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A review of two theories of motion sickness and their implications for tall building motion sway

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Abstract. Low-frequency building vibration is known to induce symptoms of motion sickness in some occupants. This paper examines how the adoption of a theory of motion sickness, in conjunction with a dose-response model might inform the real-world problem of managing and designing standards for tall building motion sway. Building designers require an understanding of human responses to low-dosage motion that is not adequately considered by research into motion sickness. The traditional framework of Sensory Conflict Theory is contrasted with Postural Instability Theory. The most severe responses to motion (i.e., vomiting) are not experienced by occupants of wind-excited buildings. It is predicted that typical response sets to low-dosage motion (sleepiness and fatigue), which has not previously been measured in occupants of tall-buildings, are experienced by building occupants. These low-dose symptoms may either be masked from observation by the activity of occupants or misattributed to the demands of a typical working day. An investigation of the real-world relationship between building motion and the observation of low-dose motion sickness symptoms and a degradation of workplace performance would quantify these effects and reveal whether a greater focus on designing for occupant comfort is needed.

Keywords: motion sickness; nausea; work performance; ecological psychology.

1. Introduction

New methods of building construction using stronger and lighter materials allow for buildings of greater height, with lower densities, less damping and lower natural frequencies which increases their vulnerability to wind-induced motion (Chen and Robertson 1972). Given sufficiently strong winds, building motion has been shown to be perceptible (Hansen *et al*. 1973, Isyumov 1996), induce symptoms of motion sickness (Hansen *et al*. 1973, Goto 1983), and cause fear and alarm (Khan and Parmelee 1971, Denoon 1999, Burton *et al*. 2006). In severe cases of building motion, building occupants have reported taking motion sickness tablets to mitigate symptoms of nausea (Melbourne and Cheung 1988). Reducing building movement below the threshold of human motion perception is prohibitively expensive (Isyumov 1993). There are currently no internationally accepted standards for maximum allowable levels of building motion (Kwok *et al*. 2009). Few studies have examined the effects of building motion on occupants in naturalistic (or real-world) settings (i.e., Hansen *et al*. 1973, Goto 1983, Denoon *et al*. 1999, Denoon *et al*. 2000, Kijewski-

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Correa *et al*. 2006). Naturalistic studies are important because they preserve the interaction of the complex set of variables that affect the comfort, performance and behaviour in wind-excited tall buildings which cannot easily be reproduced in simulator studies. Studies examining the potential impact of motion on task performance in naturalistic environments or simulators using random motion that mimics actual building motion (i.e., not sinusoidal motion) have not shown a significant relationship between the exposure to motion and task performance (e.g., Denoon *et al*.1999, Denoon, *et al*. 2000, Burton *et al*. 2005, 2006).

Sensory Conflict Theory (Reason and Brand 1975, Reason 1978 and Oman 1982) hypothesizes that motion sickness is induced by mismatching sensory information perceived by an individual. Typically, visual information from the eyes clashes with the perception of motion; motion is felt but not seen, or seen but not felt, and this discordance induces unpleasant sensations of motion sickness. It is possible to find Sensory Conflict Theory presented as unchallenged (e.g., Probst and Schmidt 1998, So *et al*. 2001, Eisenman 2009) despite theoretical and empirical challenges being offered as alternatives (Stoffregen and Riccio 1991). A recent alternative theory was proposed by Riccio and Stoffregen in 1991, referred to as Postural Instability theory, contends that a prolonged inability to maintain motor control in novel environments induces instability in posture inducing symptoms of motion sickness.

This article presents the theoretical and practical implications for examining the occupant response to tall-building motion sway by re-conceptualising motion sickness as a dose-response relationship within the framework of a criticism of Sensory Conflict Theory. It is argued that the prodromal symptoms (early onset symptoms) of motion sickness, such as drowsiness, are likely to occur in low-dosage motion environments, particularly wind-excited tall buildings. Failing to examine occupant effects within a theory of motion sickness, or the unchallenged adoption of Sensory Conflict Theory may mask a genuine problem for designers of tall buildings and prevent adequate design solutions. Stern (2000) suggests that a multi-disciplinary approach to existing problems can overcome the limitations of a particular discipline and provide new contexts for the study of a phenomenon and develop theories to encompass a wider range of conditions. This article integrates elements of ecological psychology, physiology, and building science to address the consequences for occupants of wind-excited tall buildings.

This article does not attempt to provide a comprehensive review of engineers' research on the comfort and perception of motion by occupants of tall buildings, nor a detailed account of all motion sickness research. A comprehensive review of occupant comfort responses to tall building motion sway can be found in Kwok *et al*. (2009). Reason and Brand (1975) developed Sensory Conflict Theory and thoroughly reviewed the literature to that point. A more recent review can be found in Stoffregen and Riccio (1991).

