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A longitudinal field study of the effects of wind-induced building motion on occupant wellbeing and work performance

S. Lamb[a,*], K.C.S. Kwok[a,1], D. Walton[b,c,2]

[a] Institute for Infrastructure Engineering, University of Western Sydney, Locked Bag 1797, Penrith, NSW 2751, Australia
[b] Health Promotion Agency, Level 4, ASB House, 101 The Terrace, PO Box 2142, Wellington 6140, New Zealand
[c] University of Canterbury, Adjunct Fellow Univ. of Canterbury, Department of Psychology, Private Bag 4800, Christchurch 8140, New Zealand

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ABSTRACT

The current study uses a longitudinal within-subjects design to investigate the effects of wind-induced tall building motion on occupant wellbeing and work performance. 47 office workers on high floors of wind-sensitive buildings and 53 control participants completed 1909 surveys across 8 months and over a range of wind conditions. The results show that the effects of building motion are emergent, as motion sickness develops after a duration of exposure to motion, which mostly manifest as symptoms of sopite syndrome, or low-dose motion sickness (tiredness, low motivation, distraction from work activities, and low mood), which occur at 2–3 times baseline rates. As motion sickness increases, work performance significantly decreases by 0.76–0.90 standard deviations below baseline. Affected individuals attempt to manage their own discomfort, and indicate a preference to work a different location during motion, take 30–40% longer breaks, and attempt to self-medicate using analgesics. Humans are adaptable, allowing most occupants to continue their work activities, but at reduced levels of performance and comfort. Design criteria for tall buildings should attempt to minimise the environmental stress of building motion on work performance and wellbeing rather than motion tolerance or formal complaint to building owners.

1. Introduction

Despite their rigid appearance, tall buildings possess elastic properties allowing them to flex in response to external forces. Strong winds can cause buildings to vibrate, or sway, at low frequencies below 1 Hz, and at low accelerations up to approximately 40 mg (1 mg is equal to 1/1000th of gravity or 0.0098 m/s^2). Tall buildings sway in the predominant wind direction and also the perpendicular direction, producing an elliptical motion. Bursts of motion occur at random intervals at the natural frequency of the building, causing an unpredictable pattern of motion. Studies have shown that building motion can be perceptible to occupants, cause fear, and induce motion sickness in some occupants (Hansen et al., 1973; Goto, 1983; Burton, 2006; Lamb et al., 2013). While researchers can predict accelerations that occupants will perceive (e.g. Tamura et al., 2006), researchers do not clearly understand the frequencies and accelerations required to induce motion sickness and other adverse effects, or understand the influence of individual differences, such as susceptibility to motion sickness. Further, researchers do not understand how building motion affects occupant wellbeing and work performance. Current building guidelines specify 'acceptable' building accelerations, but these may not be adequate to ensure a healthy work environment. Yet building motion will likely be a more common problem for design professionals and building occupants in the future due to trends toward urban densification (World Health Organization, 2010), higher levels of tall building construction (Council on Tall Building and Urban Habitat, 2013), and global warming-induced changes in weather patterns.

1.1. Previous building motion studies

Relying mostly on motion simulator studies, building designers may contend that building motion has a minimal effect on the wellbeing of occupants, except perhaps during rare events at very high accelerations over about 30–35 mg (Chen and Robertson, 1972; Isyumov and Kilpatrick, 1996; Denoon et al., 2000; Burton et al., 2005; Tamura et al., 2006; Denoon and Kwok, 2011). Researchers have limited opportunity to study actual building occupants. Building owners rarely permit the measurement of

* Corresponding author. Tel.: +64 27 421 9061.
E-mail addresses: 17097433@student.uws.edu.au, stevelamb5150@gmail.com (S. Lamb), K.Kwok@uws.edu.au (K.C.S. Kwok), d.walton@healthpromotion.org.nz (D. Walton).
[1] Tel.: +61 2 4736 0444.
[2] Tel.: +64 4 917 0060.

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building accelerations or allow researchers to approach building occupants and commercial organisations are also hesitant to commit staff resources to research. Some studies have measured actual responses to motion following severe wind events (Hansen et al., 1973; Goto, 1983; Denoon and Kwok, 2011; Lamb et al., 2013). These studies rely on occupants' retrospective assessments and single-sample measures that cannot establish motion-induced changes in wellbeing or work performance. Most research, and indeed building standards, have focused on the threshold of motion perception (e.g. Chen and Robertson, 1972; Tamura, et al., 2006; Denoon and Kwok, 2011). While a valid design criterion, wellbeing and work performance are more relevant to the quality of the indoor office environment. Building designers consider a low rate of occupant complaint to buildings owners evidence that building accelerations are within an acceptable range (Hansen et al., 1973; Isyumov and Kilpatrick, 1996). However, recent evidence shows that office workers informally complain to colleagues and family rather than to building owners (Lamb et al., 2013).

