum the two numbers and type the answer.
	Typing	Speed Accuracy	A paragraph was shown on the screen. Participants were asked to copy-type the paragraph.

Table 2. Dynamic characteristics of test conditions in the morning session.

	Bidirectional motion			
#Condition	Frequency (Hz)	Peak acceleration (milli-g)	Duration (min)	Peak factor
1	0.2	3.0	25	3.5
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		

Table 3. Dynamic characteristics of test conditions in the afternoon session.

	Bidirectional motion			
#Condition	Duration (min)	Peak acceleration (milli-g)	Frequency (Hz)	Peak factor
8	140	3.0	0.2	3.5
9	140	0.0	0	

performance measures by comparing the scores at the start and the end of the session.

Data analysis

Data analysis is conducted with Linear Mixed Models (LMMs) using the lme4 package in R (Bates et al., 2015). Mixed models are a form of regression which, as well as predicting outcomes from standard predictors (fixed effects), can additionally estimate the extent to which variation in the outcome is associated with random effects. These are grouping variables that exist naturally within the study – in this case, scores were grouped by participants, as each participant provided multiple measurements. Specifically, by including each participant's identity in the analysis, the LMM can estimate a unique baseline performance measure for each participant, so correlated scores are recognized as originating from the same individual. This not only provides estimates of how much participants vary one to another but also provides a way to accommodate multiple measurements coming from each participant, which would violate the assumptions of classical regression. Dependent variables include cognitive test scores, self-reported performance score, and subjective effort score, as outlined in the *Work performance measurement* section. Predictors are motion factors, i.e. peak acceleration, frequency, and duration of motion, plus participants' gender, motivation and stress.

To allow for cross-comparison, cognitive test scores are standardized and converted to Z-scores, representing the number of standard deviations (SD) that a score is above or below the mean. For each cognitive aspect i.e. *attention*, *memory*, *executive function*, and *office tasks*, the score is calculated by averaging the scores of their correspondent cognitive tests, as elaborated in Table 1. The 'average cognitive score' is calculated as the average score of all cognitive tests in the battery. Self-reported performance score and subjective effort score (in terms of NASA TLX raw score) are analyzed on the Likert unit. In all LMMs, scores beyond three SD from the mean are deemed as outliers and are removed from the datasets.

Results

The findings derived from LMMs are presented in two distinct sections: one explores the effects of peak acceleration and frequency of motion on work performance scores, and one section explores the effects of motion duration.

Effects of peak acceleration and frequency on work performance

Table 4 shows the LMM results with peak acceleration and frequency as the main predictors.

In Table 4, continuous predictors are peak acceleration (in the range of 0–10 milli-g), frequency (in the range of 0–0.5 Hz), motivation and stress (in the range of 1–7 Likert unit). Participants' gender is a categorical predictor with 2 levels: male and female. The term 'Acceleration*Frequency' represents the interaction between peak acceleration and frequency, testing whether the effect of one predictor depends on the level of the other. The 'estimate' represents the slope of change in a dependent variable with respect to a predictor, followed by the lower and upper bounds of 95% confidence intervals, CI L and CI H respectively (Cumming, 2013). For continuous predictors, the estimate is the slope change per unit increase in the predictor; 1 milli-g for peak acceleration, 1 Hz for frequency, and 1 Likert unit for motivation and stress. For gender, however, the estimate is the score difference between males and females, with females serving as the reference

Table 4. Linear mixed model results: effects of peak acceleration and frequency of vibration on work performance scores.