2. Human response to wind-excited tall buildings

Hansen *et al*. (1973) conducted the first full-scale survey of the occupant response to building vibration, administered after wind storms subjecting the buildings to accelerations of 2 mG (1/1000th gravitational acceleration) and 5 mG (R.M.S.), respectively. The latter equates to a peak acceleration of approximately 17.5 mG (Isyumov 1993). Auditory cues were the most reported mode of perception of building motion, followed by sensations of self-movement, visual detection of moving fixtures, and comments from co-workers (Hansen *et al*. 1973). Using a similar method, Goto (1983) found that over 95% of occupants above the 13th floor of the test building were able to perceive building motion. Sensations of motion and auditory perception were the most frequently reported cues to building movement. Nearly three-quarters of respondents reported experiencing physiological or psychological symptoms, including motion sickness, headaches and "uneasiness and strain", the likelihood of which increased as the floor occupied increased. Goto (1983) suggested that most occupants cannot perceive acceleration below 1 mG (R.M.S.). At 4-6 mG, half of the building occupants will sense motion, including those at work, and above 10 mG, occupants will begin to experience motion sickness.

Denoon *et al*. (1999) examined perception thresholds of occupants working in two airport control towers and examined cognitive performance in a sample of students in a port communications centre. Occupants were provided with a set of five buttons, corresponding to different magnitudes of perceptible motion, which they were asked to press when they perceived motion. A threshold of perception was found to occur between 0.6 and 0.7 mG (R.M.S.). However, the effect of motion on performance was inconclusive. Peak accelerations were found to have a relatively larger influence over the perception of motion, which has been observed by Chen and Robertson (1972) and Melbourne and Palmer (1992). Kareem *et al*. (2002) suggest that peak acceleration is a more appropriate measure for the perception of motion, as peak levels are more salient, and that R.M.S. is an average level of acceleration, or a more effective measure of exposure to motion. Similar thresholds of perception have been confirmed by many simulator studies including: Khan and Parmelee (1971), Chen and Robertson (1972), Irwin (1981), Kanda *et al*. (1988), Goto *et al*. (1990), Shioya *et al*. (1992), and others. Kwok *et al*. (2009) summarises that thresholds of the perception are similar across studies, despite different measurement techniques, all showing thresholds of perception to decrease as frequency increases between 0.1 Hz and 1 Hz. Two notable studies by Burton *et al*. (2005, 2006) will be discussed in more detail in subsequent sections.

3. Motion sickness

The four most reliably produced symptoms of motion sickness are pallor, nausea, cold-sweating and vomiting (Reason and Brand 1975). The concept of 'sickness' is emotionally-laden and, at first consideration, it is wrongly applied to the consequences of a phenomenon relatively rarely displayed in occupants of buildings. In particular, vomiting is rarely, if ever, observed. Prodromal, or early onset symptoms, that precede the higher-level symptoms include: increased salivation, drowsiness, nystagmus (involuntary eye movements), and hyperventilation (Reason and Brand 1975). Others symptoms are lassitude, impaired hand-eye coordination, reluctance to communicate, and difficulty in temperature regulation (Kennedy *et al*. 2010). In broad terms, the incidence of motion sickness is a result of the complex interaction between the severity of the motion environment, the level of individual susceptibility and the duration of exposure to motion (Reason and Brand 1975). Exposure to a long duration of a mild motion environment will result in "head" symptoms first which may progress to "gastric" symptoms in moderately susceptible individuals, or may not progress in less susceptible individuals. Whereas even short exposure to severely nauseogenic environments will result in "gastric" symptoms very quickly, "head" symptoms will be less salient if present at all (Reason and Brand 1975). It is these prodromal, or typically "head" features of motion sickness, that potentially are of the most interest to designers of tall buildings.

A phenomenon referred to as Sopite Syndrome (Graybiel and Knepton 1976) describes the effect of long duration exposure to low-frequency, low-acceleration environments, and generally reflects an effect of being 'rocked to sleep'. Graybiel used a Slow Rotation Room (SRR) built at the Naval Aerospace Medical Research Laboratory in Pensacola, Florida. Test subjects and experimenters present in the SRR displayed an increased frequency of yawning, drowsiness, lack of motivation for work (physical or mental), reluctance to participate in group activities, daydreaming and low-level depression. These are essentially a class of "head" symptoms that may never progress to the more severe symptoms. Graybiel and Knepton (1976) describe Sopite Syndrome stating that, "The onset was insidious, and the unsophisticated might attribute the yawning and drowsiness to boredom and relaxation. More distinctive symptoms, however, included a disinclination to be active physically or mentally." (p. 876).

Any adequate theory of motion sickness should explain a set of observed outcomes while reconciling a difficult joining of theories of perception and action. First, the theory must explain why otherwise healthy people suffer the symptoms of motion sickness (i.e., the response) in relation to a dosage, when dosage is considered as both real motion (such as on ships or in cars: e.g., Griffin and Newman 2004, Turan *et al*. 2009) and apparent motion (such as that which occurs in driving simulators: e.g., Ebenholtz 1992, Brooks *et al*. 2009). Second, the theory should account for habituation to motion effects in both real and experimental conditions (e.g., through the use of vision-reversing prisms: e.g., Reschke *et al*. 2006). Third, the theory should eliminate the possibility of sickness being induced under normal motion such as running, walking or cycling. Fourth, the theory should accept individual variability in responsiveness to motion, across conditions (e.g., drivers compared to passengers) and people (e.g., Golding 1998, 2006). Fifth, the theory should explain why there is an apparent absence of sickness either naturally (in the very young) or due to vestibular damage (either natural or due to experimentation with animals). Sixth, the theory should account for the wide variety of settings in which motion sickness is exhibited and contrast them with those that do not. For example, it is reported that scuba-divers are never motion sick whereas motion sickness is commonly observed in weightless environments such as space (Stoffregen and Riccio 1991). Seventh, the theory should explain how symptoms can be self-induced in the absence of a provocative environment, e.g., standing upright and then spinning on the spot.

