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Cybersickness in the presence of scene rotational movements along different axes

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Abstract

Compelling scene movements in a virtual reality (VR) system can cause symptoms of motion sickness (i.e., cybersickness). A within-subject experiment has been conducted to investigate the effects of scene oscillations along different axes on the level of cybersickness. Sixteen male participants were exposed to four 20-min VR simulation sessions. The four sessions used the same virtual environment but with scene oscillations along different axes, i.e., pitch, yaw, roll, or no oscillation (speed: 30°/s, range: ± 60°). Verbal ratings of the level of nausea were taken at 5-min intervals during the sessions and sickness symptoms were also measured before and after the sessions using the Simulator Sickness Questionnaire (SSQ). In the presence of scene oscillation, both nausea ratings and SSQ scores increased at significantly higher rates than with no oscillation. While individual participants exhibited different susceptibilities to nausea associated with VR simulation containing scene oscillations along different rotational axes, the overall effects of axis among our group of 16 randomly selected participants were not significant. The main effects of, and interactions among, scene oscillation, duration, and participants are discussed in the paper.

Keywords: Cybersickness; Virtual reality; Vection; Scene movement

1. Introduction

1.1. Virtual reality systems and their associated cybersickness effects

Head-coupled virtual reality systems were developed to improve the visual interface between human operators and aircraft flight control, navigation, and weapon systems (Birt and Furness, 1974). The technology provides an advanced interface for users to interact with computer-generated (virtual) environments (e.g., Kalawsky, 1993; Earnshaw et al., 1995; Furness and Barfield, 1995; Carr and England, 1995; Vince, 1995). Image projections forming the virtual environment are presented through either a Head-Mounted Display (HMD) or a multiple-screen projection system (e.g., CAVE™), enabling users to choose what they look at by moving their heads, while they can also navigate through the virtual environment using a mouse or joystick-type device. Virtual reality systems are extensively reported as useful for training (e.g., driving simulation: Kuhl et al. (1995) and Bayarri et al. (1996); flight simulation: Haas (1984); teleoperation: Rod and Pardini (1996); machine operation: Lin et al. (1996); and health therapy: Lamson (1997)).

Despite the benefits for simulation and training applications, Virtual Reality (VR) systems have some shortcomings. Wilson (1996) and Stanney et al. (1998b) reviewed the ergonomics issues related to the use of VR systems. In both reviews, associated sickness with symptoms similar to those of motion sickness has been highlighted as one of the major aftereffects. The term 'cybersickness' has been used to describe the motion sickness that is caused by virtual reality systems (McCauley and Sharkey, 1992), and it has been associated with the occurrence of vection (an illusion of self-motion) (Hettinger and Riccio, 1992). Stanney et al. (1997) and Cobb et al. (1999) reported that the symptoms experienced by users of HMD-based Virtual Reality (VR) simulation systems are different from those with non-VR simulators. The former reported a difference in sickness profiles as measured by the Simulator Sickness Questionnaire (SSQ, Kennedy et al., 1993) while the latter reported a unique combination of sickness symptoms as measured by a variety of self-reported scales

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including: physiological indicators, interview, and performance measures. The term VRISE (Virtual Reality Induced Symptoms and Effects) is proposed by Cobb et al., 1999 to distinguish cybersickness from simulator sickness and motion sickness experienced in transport systems.

A review of literature shows that studies reporting sickness symptoms among users who navigate through a virtual simulation have been plenty (e.g., passive navigation: So, 1994; active navigation: Cobb et al., 1999; Regan, 1995; Stanney and Kennedy, 1997, 1998; Kolasinski and Gilson, 1998; Draper, 1998). Wilson (1996) and Kennedy et al. (1997) provided comprehensive reviews on studies of cybersickness. The former review offers a broad summary of the current knowledge about the aftereffects of VR systems, while the latter focuses on analyzing the symptoms of cybersickness. Both studies acknowledge that more research is needed for the understanding of the causitive mechanisms of cybersickness. Among the many suggestions for future research, studies on the contribution of scene content variables to cybersickness has been recommended (Kennedy et al., 1997). Also, in order to measure the possible reactivity to subjective questionnaires, the use of a control condition should be considered (Wilson, 1996).