Predictor	Average Cognitive score			Subjective effort score			Self-reported performance score		
	Estimate	CI L	CI H	Estimate	CI L	CI H	Estimate	CI L	CI H
Acceleration	**0.02****	0.01	0.04	**0.05****	0.02	0.07	**−0.04****	−0.08	−0.01
Frequency	**0.41****	0.09	0.74	0.37	−0.09	0.82	−0.45	−1.16	0.26
Acceleration*Frequency	0.01	−0.07	0.10	−0.02	−0.14	0.10	−0.08	−0.26	0.10
Motivation	−0.06	−0.13	0.00	−0.09	−0.19	0.00	**0.60****	0.46	0.74
Stress	−0.01	−0.06	0.04	**0.20****	0.12	0.27	−0.05	−0.15	0.06
Gender	0.08	−0.39	0.54	0.31	−0.09	0.71	0.37	−0.02	0.75
R^2	0.73			0.63			0.58		
Predictor				**Attention**					
	Attention score			Visual search score			RVIP score		
	Estimate	CI L	CI H	Estimate	CI L	CI H	Estimate	CI L	CI H
Acceleration	**0.03****	0.01	0.06	**0.03****	0.01	0.07	0.00	−0.04	0.04
Frequency	0.02	−0.46	0.50	0.52	−0.12	1.16	−0.42	−1.07	0.23
Acceleration*Frequency	0.07	−0.06	0.19	0.00	−0.16	0.17	0.13	−0.05	0.31
Motivation	−0.03	−0.13	0.07	−0.08	−0.21	0.06	0.01	−0.13	0.16
Stress	0.01	−0.07	0.09	−0.07	−0.17	0.04	0.11	−0.00	0.21
Gender	**0.57****	0.05	1.08	0.47	−0.16	1.10	**0.68****	0.10	1.25
R^2	0.63			0.57			0.51		
Predictor				**Memory**					
	Memory score			Letter span memory score			Corsi score		
	Estimate	CI L	CI H	Estimate	CI L	CI H	Estimate	CI L	CI H
Acceleration	0.01	−0.02	0.04	−0.01	−0.05	0.03	0.01	−0.03	0.05
Frequency	**0.58****	0.05	1.10	**0.80****	0.08	1.52	0.19	−0.49	0.88
Acceleration*Frequency	−0.09	−0.22	0.05	−0.16	−0.34	0.02	0.02	−0.16	0.19
Motivation	−0.08	−0.19	0.03	−0.09	−0.24	0.06	−0.03	−0.18	0.11
Stress	0.07	−0.02	0.15	0.01	−0.10	0.12	**0.17****	0.06	0.28
Gender	−0.22	−0.76	0.31	−0.25	−0.90	0.39	−0.22	−0.96	0.52
R^2	0.55			0.51			0.62		
Predictor				**Executive function**					
	Executive function score			Stroop score			Go- No Go score		
	Estimate	CI L	CI H	Estimate	CI L	CI H	Estimate	CI L	CI H
Acceleration	**0.03****	0.01	0.07	**0.04****	0.01	0.07	0.01	−0.11	1.78
Frequency	0.13	−0.46	0.72	−0.17	−0.83	0.52	**0.84****	0.11	1.58
Acceleration*Frequency	0.07	−0.09	0.22	−0.06	−0.23	0.12	0.20	−0.11	0.40
Motivation	−0.10	−0.22	0.02	−0.02	−0.16	0.11	**−0.19****	−0.34	−0.04
Stress	−0.06	−0.15	0.03	−0.03	−0.17	0.11	−0.11	−0.23	−0.01
Gender	**0.49****	0.02	0.96	**0.70****	0.11	1.30	0.26	−0.29	0.81
R^2	0.46			0.54			0.42		
Predictor				**Office tasks**					
	Office task score			Addition score			Typing score		
	Estimate	CI L	CI H	Estimate	CI L	CI H	Estimate	CI L	CI H
Acceleration	**0.03****	0.00	0.04	**0.04****	0.01	0.07	0.01	−0.01	0.03
Frequency	0.28	−0.10	0.62	0.06	−0.52	0.63	**0.47****	0.12	0.83
Acceleration*Frequency	0.07	−0.02	0.17	0.09	−0.06	0.24	0.03	−0.06	0.12
Motivation	−0.04	−0.12	0.04	−0.04	−0.16	0.08	−0.03	−0.11	0.05
Stress	0.01	−0.05	0.07	0.01	−0.09	0.10	0.04	−0.02	0.10
Gender	−0.20	−0.79	0.38	−0.62	−1.32	0.08	0.19	−0.60	0.97
R^2	0.78			0.68			0.87		

Note: **Estimates with confidence intervals that do not encompass 0.

(intercept). Positive estimates are associated with an increase in the slope while negative estimates indicate a decrease. Estimates with confidence intervals that include 0 indicate a negligible relationship between the variables while estimates with confidence intervals that do not include 0 are likely to represent statically significant relationships (Cumming, 2013), highlighted in bold with an asterisk in Table 4. R^2 represents the variance explained by the predictors in the LMM. In all models, the full model was initially employed, including all predictors, and subsequently, the backward approach was used to eliminate the predictors with negligible effects. The effect size is calculated in terms of Cohen's f^2, indicating the proportion of the variance explained by predictor(s) to the unexplained variance. Small, medium, and large effect sizes are associated with Cohen's f^2 magnitudes of 0.02, 0.15 and 0.35 (Lorah, 2018).