Treisman (1977) is credited with the theory that motion sickness is caused by the body believing that its unnatural environmental inputs (apparent and extreme real motion) are due to ingested toxins. The adaptive response to such conditions is vomiting and Treisman regarded such responses in the absence of ingested toxins is maladaptive. Bowins (2010) argues to the contrary that motion sickness serves that adaptive purpose of providing negative reinforcement for situations that might pose a threat for an individual's survival, functioning similar to pain. Treisman's theory is a good example of the typical focus on only the extreme response set (i.e., vomiting) in high-dosage conditions. The theory therefore does not explain why a person might feel sick or nauseous in a sustained low-dose nauseogenic environment. Understanding the effects of motion sickness in real-world and sustained low-dose environments is critical to the development of a comprehensive theory of motion sickness, but these conditions are seldom considered in research and are often overlooked by theory.

The approach to studying the effects of building motion on occupants has been directed by the goal of establishing a set of minimum design parameters which constitute 'acceptable' building motion. This precedent was set by Hansen *et al*. (1973) who made the distinction between the threshold for the perception of motion and the tolerance of that motion. This approach has directed attention away from the effects of motion on performance that fall below the threshold of perception or may be subtle or difficult to detect, that is, prodromal or low-dose effects such as drowsiness, fatigue, reluctance to work, and mild depression. The study of wind effects on tall buildings is a unique context that can make significant contributions to the theoretical debate which has emerged in the study of conditions that lead to nausea and motion sickness aside from solving very practical concerns for designers of buildings. Motion sickness has been traditionally studied with a concern to understand what makes people 'sick' with methods designed to induce, reproduce and mimic these outcomes (e.g., Alexander *et al*. 1947, Graybiel 1969). This approach is appropriate when attempting to recreate the real-world conditions, such as a vomit reaction in fighter pilots during combat which might be life-threatening, but designers of buildings are typically concerned with a methodologically unique context of asking questions only about effects which are prodromal to motion sickness.

4. Sensory conflict theory

Sensory Conflict Theory postulates that sensory systems such as the visual, vestibular and non-vestibular proprioceptors become at variance with one another against expectations, based on previous experience with the environment (Reason and Brand 1975, Reason 1978, Oman 1982). The vestibular system, located in the inner ear, is primarily responsible for the detection of linear and angular acceleration, and non-vestibular proprioceptors provide an individual with information about their body's movement. If an individual's eyes detect movement when none is expected or detected by other sensory systems (i.e., vestibular-visual conflict), and this movement is sustained, rather than fleeting, the individual may experience motion sickness. Variants of this Theory have enjoyed a hundred year reign despite being anomalous to the convergence of theory in physiology, perception and cognition (Riccio and Stoffregen 1991).

Sensory Conflict Theory is credited with the capability of resolving what would otherwise become etiologically different forms of motion sickness (Probst and Schmidt 1998). The basic mechanism, and the point of controversy for proponents of Sensory Conflict Theory, is the comparator system that evaluates sensory inputs from vestibular, visual or other physiological systems and compares these inputs with those previously experienced and stored. Thus Sensory Conflict Theory posits credible mechanisms for resolving the observed occurrence of motion sickness in both real and apparent motion.

Stoffergen and Riccio's (1991) central criticism of Sensory Conflict Theory is its reliance on the core of 'conflicting perceptual systems'. They argue this notion of 'conflict' is a hypothetical construction within a theoretical perspective of the operation of human perceptual systems. The hypothetical construction is a placeholder to describe the mechanism for motion sickness but it carries no real explanatory power. Conflicting perceptions are not verifiable because we cannot directly observe them, there is no way to systematically measure the degree of inter-modal conflict, and no reference point exists by which to determine what constitutes conflict and what is normal.

Stoffregen and Riccio (1991) add that input-conflict (conflict between senses) relies on some mechanism to decipher which of the conflicting mechanisms is veridical, or a notionally 'true' representation of the environment, else the apparent 'conflict' cannot logically exist. In one case a person's visual system perceives movement when there is none and this makes them sick, in the same conditions movement is perceived when there is movement and this produces the same symptoms. To impose a 'conflict', a standard of correctness or a position from which to evaluate is necessary. Sensory Conflict Theory creates the comparative system to impose the standard by disregarding what actually happens in the world. Decoupling the sensory inputs means they are 'uncorrelated', 'at variance', or 'lack congruence' and it is this which creates the motion sickness problem for perceivers.

Stoffergen and Riccio (1991) contend, for example, that each of our eyes presents us with conflicting (i.e., incongruent) information about the world and this, being normal, causes no particular disturbance. In defence of Sensory Conflict Theory one can respond that if our eyes presented us with different 'perceptions' (rather than 'information inputs') one might feel nauseous. Again, with equal force, critics of Sensory Conflict Theory can counter that we do in fact integrate different sources of conflicting information into a unified perception, so it is unnecessary to posit the idea of conflicting perceptions as the cause of motion sickness. Further, why do some conflicting inputs make us ill while others are regarded useful and adaptive? Depth perception is achieved, for example, because of two slightly incongruent visual inputs. How does Sensory Conflict Theory advance our understanding if it cannot reconcile these basic conditions, which after all are the very purpose for its construction?