In 1997, a special scientific session with over 25 top researchers from different countries was held to discuss research concerning cybersickness (Stanney et al., 1998b). As stated with reference to the session, "The two most critical research issues identified were (a) standardization and use of measurement approaches for aftereffects and (b) identification and prioritization of sensorimotor discordances that drive aftereffects." This paper will focus more on the second research area as proposed by Stanney et al. (1998b), in particular, the effects of scene movements along different axes are studied.

Studies investigating the various contributing factors toward cybersickness are categorized in Table 1. The purpose of the categorization is to illustrate the relative

Table 1
Tally of experimentals investigating the causitive factors of cybersickness[a]

Groups	Variables investigated	References	Tally
(1) Studies investigating variables related to *how* virtual simulation is presented	Duration of exposure (excluding studies with only two levels of duration: before and after the exposure.	Cobb et al. (1999), Regan (1995); Regan and Price (1994), Singer et al. (1998), So (1994); So and Lo (1998); Stanney and Kennedy (1998)	No. of studies = 20
	Types of VR displays	Ramsey et al. (1999); Howarth and Costello (1997); Lampton et al. (1994); Nichols et al. (2000)	
	Display's field-of-view	Dizio and Lackner (1997)	
	Display lags	Cobb et al. (1999), Dizio and Lackner (1997); So (1994)	
	Stereoscopic presentation and IPD mismarch	Ehrlich (1997); Howarth (1999); Rushton and Riddell (1999); Wann et al. (1995), Wann and Mon-Williams (1997)	
	Method of navigation	Howarth and Finch (1999); Rich and Braun (1996); Stanney and Hash (1998)	
(2) Studies investigating participant-related variables	Age, gender, pre-exposure posture stability	Ehrlich (1997); Ehrlich et al. (1998); Kennedy et al. (1994b); Kolasinski (1996); Kolasinski and Gilson (1999); Regan and Price (1994); Rich and Braun (1996)	No. of studies = 14
	Sitting vs. Standing	Regan and Price (1994)	
	Habituation	Cobb et al. (1999); Howarth and Hill (1999); Kennedy et al. (1993); Regan and Price (1993)	
	Menstrual phase	Ramsey (1997)	
	Individual differences	Cobb et al. (1999)	
	Amount of head movement interactions	Regan (1995); So (1994)	
	Drug treatment	Regan (1995)	
(3) Studies investigating variables related to *what* is presented in a virtual simulation	Types of scene background	Kennedy et al., 1994; Slater et al. (1996)	No. of studies = 3
	Quantifying scene movement in a VE	Kennedy et al. (1996a)	

[a]Note: Studies are divided into 3 groups according to the factors that are investigated: (i) factors concerning how a virtual simulation is presented, (ii) subject-related factors, and (iii) factors concerning the content of a virtual simulation. (Studies of simulator sickness and studies purely investigating methods to measure and characterize cybersickness are excluded).

amount of research that has been done on each factor. There are three categories of studies, investigating (i) variables related to *how* a virtual simulation is presented and controlled (e.g., duration, update lag, and navigation period), (ii) participant-related variables (e.g., age, gender, posture), and (iii) variables related to *what* is presented during a virtual simulation (e.g., VEs with different complexity, VR simulations with different scene movements). The tally and references for each category are shown in Table 1. It should be noted that this classification excludes studies conducted to investigate and standardize methods to measure cybersickness (e.g., Cobb, 1999; Nichols et al., 1997; Kennedy et al., 1995; Stanney et al., 1999) and studies to analyze the profile of cybersickness symptoms (e.g., Kennedy and Stanney, 1997; Kennedy et al., 1997). These studies are of vital importance to the knowledge concerning cybersickness, however, the authors would like to limit the scope to the quest for contributing factors of cybersickness. Detailed review of research concerning the methods to measure and characterize symptoms of cybersickness can be found in Stanney et al. (1998b).

The authors acknowledge that the classification in Table 1 may not reflect the original aims of the reviewed articles and by no means reflects any ranking by importance. Furthermore, there may be interaction effects among the three types of variables. For example, a variable affecting *how* a VE is presented may also affect *what* is being perceived by the participants. Nonetheless, inspection of Table 1 indicates that there are relatively fewer studies focusing on the effects of *what* is being presented during a VR simulation (3 as compared to 20 and 14 in the first two groups). Studies cited in the first two groups will not be discussed here as they are of less relevance to this paper. Readers can refer to the reviews by Stanney et al. (1998a, b) and Wilson (1996, 1997, 1999).