The strength of the relationship between peak acceleration and the scores of *attention*, *executive function*, and *office task* cognitive aspects is statistically significant, as presented in Table 4; 1 milli-g increase in peak acceleration is associated with 0.03 SD increase in the scores- indicating lower cognitive performance of participants. The associated effect sizes are small to medium, ($f^2 = 0.06$) for *attention* and *executive function* and ($f^2 = 0.04$) the *office task* aspect. The *memory* performance is affected by frequency of motion; a 0.58 SD increase in the score due to 1 Hz increase in frequency, with an effect size of ($f^2 = 0.04$). Furthermore, higher scores in the *attention* and *executive function* aspects are linked to males, suggesting that males exhibit lower cognitive performance compared to females. Figure 5 presents the scores of each separate cognitive aspect in SD unit plotted against peak acceleration within the range of 0–10 milli-g, with a linear regression line fitted to the data points. The shaded strip surrounding regression lines represents 95% confidence intervals. The figure illustrates a clear positive slope of the regression line in *attention*, *executive function*, and *office task* aspects, where 10 milli-g increase in peak acceleration is associated with 0.3 SD increase in the scores. In the *memory* aspect, however, the regression line appears relatively flat. These findings align with the statistical results discussed above.

Looking into individual cognitive tests in Table 4, increases in peak acceleration are associated with higher scores on the *Stroop*, *visual search*, and *addition* tests. The effect sizes for *Stroop* and *addition* are small to medium ($f^2 = 0.07$) while the effect size for *visual search* is small ($f^2 = 0.02$), indicating that peak acceleration explains a relatively small portion of the variance in *visual search* task performance. Increases in *letter span memory, typing, and Go- No Go* scores are associated with increases in frequency; the effect size of these tests is small to medium ($f^2 = 0.05$).

Average cognitive score, self-reported performance score, and subjective effort score

As explained in the *Data analysis* section, the average cognitive score is the average score of all cognitive tests included in the battery. According to Table 4, higher average cognitive scores are associated with increases in both peak acceleration and frequency magnitudes. The associated 95% confidence intervals do not encompass 0, indicating the effects of peak acceleration and frequency on cognitive performance are statistically significant. The combined effect of peak acceleration and frequency demonstrates a medium effect size ($f^2 = 0.15$), indicating a noticeable influence of these motion factors on diminishing cognitive performance of participants. Figure 6 illustrates the relationship between average cognitive score and peak acceleration. The left-hand plot presents all data points, along with the fitted regression line, and features a grey strip indicating the 95% confidence intervals. The right-hand plot categorizes the data points into the two frequency levels of 0.2 and 0.5 Hz. As peak acceleration increases from 0 to 10 milli-g, the average cognitive score increases by 0.26 SD and 0.45 SD for frequencies of 0.2 and 0.5 Hz, respectively (Figure 6).

Peak acceleration impacts both subjective measures of work performance, i.e. subjective effort and self-reported performance, with a small-to-medium effect size for subjective effort ($f^2 = 0.10$) and a small effect size for self-reported performance ($f^2 = 0.02$). The effect of frequency on both measures is found to be negligible. Figure 7 depicts the relationship between peak acceleration and the two subjective measures through regression, accompanied by 95% confidence intervals. The left-hand plot represents subjective effort, and the right-hand plot represents self-reported performance, both measured in Likert units. The plots reveal a distinct trend in score changes as peak acceleration increases from 0 to 10 milli-g. Notably, there is an increase in subjective effort and a decrease in self-reported performance, both of which suggest a decline in subjective work performance with higher peak accelerations.

Effects of duration of motion

The analysis procedure is similar to that discussed above in the *Effects of peak acceleration and frequency on work performance* section. The only difference is that motion duration is considered as the main predictor instead of peak acceleration and frequency. In the following LMMs, duration is considered as a categorical predictor with two levels: start time and end time of the experiment. This is associated with the way work performance scores were measured in the afternoon session at