The notion of Sensory Conflict is further complicated by a long history of adjustments or variations to the main theory to account for the varied circumstances in which motion sickness can arise (e.g., Bos and Bles 1998). Susceptibility to motion sickness across situations cannot be predicted (Kennedy *et al*. 1990) and obviously not all sensory conflicts cause sickness. For example high frequency vibrations do not usually cause motion sickness. To account for such circumstances, proponents of Sensory Conflict Theory will place various restrictions on the nature of the conflicting systems. These include band-pass filters, thresholds, and sensory duration (Oman 1982). For the building designers, the problem of setting and determining the limits of 'acceptability' and its relationship to thresholds, the frequency at which wind-induced building excitation causes discomfort and so on becomes clear.

Very few studies examining occupant effects make explicit reference to any theory on motion sickness (e.g., Khan and Parmelee 1971, Chen and Robertson 1972, Hansen *et al*. 1973, Isyumov 1993, Denoon *et al*. 1999). However, some studies implicitly support Sensory Conflict theory. Isyumov (1993) suggests that torsional motion creates the appearance of a 'swinging horizon' that accentuates perceptions of motion, therefore visual cues to motion should be minimised. Reed *et al* (1973) even state that "Motion sickness symptoms can be caused by information received by the eyes" (p. 692). The assumptions underlying these studies are that limiting visual and auditory cues to motion will reduce occupant discomfort. Reducing visual cues might make motion less obvious, with fewer moving fixtures, though actual exposure to motion is unlikely to be affected. This is further supported by Goto *et al*. (1990) who found that individuals were able to perceive motion before the effects of motion were apparent by the movement of nearby physical objects.

Burton *et al*. (2006) is one of the few studies to attempt to reconcile experimental findings within a theory of motion sickness. Burton *et al*. (2006) suggests that when occupants look out a window at a far away object, such as another building, the occupant's body movement which has been magnified by the building motion, is misinterpreted as building motion and under the assumption that they are stationary. In reality, the apparent motion of the building is due to the individual moving, not the building. The occupant receives motion cues from the vestibular system against a contradictory visual scene, and therefore "misinterpret sensory information" (p. 302) leading to feelings of motion sickness. While Sensory Conflict Theory is not explicitly stated, the theory is certainly implied.

Concern for tall building motion sway and the development of Sensory Conflict Theory has some historical overlap as Hansen *et al*. (1973) first addressed the issue of whether tall building motion sway would be acceptable to owners and occupants of tall buildings at around the same time leading proponents of the Theory formalised it (Reason 1978, Reason and Brand 1975, Oman 1982). It should be obvious that whether building sway is 'acceptable' to occupants is at least a different design criterion than the notion that building excitation may induce a 'sickness' or any other practical concern for occupants (such as fatigue). Notwithstanding, the notion that tall building motion sway generates a sickness, or creates a 'sick building', was being taken up and considered (Dixon 1990). In other contexts, such as the armed services, there is a much longer history of investigations concerning the influence of motion sickness and decrements in task performance (Kennedy *et al*. 2010).

5. The ecological alternative to Sensory Conflict Theory: Postural Instability Theory

Riccio and Stoffregen (1991) proposed an ecological theory (following Gibson 1979) of motion sickness. Posture, or sustained control over the body's movement, is essential for any successful interaction with their environment, e.g., walking, bending down to pick up an object etc. Postural stability is defined by Riccio and Stoffregen (1991) as the "coordinated stabilisation of all body segments" (p. 199). They argue that postural instability occurs in novel environments when "we fail to perceive the new dynamics or if we are unable to assemble and execute the control actions that are appropriate for the new dynamics" (p. 204). Riccio and Stoffregen (1991) hypothesised that motion sickness occurs when an individual is unable to maintain control of their posture for a sustained period of time. Borrell (2009) summarised Postural Instability Theory stating that "motion sickness is really a sign that the motor-control system is going haywire".

Motion sickness does not occur as a result of normal body sway, which occurs between 0.1 and 0.4 Hz (Stoffregen and Riccio 1991). Exposure to vibration in a similar frequency range to natural sway is thought to cause wave interference and contribute to postural instability, therefore causing motion sickness (Stoffregen and Smart 1998). Riccio and Stoffregen (1991) limit their theory to predicting conditions that will induce motion sickness and do not attempt to explain why those conditions produce particular physiological reactions (i.e., nausea and vomiting), though it should be noted that Sensory Conflict theory does not provide a causal explanation for the occurrence of its symptoms either.

Strategies to control posture must take account of both environmental conditions and goals of behaviour. Riccio and Stoffregen (1991) give an example analogous to the concern building sciences have for tall building motion sway. Consider a vehicle motion around an unbanked corner. The natural tendency for a vehicle occupant is to maintain orientation with regard to task performance, that is, the driver will maintain head alignment with the usual orientation to the dashboard. Body movement (torso alignment) is maintained in the gravitational force vector and this minimises the effort required to control orientation. The result is an "opposite tilt" of head and body, importantly, Sesek and Riccio (1989, cited in Riccio and Stoffregen 1991) observe that people do not maintain opposite tilt with their eyes closed. The resulting head tilt observed in drivers with their eyes open is necessary to maintain the goal-directed behaviour of maintaining vehicle control, which emphasises the importance of the link between perception and action in the ecological approach.