Table 1 notes three studies on the effects of scene content on the level of cybersickness. Kennedy et al. (1996a) and Slater et al. (1996) reported experiments conducted to investigate the effects of scene motion on the level of cybersickness. The latter investigated task performance of a 3D chess game presented inside different VEs. Although an eight-point sickness rating scale was used to obtain the levels of sickness before and after VR exposure, the sickness results were not reported. Instead, the paper focused on task performance. Kennedy et al. (1996a) reports a metric to quantify the visual scene movements perceived during a VR simulation. This metric is referred to as the Human Judged Kinematic Cluster Scores (HJKC) scores. Kennedy and his colleagues showed that the HJKC scores significantly correlated with the levels of cybersickness. The work by Kennedy represents a major contribution in showing that scene movements in a VR simulation can significantly contribute to the levels of cybersickness. In 1994, Kennedy and his colleagues compared the sickness symptoms obtained from over 6500 participants of various military VR and non-VR simulators (Kennedy et al., 1994a). After correlating the sickness symptoms with various parameters associated with the simulators and the content of their simulations, one of their observations is that scene or target movement could make major contributions to eye strain (one of the symptoms of cybersickness). The two studies by Kennedy and his colleagues suggested that scene movement in a VR simulation can affect the level of cybersickness. This is consistent with the current knowledge that cybersickness is a type of visually induced motion sickness (Hettinger and Riccio, 1992). According to the sensory conflict theory (Reason and Brand, 1975; Benson, 1984), when an observer views a moving scene with wide field-of-view, there is commonly an illusion of self-motion (vection) in the opposite direction of the moving scene. This experience can be nauseogenic (e.g., Griffin, 1990; Oman, 1993).

Since cybersickness is a type of visual-induced motion sickness, a logical research direction is to study the effects of visual scene movement on the level of cybersickness. This paper reports a study on rated levels of cybersickness in the presence of a rotating scene along different axes. The aim is to identify the dominant axis or axes of rotational scene movement associated with cybersickness. In studies of seasickness, Lawther and Griffin (1986, 1988) reported that ship motion along the vertical axis was the main cause of sea sickness. This conclusion subsequently led to the development of the Motion Sickness Dose Value (MSDV) for predicting seasickness based on the measured vertical motion of a ship (BSI, 1987). Similarly, if the relative contributing effects of scene movement along different axes are determined, it would be a step forward in identifying the various contributing factors of cybersickness. This study is consistent with the second critical research issue proposed by Stanney et al. (1998b), in that this study aimed to identify and prioritize the dominant axis or axes of rotational scene movement that contribute towards cybersickness. Furthermore, this aim is consistent with the recommendation by Kennedy et al. (1997) to study the effects of scene content variables.

1.2. Previous studies on motion sickness induced by scene rotational movements along different axes

The review of literature in Section 1.1 indicates that there is no previous published study investigating cybersickness as a function of scene movement along different axes. Consequently, attention is turned to studies concerning vection-induced sickness in non-VR systems.

A review of this literature indicates that there have been many studies of vection-induced sickness using rotating drums (sometimes referred to as optokinetic drums or vection drums) (e.g., Hu et al., 1989, 1991, 1997; Reid et al., 1994; Stern et al., 1989, 1990, 1993; Koch et al., 1990; Kennedy et al., 1996b), optical (optokinetic) projections (e.g., Muller et al., 1990), and simulators (e.g., Dizio and Lackner, 1991; Kennedy and Frank, 1984; Kennedy et al., 1997). Due to the very nature of a simulator, scene movements were usually along multiple axes and the effects of scene movement in one single axis were not isolated. Therefore, this review will not focus on studies on simulator sickness (see Kennedy and Frank (1984) for a detailed review). A review of studies using rotating drum and optokinetic projections indicate that scene movement is usually presented along a single axis (e.g., yaw axis: Stern et al., 1989; Hu et al., 1997; Reid et al., 1994; pitch axis: Muller et al., 1990; roll axis: Griffin, 1990; Reinhardt-Rutland, 1981). A review of these studies indicated that the viewing of scene movement along each of the three rotational axes has been associated with a reported sensation of vection and symptoms of nausea. Hu et al. (1997) reported an increase in vection sensation and sickness symptoms in subjects exposed to a rotating drum with 24 pairs of black-and-white stripes rotating at 60°/s along the yaw axis. Reid et al. (1994) reported that vection generated during an exposure to an optokinetic drum rotating along the yaw axis caused symptoms of nausea in over half of their 12 participants. Muller et al. (1990) studied the effects of rotating speeds (10–200°/s) along the pitch axis of an optokinetic projection of random-dots. Vection sensation was reported after 3–8 s of exposure. The best example to demonstrate vection occurrence in viewing scene movement along the roll axis might be the classical example of the *haunted swing*, where audiences are seated between two slowly swinging *walls*. The viewing of the swinging walls produced sensation of vection in stationary audiences (Griffin, 1990). Reinhardt-Rutland (1981) reported that viewers of a stationary disc (subtending a viewing angle of 36°) with a rotating circumference at 22.8°/s could experienced an illusion of rotating motion of the stationary disc in the opposite direction to the circumference. Although these studies suggest that vection and the associated nausea symptoms can occur with scene rotations along all three axes, the effects of scene movement along these different axes have not been compared. Tiande and Jingshen (1991) did, however, compare the effects of scene rotation in different axes. Scene rotations were presented with a rotating sphere at a speed of 45°/s. Results of 26 stationary participants indicated that scene movement along the pitch axis was associated with the highest level of motion sickness symptoms followed by roll axis and yaw axis.