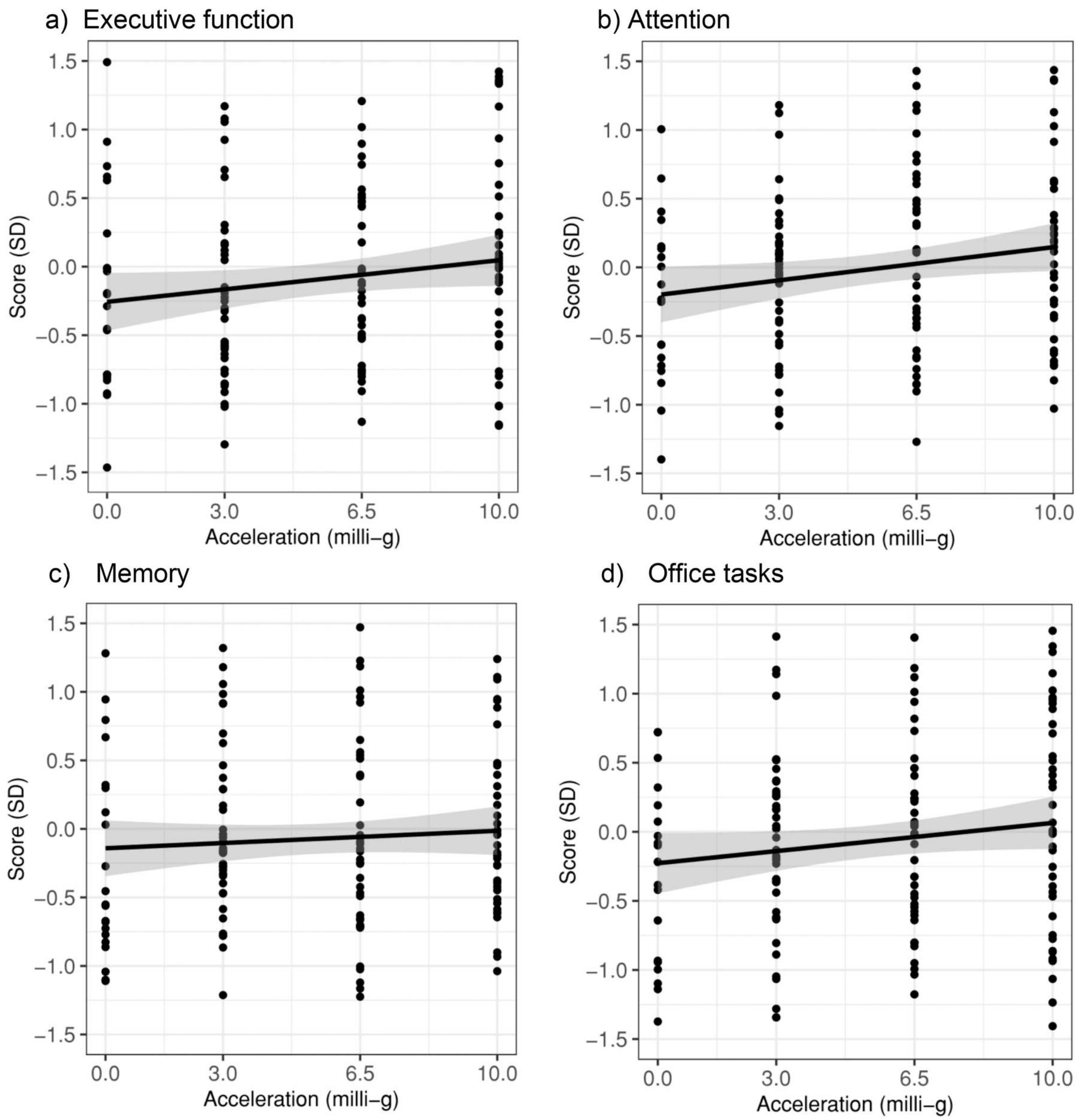

Figure 5. Score of cognitive aspects: (a) executive function, (b) attention, (c) memory, and (d) office task (in SD) against peak acceleration (in milli-g), with data points and regression lines.

these two points, as discussed in the *Test procedure* section. Table 5 presents the results of LMMs.

In Table 5, the estimates reflect the magnitude of change in dependent variables from the start time to the end time of the afternoon session, with the start time serving as the reference point (intercept). The categories 'Motion group' and 'Control group' refer to participants exposed to motion (Condition 8) and no-motion (Condition 9), respectively, as elaborated in Table 3. As shown in Table 5, increases in the attention score are associated with increases in motion duration. Apart from that, the effect of motion duration across all other work performance scores is not statistically significant. This suggests that the research data do not show any influence of motion duration on participants' work performance.