Postural instability has gathered empirical support over the last two decades. Bonnet *et al*. (2006) used to moving room which oscillated along the anterior-posterior axis of standing participants. Increased postural activity was observed in all participants, but more so for those who became motion sick. Postural instability was observed in participants who later became sick, before they experienced symptoms of motion sickness. Yokota *et al*. (2005) exposed groups of high and low susceptibility participants to a virtual environment which oscillated with a roll 60º at frequencies between 0.1 Hz and 0.4 Hz. Significantly more postural instability was observed in high susceptibility participants than those with low susceptibility. Villard *et al*. (2008) found that motion sickness was induced in 42% of participants exposed to a virtual moving room. They observed that an increase in the variability of postural activity in the group that became sick, relative to the well group. In addition to the increase in sway in the anterior-posterior direction (i.e., along the axis of the moving room), an increase in medio-lateral sway was also observed. Stoffregen (2008) observed participants playing a video game who eventually became motion sick, showed increase in postural variability compared with those who did not. Littman *et al*. (2010) found a similar result, finding an increase in postural activity when in control of the video game, rather than watching a pre-recorded video of game play, indicating that the amount of body sway is less important than selecting an appropriate control strategy for the environment. Stoffregen *et al*. (2010) found that increasing stance width stabilised participants' posture by decreasing medio-lateral sway, which subsequently significantly reduced the incidence of motion sickness during exposure to a moving room.

Postural Instability has been challenged by several investigators. Warwick-Evans *et al*. (1998) tested one particular hypothesis that lying down, which should effectively reduce the effort or control necessary to maintain postural control, was not supported. Flanagan *et al*. (2004) tested the relative effects of sensory conflict, postural instability and eye moments on the incidence of motion sickness finding that sensory conflict had the largest impact, although the ability to experimentally manipulate sensory conflict is questionable, given that conflict can only occur in the context of previous experiences with the environment, which cannot be controlled for or measured. While they measured postural instability using motion tracking hardware in one condition, they failed to use the same measure of postural activity in the so-called 'sensory conflict' condition, instead measuring the number of time participants grabbed a bar for balance. Bos (2010) argues against Postural Instability Theory, citing studies that show increases in postural instability despite a decrease in symptoms of motion sickness and suggests short exposure to highly nauseogenic environments should not occur under Postural Instability Theory. Finally, Bos (2010) argues that if people are 'aware' of how sensory information should cohere, then it must relate to some measureable activity in the brain. However, this is not supported by moving room experiments where participants are often not aware the room is moving at all, hence an important lack of awareness of the characteristics of the stimulus.

Other theories of motion sickness exist. Ebenholtz *et al.* (1994) suggest that changes in visual stimulation interact with the vestibular ocular reflex and produce motion sickness. Eisenman (2009) theorises that vestibular stimulation releases acetylcholine as a secondary effect bringing about symptoms of motion sickness, introducing a feedback loop, producing further quantities of acetylcholine.

Debate over the true cause of motion sickness is unlikely to be concluded in the immediate future. Postural instability might eventually be found to only be a corollary of motion sickness as Bos (2010) suggests, or perhaps a superior theory will emerge, but postural instability does appear to at least appear to be a reliable, and observable, indicator of the incidence of motion sickness. It is therefore at least a useful measureable indicator of the effect of building motion on individuals in tall buildings and in simulators mimicking those conditions.

6. Postural instability in wind-excited tall buildings

Wind-excited tall buildings typically vibrate in the range of 0.063 – 1 Hz, and this is the frequency range used in the first attempt to set an international standard for acceptable levels of building motion, ISO 6897: 1984 (International Organisation for Standardisation 1984). Stoffregen and Smart (1998) suggested that postural instability may be a result of wave interference, where two or more waveforms in a narrow frequency range interact. When wave peaks coincide, the waveform increases in amplitude, when a peak in one waveform corresponds to a trough in the other, the sum of the waveforms decreases in amplitude. It seems reasonable to expect that the random movement of the building, coupled with an individual's natural body sway in response to this random movement, could cause wave interference which is difficult to anticipate, and therefore the individual counters with natural adjustments to maintain posture. However, this would not necessarily pre-empt adaptation to the environment. Even if this were the case, the level of dosage of motion that interferes with postural control would need to be understood.

Postural Instability theory, in contrast to Sensory Conflict Theory, places people as active participants in their environment, albeit here considered are environments that are mostly beyond their control. Individuals are considered as active managers of the dose-response relationship (meaning here, the amount of building vibration they are subjected to and how they respond). Sensory Conflict Theory regards people as reactive to environmental inputs and passive in mediating the dose-response relationship. This has led to a tradition of ignoring the role of the participant's behaviour in experimental circumstances which might induce motion-sickness. This tradition has had a spill over to building sciences, and also experimental research such as moving room experiments (e.g., Lishman and Lee 1973) which artificially change aspects of the visual environment to induce changes in posture. This often results in motion sickness, but the motion sickness is attributed to sensory conflict, not to the loss of postural stability because the individual is visually 'tricked' into believing posture must be change to maintain balance, where in reality this movement actually causes instability, not corrections in an attempt to maintain stability (Riccio and Stoffregen 1991).