2. Method and design

2.1. Objective and hypotheses

The objective of this study is to determine the relationship between the axes of visual scene oscillation and the rated level of cybersickness. It was hypothesized that (i) a virtual environment without scene oscillations would produce lower levels of sickness, and (ii) visual scene oscillations in the pitch and roll axes would produce higher levels of sickness than scene oscillations in the yaw axis. The first hypothesis is based on the assumption that cybersickness is a type of vection-induced motion sickness (Hettinger and Riccio, 1992). This assumption has been shared by others who have investigated vection-induced motion sickness (e.g., Kennedy et al., 1996b) and cybersickness (e.g., McCauley and Sharkey, 1992). If cybersickness is a type of vection-induced motion sickness, then it is logical to expect that the absence of any scene oscillation will prevent the occurrence of vection and, hence, its associated sickness. The second hypothesis was based on the assumptions that (i) vection will occur when participants view a VE with scene oscillations in all three axes and (ii) there will be more mismatch between the vection sensation and the vestibular cues in the pitch and roll axes than in the yaw axis. It is worth noting that, during vection in all three rotational axes, there is an absence of appropriate motion cues as detected by the semi-circular canals. However, during vection in the pitch and roll axes, there is an additional mismatch. This additional mismatch is the absence of the appropriate gravitational acceleration cue detected by the otolith during physical pitch and roll oscillations. Such a mismatch does not occur during yaw vection because both physical head oscillation and vection in the yaw axis do not introduce any changes in gravitational acceleration cue to the otolith as the yaw axis oscillation is rotating about the vertical axis. As a result, in this study, vection in the pitch and roll axes should be associated with more sensory mismatch than that in the yaw axis. This second hypothesis is also consistent with the findings by Tiande and Jingshen (1991).

2.2. Participants

Sixteen male Chinese volunteers participated in the experiment. They were university engineering students and staff members with an average age of 26 yr. A payment of HK$200 was given to each participant at the end of the experiment as a compensation for their time and travel expenses. Participants of the same gender were used in this study because it has been reported that gender can have a significant effect on susceptibility to motion sickness (Griffin, 1990; So et al., 1999). A review of the literature indicates that females have reported higher Simulator Sickness Questionnaire (SSQ) scores than males although the difference was not statistically significant in some studies (Kennedy et al., 1994b; Kolasinski, 1996; Kolasinski and Gilson, 1998). Using participants of both genders to study the effects of gender, however, increases the number of participants, which was not possible due to the available resources at the time of the study, and more male participants were available. The authors acknowledge that this will limit the generalizability of the study and future studies using female participants should be conducted. All participants were healthy and free of medication and illness, having been prescreened using a health questionnaire and required to pass a color blindness test. All participants gave written consent for their participation and the experiment was approved by the Human Subject and Research Ethics committee at the Hong Kong University of Science and Technology.