Discussion

Cognitive performance

The findings revealed that the average cognitive performance, as represented by the 'average cognitive score' in Table 4 and Table 5, was influenced by simulated wind-induced vibrations. Higher peak acceleration and frequency magnitudes were correlated with increased average cognitive scores, indicating a reduction in cognitive performance. The combined effect size of peak acceleration and frequency amounted to a medium effect ($f^2 = 0.15$), which means that peak acceleration and frequency explain about 15% of the variance in the average cognitive score relative to the unexplained variance. In other words, the study results

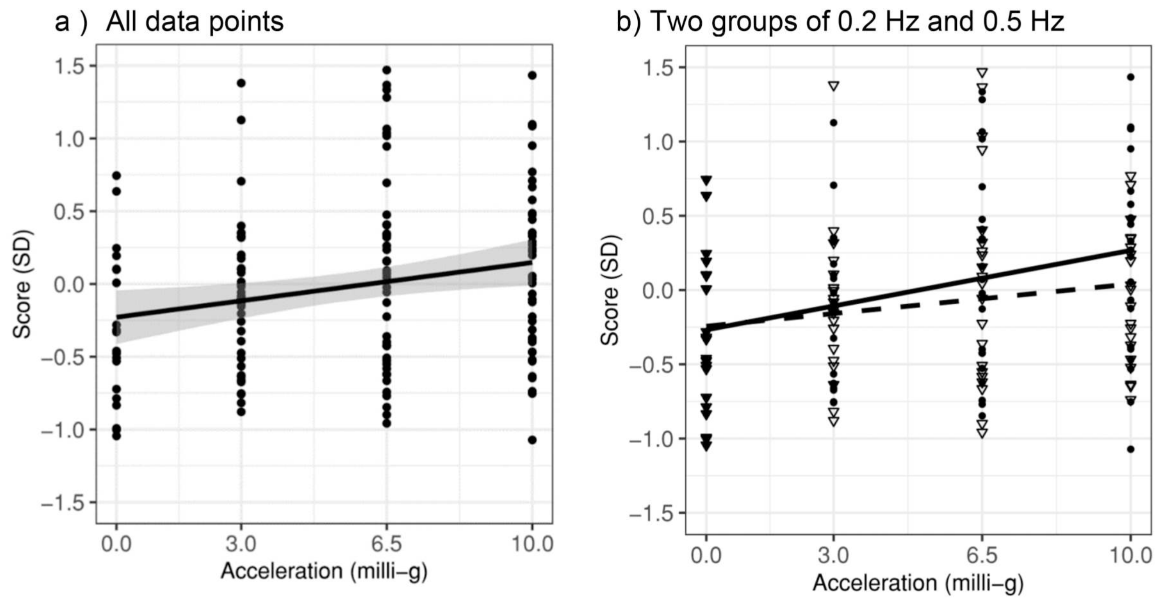

Figure 6. Average cognitive score (in SD) against acceleration (in milli-g). (a) Regression line fitted to all data points; (b) regression lines for two groups of data: dashed line and triangular points for the 0.2 Hz level, solid line and circular points for the 0.5 Hz level.

suggest a significant influence of peak acceleration and frequency of motion on cognitive performance reductions. The 0.2 SD increase in the average cognitive score due to 10 milli-g increase in peak acceleration is noteworthy, especially considering all peak acceleration magnitudes remained at or below 10 milli-g, 'the comfort and wellbeing' threshold proposed by Kwok et al. (2015). Duration of motion had a negligible effect on the average cognitive score, suggesting that 140 min of exposure to sub-perceptible motion, with a peak acceleration of 3 milli-g, did not impact the cognitive performance of participants. However, it should be noted that the average cognitive score increased by 0.2 SD for motion-exposed participants, while it slightly decreased by 0.06 SD for those in the control group (Table 5). This implies that cognitive performance was reduced due to motion exposure, although not significantly, while it exhibited a slight improvement in the absence of motion.

Exploring cognitive aspects individually, the results suggested that higher peak acceleration magnitudes were associated with higher *attention*, *executive function*, and