Many studies have examined the perceptual threshold of sinusoidal motion, and are reviewed in Kwok *et al*. (2009). Burton *et al*. (2005) is one of the few experimental studies to examine the effect of low-frequency bi-axial random vibration on occupant comfort. A motion simulator was used to produce motion in the range of 0.125 Hz to 0.500 Hz, with peak accelerations of 1 to 24 mG, using three types of waveform inputs (sinusoidal, random and intermittent), over two durations of exposure (12 minutes and 50 minutes). The most nauseogenic frequencies were found to be 0.25 Hz and 0.50 Hz, where 40% of participants who reported nausea exited the motion simulator, and 80% of this group exiting the motion simulator after more than 30 minutes of exposure. Near sinusoidal waveforms (smooth and predictable repetitive motion) resulted in no reports of nausea. The authors speculate that participants subject to sinusoidal motion have a "greater control of the vibration characteristics" (p. 7). Higher peak acceleration, for short periods, also resulted in a lower incidence of nausea. Symptoms of motion sickness were significantly less likely to be reported in

12 minute sessions than 50 minute sessions, despite the same levels of acceleration. Similar patterns of results were reported for difficulty of concentration when participants were engaged in a distracter task. Burton *et al*. (2005) suggest that the unpredictability of the random motion, and the duration of exposure were the key causes of the nausea.

Another study by Burton *et al*. (2006) examined how building movement affected body movement, and how any magnification of body movement contributed to the perception of motion. Accelerometers were placed on the head and torso of participants. Burton *et al*. (2006) observed an increase in torso acceleration within the range of natural body sway (0.1 - 0.4 Hz). While Burton *et al*. (2006) were not attempting to examine body movement in the context of Postural Instability Theory, these findings do illustrate that a change in postural activity does occur, can be measured, and occurs within the frequencies that exist in tall buildings subject to wind excitation.

Table 1 presents a summary of variables that are thought to affect the incidence of motion sickness in wind excited tall buildings and how these variables are conceptualised or make differing predictions under Sensory Conflict theory and Postural Instability theory.

Table 1 Comparison of the implications of occupant and environment variables in wind-excited tall buildings under Postural Instability Theory and Sensory Conflict Theory

Occupant or building variables	Implications under Sensory Conflict Theory	Implications under Postural Instability Theory
Conception of an individuals' interaction with their environment	Occupant is passive to the motion stimuli.	Occupant actively controls their exposure to motion by altering behaviour, e.g., take more breaks, perform simpler tasks.
Visual cues	Visual cues highly important	Visual cues to motion less important
Audio cues	Relatively small influence on MS, other than cueing occupants to the perception of motion	Relatively small influence on MS, other than cueing occupants to the perception of motion
Frequency of building motion	Relatively less important	Important because of predicted interference with natural body sway
Building acceleration	Important because MS is hypothesised to scale to the amount of sensory conflict	Important because higher levels of acceleration will generate more postural instability
Age of occupants	Predicts that older people will be less susceptible to MS	Predicts older people will suffer more from MS
Work behaviours, e.g., reading off a computer screen	Work tasks such as reading off a computer screen will likely increase sensory conflict, and induce MS in some occupants.	Work tasks such as reading off a computer screen will likely contribute to postural instability, as they interfere with the ability to counter building motion.
Potential methods of reducing symptoms of motion sickness	Limit building motion, decrease visual cues to motion	Reduce posturally demanding tasks at problematic levels of building motion. Increase occupant stability (see Stoffregen *et al*. 2010)

7. A dose-response model for studying motion sickness in tall buildings

The concept of a dose-response model is developed within the domain of toxicology and has a long history (Waddel 2010). When motion sickness is understood within a dose-response model, it is typical to represent the relationship between dose (movement) and a single measurable variable, usually the percentage of people exposed to the dosage that vomit (e.g., McCauley *et al*. 1976). It is tempting to be critical of the simplicity of the response measurement but it is also not unusual, especially in toxicology where the interest is the levels of dosage causing death.

Fig. 1 represents a set of hypothetical dose-response models for the environment (dose) and motion sickness (response). It should be noted that the slope of the curves are arbitrary; the actual relationship might be steeper or shallower. It is difficult to define what constitutes a low or high dose environment in a single variable. However, based on the frequency of use of the dependent variables in research (i.e., nausea and vomiting), high-dose environments and high dose symptoms appear to have had the effect of biasing research towards the high end of the dose-response relationship. The difference between high and low-dose environments is likely to be related to more than the one variable that usually defines the dose. High dose motion environments are likely to be associated with longer durations of exposure, higher levels of acceleration, lower frequencies and random motion as opposed to sinusoidal motion.

The dashed line in Fig. 1 represents an alternative hypothetical concept of the dose-response curve to nauseogenic environments. It represents that exposure to a potentially nauseogenic environment may be desired in some instances, e.g., for short durations high acceleration environments such as rollercoasters are considered enjoyable by many people. In other instances, expose to low-level provocative environments motion may help an individual to adapt to that environment, therefore symptoms may be alleviated if the dose is held constant, or tolerance is acquired over time. Positive effects of low-dose exposure to a toxin are referred to as ‘Hormesis’, derived from the Greek word ‘Hormo’ meaning ‘to excite’.