2.3. Apparatus

The virtual scene was constructed using a virtual reality authoring software (dVISE) running on a Silicon Graphics Onyx workstation. Images were presented on a VR4 LCD Head-Mounted Display with a field-of-view of 48° horizontal and 36° vertical. Head orientation was monitored with a Polhemus FastTrack system. The experiment room was air-conditioned with an average temperature of about 23°C. The inherent response lag of the virtual environment to head movement was about 67 ms. This comprises a 33.3 ms computational lag; 16.7 ms video refresh delay; and 16.7 ms head tracker delay. As this experiment requires the participants to hold their heads stationary, the effects of any lag in response to the head tracker's movement should be invisible to the participants. The only observable lag is the frame delay (33.3 ms — an average frame rate of 30 Hz). There have been conflicting reports on the effects of lag on cybersickness. Dizio and Lackner (1997) reported that sickness ratings increased continuously when lags increased from 67 ms to 367 ms. However, So (1994) reported that an increase of lag from 75 to 355 ms lag did not significantly affect the level of cybersickness. Since a frame delay of 33 ms is lower than the baseline lags used in the studies by Dizio and Lackner (1997) and So (1994), its effect on cybersickness is assumed to be not significant. Moreover, the frame delay was the same among all conditions.

2.4. Experimental design

The experiment investigated four levels of scene oscillations: no scene oscillation and scene oscillation along the pitch axis, yaw axis, and roll axis. It was a within-subject full factorial experiment. There were 16 participants and all participants took part in all 4 conditions. The order in which the 4 conditions were presented to the participants was balanced using a randomized block design with four 4×4 Latin squares. In other words, the 16 participants were randomly assigned into 4 groups of 4 and within each group, the sequence in which the 4 conditions were presented to each of the 4 participants followed the structure of a 4×4 Latin square. The result was that there were equal numbers of participants who were exposed to a particular condition first, second, third, and last. The condition with no scene oscillation can be treated as a control condition. The use of a control condition is recommended as a measure to estimate any possible reactivity to the questionnaire (Wilson, 1996).

Each exposure to a condition took 20 min and was separated by, on average, 12 d (out of the 48 separation periods, 23 were 14 d or more, 20 were 12 d, and 5 were 7–8 d). Regan and Price (1993) reported that repeated exposure to the same virtual environment with separation of less than seven days could significantly affect the levels of cybersickness, while Cobb et al. (1999) also reported that repeated exposure to the same VR simulation in consecutive weeks can reduce the level of cybersickness. In this study, although the four conditions exposed the participants to VR simulation with different scene movements, precautions were taken to balance the order of presentation of the four conditions to minimize any biases caused by habituation. The speed of scene oscillation was 30°/s and the range of oscillation was $\pm$ 60° (i.e., 120°). The speed was comparable to that used in studies of vection-induced motion sickness caused by rotating drums (e.g., Stern et al., 1989). The range of scene oscillation follows the normal range of head rotation of the cervical spine (American Academy of Orthopaedic Surgeons, 1965). Sample scenes are shown in Fig. 1.

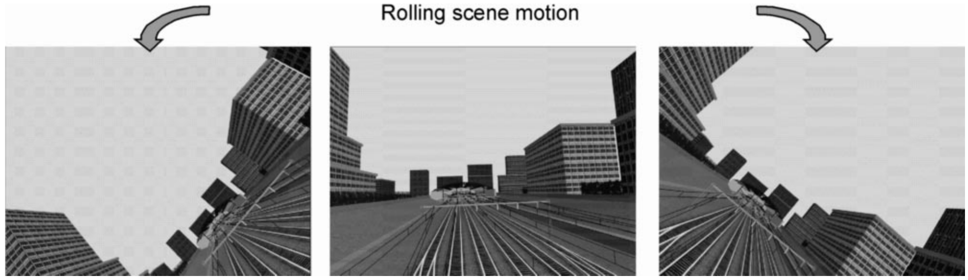

Fig. 1. Sample scenes of what the participants saw on the *head-mounted display* during scene oscillations in the roll axis. The virtual environment contains some buildings, a train station, tracks, cables, and bridges.

2.5. Procedure and measurements

Before each exposure, participants were required to rest for five minutes in an air-conditioned experiment room. They were then asked to complete a pre-exposure Simulator Sickness Questionnaire (SSQ) documenting the severity levels of 28 sickness symptoms (Kennedy et al., 1993) and a motion sickness history questionnaire previously used in a motion sickness survey (So et al., 1999). A one-minute practice session was given followed by a 20 min virtual simulation. Nausea ratings were obtained verbally at five-minute intervals according to a seven-point scale: 0 — no symptom; 1 — any unpleasant symptom, however slight; 2 — mild unpleasant symptom; 3 — mild nausea; 4 — mild to moderate nausea; 5 — moderate nausea but can continue; 6 — moderate nausea, want to stop. After the exposure, participants were asked to complete a post-exposure SSQ and a questionnaire assessing the realism of the simulation. The participants were then asked to rest for about 10 min before they were discharged.