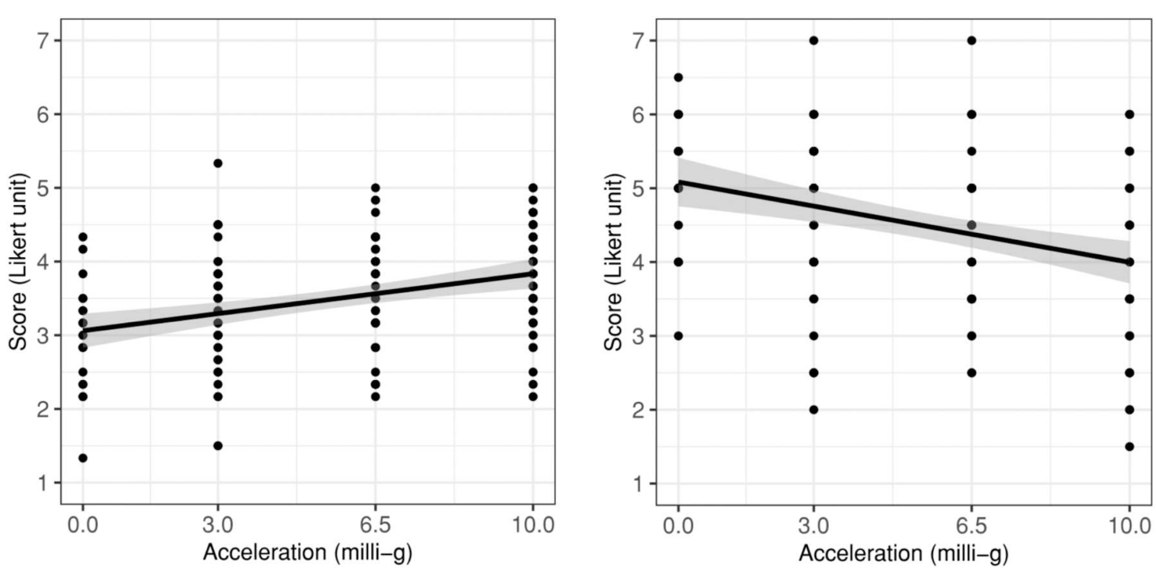

Figure 7. (a) Subjective effort score (in Likert units) against acceleration (in milli-g); (b) self-reported score (in Likert units) against acceleration (in milli-g). Both graphs feature data points and regression lines.

office task performance scores, higher frequencies were associated with higher *memory* scores, and higher *attention* scores were associated with increases in sub-perceptible motion duration. Consequently, peak acceleration emerged as a prominent motion factor, exerting a broader influence on cognitive abilities. Additionally, the efficacy of the cognitive tests included in the battery was evaluated. Among these cognitive tests, *Stroop* and *addition* were influenced most by motion, as evidenced by their corresponding small-to-medium effect sizes ($f^2 = 0.07$). In contrast, simulated motions had no significant impact on *RVIP* and *Corsi* tests, indicating the potential of enhancing or substituting these tests in future VSimulator studies.

In summary, the results indicated that simulated wind-induced vibrations had an impact on participants' cognitive abilities under controlled condition in VSimulator. This is in contrast with previous studies involving motion simulators, which included both unidirectional and bidirectional horizontal motions, as well as different levels of acceleration, frequency and peak factors, but did not reveal a significant correlation between such motions and participants' cognitive performance (Burton, 2006; Denoon et al., 2000b). Jeary et al. (1988) also found no correlation between simulated sinusoidal vibrations and participants' cognitive task performance in a real-life 10-storey building. At present, the authors are not aware of an exact reason for this contrast, but a more realistic simulation of wind-induced vibrations permitted by VSimulator and the inclusion of multiple cognitive aspects in the test battery might be likely explanations.

Field experiments conducted by Denoon et al. (2000a) and Lamb and Kwok (2019) did not provide conclusive evidence regarding the effects of wind-induced vibrations in real-life buildings on the cognitive abilities of office workers. Lamb et al. (2014) observed reductions in cognitive performance using Stroop test in real-life office buildings, but they reported that these objective effects were less pronounced than changes in subjective work performance measures.

Subjective measures

The findings suggest that increases in peak acceleration magnitudes were associated with higher subjective effort scores ($f^2 = 0.10$), as measured via NASA-TLX. The findings contrast with the results of the most recent field study by Lamb and Kwok (2019), who also utilized NASA-TLX to assess effort. In their study, they observed large reductions in participants' subjective effort as the acceleration dose increased. The discrepancy in results may be attributed to the distinct nature of the field study, where participants were engaged in their daily routines, as opposed to more controlled conditions and specific activities employed in VSimulator study. In the field study, building motions led to reduced task effort, thereby impairing participants' work performance (Lamb & Kwok, 2019). In contrast, in this study, increased peak acceleration intensified the severity of motion, prompting participants to exert more effort to maintain the required cognitive performance levels to conduct the test battery. In real-life wind-induced motion scenarios, individuals can pause work or relocate to reduce exposure to motion. However, in a motion simulator setting, participants anticipate experiencing motion and are more likely to persist, increasing their task effort despite discomfort.