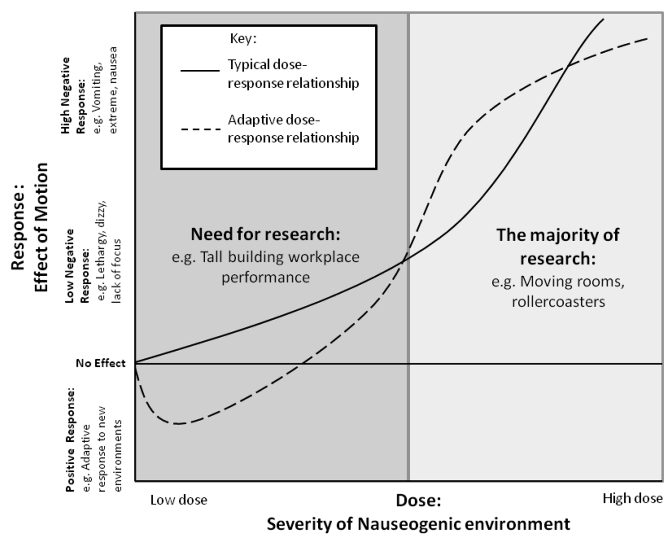

Fig. 1 Hypothetical representation of different models of dose (environment)-response (motion sickness) in nauseogenic environments.

It should be noted that from the perspective of Postural Instability Theory, the dose-response relationship is also an oversimplification in the respect that the dose-response relationship is mediated by the individual's behaviour in a real-world setting. Riccio and Stoffregen (1991) state that there is no simple relation between the environment and what makes people sick, primarily because the individual is an active participant whose behaviour can exacerbate or alleviate demands on their posture, and therefore symptoms. It is this that causes concern for workplace design. Implicit in studies of simulated building movement is the notion that perception of movement, or occupant discomfort, is above the threshold for a productivity decrement. It is argued there that low levels of vibration are sufficient to cause low-level postural instability which may decrease productivity either through the onset of fatigue, or by the individual decreasing the demands on their performance by taking more breaks or other behaviours that will limit productive hours.

8. Postural instability in a low-dose environment

Postural Instability Theory, in the context of a dose-relationship, presents a framework for generating testable hypotheses about the potential effects of tall building motion sway on occupant comfort and workplace productivity. Riccio and Stoffregen (1991) state that there are environments that cause postural instability at a sufficiently low-level that an individual can tolerate; explicitly mentioning the workplace giving the example of "workstation sickness" (Morrissey and Bittner 1986). Wind-excited buildings produce a pattern of motion that requires a different set of postural needs (or 'control actions') compared to a stable environment; therefore presenting 'new dynamics' that require adaptation by the building occupants.

Postural instability occurs at such a small level that individuals, particularly in low-dose environments, would be unlikely to attribute (and therefore report via survey etc) any symptoms of discomfort to motion sickness or even to their environment at all. Nisbett and Wilson (1977) categorise individuals' awareness of the relationship between environment variables and the effect that they have on them into three categories: (1) the stimulus affected the participant, but they were not aware of the stimulus, (2) the participant not conscious of the response itself, and (3) the participant was aware of the stimulus, but unaware that it had affected them. At a low-dose, it is argued that the majority of occupants will fit the first category. That is, building motion will induce low-dose symptoms associated with Sopite Syndrome, but they will be unaware of the cause. Higher doses may make the motion more easily perceptible, but symptoms of drowsiness, distraction and daydreaming are expected to be misattributed to other factors. Wendt (1944, quoted in Graybiel and Knepton 1976) suggests that "much motion sickness is of a severity so low that it escapes the attention of both the victim and his associates. This 'subclinical' phase may not progress beyond the early stages of mild emotional depression and loss of motivation".

Prodromal responses in low-dose environments have been neglected by researchers, possibly because the main dependent measures of these symptoms are contaminated by the same symptoms arising through numerous other causes including colds, hangovers, and emotional upset. The language used by researchers of building sway is of 'nauseogenic motion' and even this concession to the variation from traditional measures of motion sickness masks the importance of other prodromal responses, such as lethargy and decreased task performance. It is probably only the demands of real world settings such as those concerning 'occupant comfort' in tall buildings that might encourage researchers to examine the nature of the relationship and low dosage responses.

It would be inconsistent with Postural Instability Theory to simply ask people about their experiences of motion sickness in low dosage environments. Individuals are likely to associate symptoms of lethargy, headaches, and tiredness as reasonably common effects in everyday ‘working life’. A better approach is to examine those aspects of individual behaviour that vary with building motion: task performance, individual compensatory behaviours (such as taking longer or more frequent breaks), perceptions of task performance and a measure of postural control. In practice this means one needs to observe the behaviours of individuals in response to low-dose motion and compare these to situations in which there is no motion.

Postural Instability Theory also offers a number of other testable hypotheses. Riccio and Stoffregen (1991) argue that some tasks such as mental calculation should have no effect on the perception-action interaction, therefore will not affect susceptibility. However, tasks that involve perception and action, such as visual searching, and presumably reading, usually do increase susceptibility (Benson and Guedry 1971, Guedry *et al*. 1982). The problem is therefore, a low-dose environment coupled with activities that contribute to susceptibility.