During the 20 min virtual reality simulation, participants were asked to sit in an up-right posture with their backs touching the backrest. Also, they were instructed to look forward throughout the test to eliminate the influence of head movement, which may be a subject of interest for future studies. In the condition without scene oscillation, participants were viewing a stationary virtual environment. In all conditions, the viewpoint would have followed the head orientations of the participants had they in fact moved their heads. During all the conditions, the experimenter was watching the participants to ensure that their heads remained stationary and facing forward. Although there were times when individual participants slightly tilted their heads along the axis of the scene movement, they were immediately reminded to hold their heads steady. The average r.m.s. head rotations as measured by the head tracker were less than 5° in all conditions.

3. Results and discussion

3.1. Results from ANOVA analyses

The mean nausea ratings obtained with the four scene oscillation conditions are shown in Fig. 2. The figure indicates that ratings increased with increasing exposure time. Both the nausea rating and SSQ measurement passed the test for normalies and parametric analyses were conducted. An ANOVA (General Linear Model) on nausea ratings was performed and duration of exposure, participant, and scene oscillation condition were found to have significant effects on nausea ratings ($p < 0.001$, Table 2). However, all the two-way interactions were also significant. Consequently, the interaction effect has to be studied before discussing the main effects. Three-way interactions were not calculated due to lack of degrees of freedom in the data.

In addition to the nausea ratings, the participants completed a Simulator Sickness Questionnaire before and after the twenty-minute virtual reality simulation (Kennedy et al., 1993). Over 50 percent of the participants exposed to scene oscillations reported an increase in general discomfort, eyestrain, fullness of head, fatigue, and difficulty in focusing. The four SSQ scores (nausea sub-score, oculomotor sub-score, disorientation sub-score, and the total sickness score) were calculated according to the formulae in Kennedy et al. (1993, 1994). Four ANOVAs were conducted to analyze the effects of scene oscillation condition, participant, and duration (pre- and post-exposure) on the four SSQ scores obtained

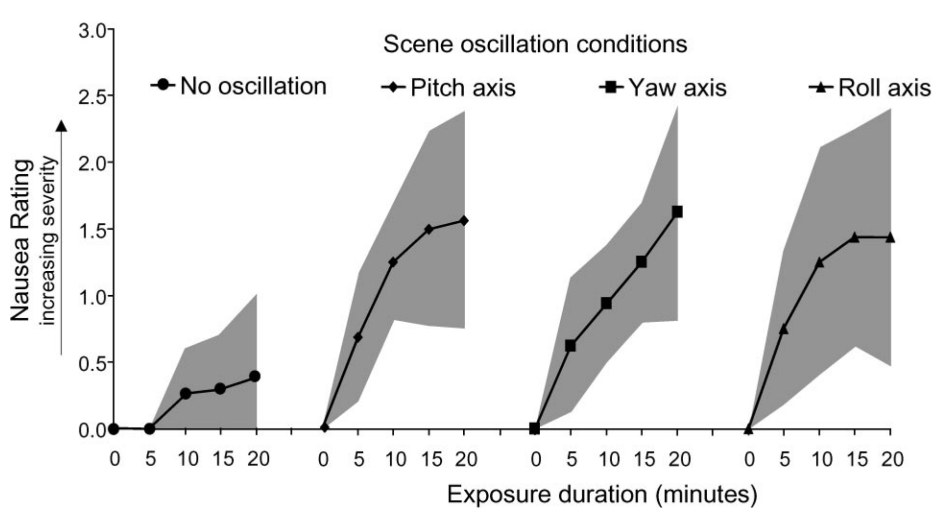

Fig. 2. Mean nausea ratings obtained in the four scene oscillation conditions as functions of exposure duration (data from 16 participants, ± one standard deviation are shown).