Simulator studies show motion to have a negligible effect on task and cognitive performance (Jeary et al., 1988; Morris et al., 1979; Denoon et al., 2000; Burton et al., 2004, 2011). These studies are limited because they use task performance measures that may be too simple to detect true performance differences, and often report ceiling effects (high baseline scores that have insufficient variability to detect actual changes in performance). Further, these studies expose participants to high acceleration motion for short durations (usually less than one hour), which may not provoke the types of symptoms that affect actual building occupants. Studies rarely consider how occupants may attempt to adapt to or compensate for building motion. Controlled motion simulator studies cannot measure unprompted behaviours that might occur in real office buildings, for example, break-taking behaviour, changing task demands and taking medication. While Denoon and Kwok (2011) examined control tower workers over the course of approximately one year, the study focused mostly on the perception of motion, but did not examine the effect of motion on work performance or occupant wellbeing. Further, airport control towers are not representative of a typical office building. Only a longitudinal study, a field study repeatedly measuring the responses of actual office building occupants over a long period, can provide convincing evidence of the real effect of building motion.

1.2. Motion sickness

Those occupants susceptible to motion sickness are most likely to report adverse effects of building motion (Lamb et al., 2013). Since the ancient Greeks discovered ‘seasickness’, humans have known that unusual motion causes a physiological disturbance characterised by nausea, dizziness and vomiting (Reason and Brand, 1975). Only in the last 40 years, NASA scientists discovered that sustained exposure to gentle accelerations can cause subtle early onset symptoms of motion sickness, called sopite syndrome (Graybiel and Knepton, 1976). Symptoms include sleepiness, difficulty concentrating, low mood, and decreased motivation, which may persist but never develop into nausea. Within a dose-response model, low-dose symptoms of motion sickness, particularly sopite syndrome, are more likely to occur in the acceleration range of tall buildings than classic high-dose symptoms of nausea and dizziness (Walton et al., 2011). Recent evidence lends support to this hypothesis, as Lamb et al. (2013) report that building occupants most frequently report difficulty concentrating during building motion, a cardinal symptom of sopite syndrome. Walton et al. (2011) argue that symptoms of low-dose motion sickness are common and can occur for reasons other than building motion, and occupants may misattribute these symptoms to normal work stress and fatigue.

1.3. The current study

This study aims to understand the effects of wind-induced building motion on occupant wellbeing and work performance, particularly in terms of low-dose motion sickness. Low-dose symptoms of motion sickness, tiredness, distractibility, low-mood and low-motivation, can occur for reasons other wind-induced building motion. The challenge for building motion research is to delineate the symptoms that occur with some baseline incidence in the workplace, from those that occur with greater incidence because of building motion, requiring both a sophisticated experimental design and complex statistical techniques. Some of the terms and techniques are likely to be unfamiliar to an engineering audience, and we attempt to explain these throughout.

The current study uses a longitudinal within-subjects design, a technique that examines how the normal response of an individual changes in response to an environmental variable (or manipulated variable) over a long period of time. Wellington, New Zealand, is one of the windiest cities in the world due to its unique geography, caused by mountain ranges that channel prevailing winds, creating a consistently high wind climate (see Lamb et al., 2013). Forty-seven office workers in 22 wind-sensitive Wellington buildings, and a control condition of 53 office workers on near-ground floors, completed a total of 1909 online surveys over 231 days (8 months). A control condition allows us to investigate the baseline incidence of symptoms that may appear like low-dose motion sickness and to establish normal level of work performance in an office environment not subject to building motion. The study used online surveys to unobtrusively measure the occupant response to motion during work hours over a range of wind conditions from calm (1.2 m/s) to near gale (29.0 m/s) allowing us to examine how wellbeing and work performance change in response to building motion. The survey measured four main responses to building motion: (1) the perception of building motion, (2) low- and high-dose symptoms of motion sickness, (3) self-reported work performance and objectively measured task performance, and (4) compensatory or adaptive behaviours. The human vestibular system, located in the inner ear, is sensitive to changes in environmental accelerations, capable of detecting accelerations of 2–5 mg in the frequency range of tall building motion (Tamura et al., 2006; Denoon and Kwok, 2011). Therefore, occupant reports of motion, supported by objectively measured wind speeds and predicted building accelerations, provided the independent measure of building motion. A sample of building accelerations supplements these analyses.

2. Method

2.1. Participants

Respondents who work in wind-sensitive buildings and completed the survey reported in Lamb et al. (2013) received an invitation to participate in the current study. Participants recruited from the survey distributed additional study invitations to their work colleagues. All participants gave their informed consent. The study recruited 108 participants in total. The analysis excluded one participant who reported she became pregnant during the study, because morning sickness may be confused with motion sickness. The analysis excluded 7 further participants from the experimental condition as they reported no instances of building motion during the duration of the study. The experimental condition comprised 47 individuals who worked in the top third of tall buildings, or above the 10th floor who reported perceptible wind-induced motion in that building. 53 participants worked on the 3rd floor