Riccio and Stoffregen (1991) argue that there is a fundamental relationship between postural control and performance, where a decrement in postural control causes a decrement in performance. Performance continues but in a reduced capacity. Small performance decrements across a large number of employees could represent a large cost to an organisation. Riccio and Stoffregen (1991) speculate that the duration of exposure directly relates to the intensity of symptoms, and that the magnitude of movement may also relate to the severity of symptoms. It is important to consider what types of activities typically occur in the workplace, and how these might affect susceptibility to motion sickness. If established with further research the notion would require a re-orientation in our thinking about the use of the highest floors in tall buildings.

9. Recommendations for future research

The two main theories of motion sickness imply different approaches to research, and among these concerns there is an important place for research on occupant response to tall building wind excitation. A traditional focus on the perception of motion to determine occupant comfort thresholds may ignore the measurable effects of motion on occupants wellbeing and productivity, mediated by the influence of individual susceptibility to motion. The active role of the participant to their dose exposure (a concept central to postural instability theory) is ignored when building occupants are considered to be subjected to an equal dosage because the sample of occupants is in a building subject to a known amount of wind excitation. This concept of ‘equal dosage’ (leading, for example, to an effort to quantify ‘measurable thresholds of acceptability) is flawed if some occupants in the potential population of building occupants either (1) avoid the building generally, (2) avoid the building when it is subject to wind excitation, or (3) actively respond to the motion caused by wind excitation to reduce the impact of the dosage on their otherwise natural response. Occupants might respond to their environmental exposure to motion without any awareness of the building’s movement, their relative dosage or its cause by doing things which are measurable but very subtle. For example, it is hypothesised that occupants subject to sustained low dosage of motion may reduce productivity, become more easily fatigued, feel less productive, take longer breaks and experience prodromal effects of motion sickness such as nausea, headaches and dizziness.

A longitudinal survey examining these factors in a sample of workers in a wind-excited instrumented building would allow building motion to be assessed in relation to the following dependant variables: (1) 'direct' (a survey of what features of movement annoy people, and how); (2) 'indirect' (on perceived productivity, effects of workplace or residential comfort); and, (3) measures of adaptivity (changes in work or life patterns). By using a mixed design, the effect size of 'social sensitivity' can be effectively eliminated in a within-subjects repeated measure of 'proprioceptive disturbance' and the effect of 'event frequency' measured. Given sufficient technical solutions, it may be possible to measure postural activity in a work environment; the challenge being to avoid disturbing workers operating within a commercial context. Objective measures of activity, though only in the context of certain jobs, such as the rate of keyboard presses (and / or mouse activity) could be related to the amount of postural activity, under the hypothesis that increased postural variability would be associated with a lower rate of key pressing. However, the limitations of such a measure highlight the difficulty of objectively and accurately measuring performance.

Developing a sophisticated understanding of the relationship between motion and human factors requires some experimental input via the use of motion simulators. A series of motion simulator experiments designed to manipulate the motion frequency, acceleration and duration of motion, measuring performance and body sway would provide a fundamental understanding of the individual contribution of each of the three preceding variables to the incidence of low-dose motion sickness. Simulator studies should be of a sufficient duration to mimic actual working conditions, and adopt more sophisticated analysis techniques such as that employed by Stoffregen *et al.* (2010) who use Detrenched Fluctuation Analysis to determine how sway changes over time, measure how 'self-similar' the pattern of sway is.

An understanding of the full range of effects of motion on building occupants will allow building designers to make informed decisions about how to design for maximal comfort and performance of occupants. Improved guidelines for serviceability criteria could be formulated to include the expected decrements in productivity based on the duration of exposure to different accelerations and across a range of frequencies. For existing buildings, other solutions may be required. Organisations could potentially screen applicants to measure susceptibility to motion sickness and avoid the selection of susceptible individuals. Other solutions may exist such as recommendations for building occupants to take breaks outside of the building when accelerations reaching a particular threshold are reached.

10. Conclusions

The unchallenged adoption of Sensory Conflict Theory by building designers and their attempts to limit or set tolerance for building sway may mask genuine difficulties for the occupants of wind-excited tall buildings to cope with undesirable building motion. In addition to simply considering low-dosage outcomes there are theoretical challenges to Sensory Conflict Theory that create testable hypotheses that can be evaluated in real-world settings such as those created by building sway. The most important outcome of Postural Instability Theory is that people actively manage low-dosage motion, and that their ability to do so varies between individuals. By re-conceptualising motion sickness as a dose-response relationship, it is argued that the prodromal symptoms of motion sickness (such as fatigue and poor work performance) are likely to occur in low-dosage motion environments such as wind-excited tall buildings and these low-dosage symptoms have been ignored by researchers. In the building sciences literature, ‘motion sickness’ is not raised directly but rather replaced with expressions to manage ‘occupant comfort’ from motion disturbance. Such expressions diminish and marginalised the theoretical and methodological considerations that might be brought to bear on the phenomena experienced by people and managed by the design and engineering of structures. Most importantly, it is predicted that the most extreme human responses to motion may not occur at all, occur rarely, or occur in so few people as to be insignificant in the conditions of wind-excited tall buildings. However, the concomitant of this thesis under Postural Instability Theory is that the minor symptoms of motion sickness are likely to be significant, managed by the active behaviour of individuals, and masked by the response behaviours of occupants.

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