This 'expectancy of motion' is a known limitation of motion simulator studies, as participants anticipate experiencing motion, and therefore, such expectations might influence their perception threshold of vibration compared to the real-life tall building motion. In this study, the following actions were taken to mitigate this concern: (1) a control condition (no motion) was implemented, (2) conditions with peak accelerations below the perception thresholds were included in the experiment, and (3) the order of test conditions was randomized. Increases in self-reported work performance were associated with increases in peak acceleration; higher peak acceleration magnitudes were correlated with lower self-reported performance scores, although the effect size was small ($f^2 = 0.02$). These findings align with the results of two recent field studies by Lamb et al. (2014) and Lamb and Kwok (2019), in which participants reported large reductions in self-reported work performance as motion increased in real-life tall buildings.

Final discussion

The results of this study showed a consistent and overall statistically significant degradation in the work performance of participants in both cognitive and subjective manners. Interestingly, this finding is despite the fact that five out of six permutations of motion frequency and peak accelerations examined in this study, satisfy the vibration serviceability criteria specified in ISO10137:2007. Figure 8 shows that motion conditions C1 to C5 (introduced in Table 2) lie below ISO10137:2007 acceptance curve for offices (solid line).

This echoes the conclusion of Lamb et al. (2016), who suggested that current vibration serviceability criteria may not be sufficient to assess the vibration serviceability of tall office buildings subjected to wind-induced vibrations. In addition, the differentiation between residential and office buildings, as suggested by distinct

Table 5. Linear mixed model results – effects of duration on work performance scores.

Average Cognitive score

Predictor	Motion group			Control group		
	Estimate	CI L	CI H	Estimate	CI L	CI H
Duration	0.20	−0.02	0.43	−0.06	−0.20	0.08
Motivation	0.07	−0.24	0.04	0.04	−0.03	0.12
Stress	0.12	−0.01	0.24	−0.06	−0.15	0.04
Gender	−0.14	−1.04	0.78	0.52	−0.08	1.12
R^2	0.92			0.87		

Subjective effort score

Predictor	Motion group			Control group		
	Estimate	CI L	CI H	Estimate	CI L	CI H
Duration	0.01	−0.45	0.39	0.21	−0.14	0.57
Motivation	−0.11	−0.23	0.35	−0.01	−0.19	0.15
Stress	0.32	−0.06	0.68	0.19	−0.05	0.43
Gender	0.85	−0.12	1.36	0.34	−0.74	1.44
R^2	0.41			0.70		

Self-reported score

Predictor	Motion group			Control group		
	Estimate	CI L	CI H	Estimate	CI L	CI H
Duration	0.22	−0.60	0.80	0.19	−0.69	1.01
Motivation	0.63	−0.00	1.04	0.54	0.18	0.90
Stress	−0.31	−0.66	0.20	−0.26	−0.79	0.34
Gender	1.05	−0.39	2.37	0.78	−0.96	2.53
R^2	0.77			0.47		

Attention score

Predictor	Motion group			Control group		
	Estimate	CI L	CI H	Estimate	CI L	CI H
Duration	**0.62****	0.10	1.19	0.13	−0.13	0.40
Motivation	0.02	−0.30	0.37	0.03	−0.09	0.17
Stress	−0.26	−0.56	0.00	0.07	−0.10	0.26
Gender	0.87	−0.03	1.81	0.22	−0.66	1.08
R^2	0.66			0.75		

Office task score

Predictor	Motion group			Control group		
	Estimate	CI L	CI H	Estimate	CI L	CI H
Duration	−0.16	−0.35	0.04	**−0.32****	−0.51	−0.12
Motivation	−0.11	−0.27	0.04	0.00	−0.11	0.09
Stress	0.02	−0.11	0.14	−0.06	−0.19	0.07
Gender	−0.61	−1.72	0.50	0.05	−1.03	1.14
R^2	0.93			0.91		

Memory score

Predictor	Motion group			Control group		
	Estimate	CI L	CI H	Estimate	CI L	CI H
Duration	0.35	−0.05	0.84	0.14	−0.24	0.54
Motivation	0.03	−0.30	0.32	0.17	−0.01	0.34
Stress	0.11	−0.24	0.36	0.00	−0.25	0.25
Gender	−0.71	−1.89	0.53	**1.00****	0.18	1.85
R^2	0.80			0.57		

Executive function score

Predictor	Motion group			Control group		
	Estimate	CI L	CI H	Estimate	CI L	CI H
Duration	0.17	−0.32	0.65	−0.05	−0.41	0.32
Motivation	−0.29	−0.60	0.00	0.06	−0.11	0.24
Stress	0.02	−0.24	0.26	−0.11	−0.35	0.13
Gender	0.04	−0.76	0.83	0.45	−0.55	1.45
R^2	0.49			0.66		

Note: **Estimates with confidence intervals that do not encompass 0.

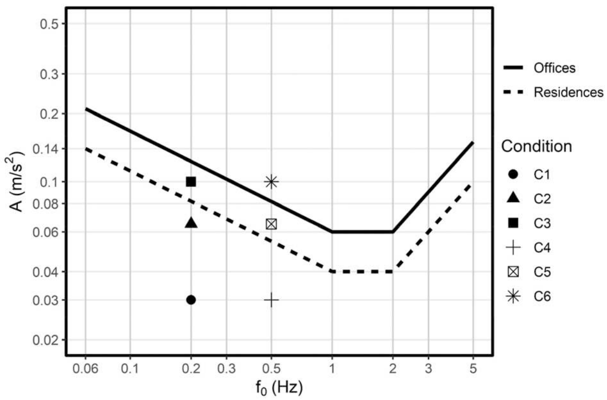

Figure 8. Experimental motion conditions (C1 to C6) plotted against the ISO 10137:2007 acceptance curves (A = peak acceleration, f_0 = building's natural frequency).

vibration acceptability curves in ISO10137:2007, may no longer be relevant in the post-COVID-19 era. Many office workers now adopt hybrid work arrangements, spending a significant portion of their workweek at home. Therefore, there is room for improvement in the serviceability criteria to account for this evolving work landscape.

It is noteworthy that the effect of wind-induced motion on work performance holds significant financial implications. Employee salaries account for approximately 100 times the costs of other business expenses, such as maintenance. Therefore, even a 1% improvement in office workers' performance can result in a significant impact (Fisk & Rosenfeld, 1997). This shows the significance of the research findings, suggesting the potential to enhance vibration serviceability criteria for tall buildings.

Conclusions

Work performance is one of the key aspects of the acceptability of wind-induced vibrations in tall building office environments. The findings of this study revealed that these vibrations can negatively impact the performance of office workers. Importantly, these effects occurred even at levels below the suggested 'comfort and wellbeing' threshold of 10 milli-g. Among the motion factors examined, peak acceleration emerged as the most influential characteristic affecting the outcomes of mental processing tests, cognitive aspects, and subjective performance measures. Specifically, increases in peak acceleration magnitudes correlated with decreases in cognitive performance and self-reported performance, while simultaneously promoting greater subjective effort from research participants.

Future motion simulator studies need to explore a wider spectrum of peak acceleration and frequency thresholds, as well as longer durations of motion. Using more research participants with a wider demographic background is recommended to increase the accuracy and significance of the results. Additionally, researchers can delve into the combined effect of motion factors and audio-visual cues, utilizing VR technology, and understanding the underlying physiological mechanisms that can lead to changes in cognitive performance for more comprehensive investigations on motion acceptability. Current serviceability criteria for tall buildings, primarily based on perception thresholds, overlook the impact of structural vibrations on the work performance of occupants. Nor, apparently, do they fully account for the subjective experience of perceptible motion. The next generation of serviceability criteria should incorporate additional motion parameters, especially duration of exposure to motion and the combined effects of acceleration, frequency, and duration of exposure to motion, to more precisely define acceptable vibration levels. They should also encompass broader measures of vibration acceptability, including work performance, health, and wellbeing, rather than solely focusing on comfort and perception of motion. This holistic approach aims to enhance the safety, serviceability, environmental sustainability, and cost-efficiency of future tall buildings.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Data availability statement

The data that support the findings of this study are available from the corresponding author, [K.H], upon reasonable request.

Ethics approval for human participants

Ethics approval was obtained from the Ethics Committee at the University of Bath (application number 4257). Prior to the test, participants signed the following documents: (1) Participation information sheet, which included a brief summary of the experiment, potential risks, data collection procedures, and confidentiality measures; (2) Health condition exclusion list, outlining any health statuses that might put the participant at risk by participating; (3) Consent form; and (4) COVID-19 screening form.

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