Table 2
ANOVA table of nausea ratings analyzing the effects of participant, exposure duration, and scene oscillation condition

Source	DF	Sum of squares	Mean square	F value	Pr > F
Scene oscillation condition	3	34.68	11.56	72.3	0.0001
Duration	4	67.34	16.84	20	0.0001
Participant	15	17.28	1.15	7.2	0.0001
Scene × Duration	12	11.33	0.94	5.9	0.0001
Scene × Participant	45	29.47	0.65	4.1	0.0001
Duration × Participant	60	20.56	0.34	2.1	0.0001
Error	180	28.77	0.16		
Corrected total	319	209.42			

Table 3
Summaries of ANOVA analyses of the 3 SSQ sub-scores and the Total Sickness Scores analyzing the effects of participant, exposure duration (pre- and post-expsoure) and scene oscillation condition

Source	DF	Pr > F results of 4 ANOVA analyses			
		Nausea sub-score	Oculomotor sub-score	Disorientation sub-score	Total sickness score
Scene oscillation condition	3	0.0032	0.0003	0.0040	0.0002
Duration (pre/post)	1	0.0001	0.0001	0.0001	0.0001
Participant	15	0.0049	0.0001	0.0001	0.0001
Scene × Duration	3	0.0156	0.0094	0.0041	0.0031
Scene × Participant	45	0.0128	0.0039	0.1943	0.0622
Duration × Participant	15	0.0151	0.0002	0.0001	0.0002
Error	45				
Corrected total	127				

before and after the simulation. The results indicate that all the three main effects were significant for all the sub-scores and the total sickness score ($p < 0.005$, Table 3). However, there were also significant two-way interactions between the effects of scene oscillation condition and duration, and between the effects of participant and duration. In the following sections, the interaction effects are explained first followed by a discussion on the main effects.

3.2. The interaction effects between scene oscillation condition and duration and the main effects of duration

Fig. 2 illustrates the interaction relationship between the effects of scene oscillation conditions and exposure duration. It can be observed that, without scene oscillation, the rate of increase of nausea ratings was lower than with scene oscillations along pitch, yaw, and roll axes. Another four ANOVAs were conducted to test the effects of exposure duration on nausea ratings obtained in each of the four conditions. Results indicated that although duration had significant effects ($p < 0.001$) in all four conditions, the F value in the no oscillation condition ($F_{4,79} = 5$) was much smaller than with scene oscillations ($F_{4,79} = 35$, 35, 18 for scene oscillation along the pitch, yaw, and roll axes, respectively). This suggests that the presence of scene oscillation can accelerate the increase of nausea rating with duration and supports the first hypothesis. According to the logic of sensory conflict theory, in the absence of scene oscillation there would be no vection and, hence, no symptoms of cybersickness. Inspection of Fig. 2 indicates that this was not the case. Without scene oscillation, there was a slight but significant increase in nausea rating after 20 min of exposure ($p < 0.001$, an ANOVA conducted solely on the data obtained in the condition without scene oscillation). There are a few possible reasons for the slight increase in nausea ratings with the absence of scene movement. It is possible that in the condition without scene movement, participants suffered from some unpleasant symptoms (e.g., fatigue) caused by the Head-Mounted Display (HMD) which weighed 0.94 kg. Over half of the participants complained about the weight of the HMD. Another possible reason might be the prolonged viewing of low-resolution images (10, 3 pixels per degree in the horizontal and vertical axes, respectively) focused at about 1 m in front of the participants. It should be noted that the highest nausea rating obtained in the no scene oscillation condition reached only ‘1’, which corresponds to ‘any unpleasant symptom, however slight’. In this study, the field-of-view of the images has been carefully matched with the optical field-of-view of the HMD ($48° \times 36°$). Nonetheless, slight optical distortion might still occur around the edge of the lens — a further possible reason for the 'slight unpleasant symptom' reported by the participants. Wilson (1996) discussed the possible reactivity effects of the sickness rating questionnaire, so the data collected in the control condition can serve as a baseline reference for the other three conditions.

A separate ANOVA conducted on nausea ratings obtained in the three conditions with scene oscillations indicated that there was no significant interaction between the effects of scene oscillation condition and duration ($p > 0.5$). Similarly, ANOVAs conducted on the four SSQ scores (nausea sub-score, oculomotor sub-score, disorientation sub-score, and the total sickness score) obtained in the three conditions with scene oscillations indicated no significant interaction between the effects of axis of scene oscillation and duration ($p > 0.3$).

3.3. The interaction effects between participant and duration and the main effects of participant

Fig. 3 illustrates that participants exhibited different rates of increase of nausea ratings. This should not be surprising as subject-variation in susceptibility to motion sickness should be expected (e.g., Lawther and Griffin, 1988; Griffin, 1990; Kolasinski, 1996). According to a recent survey of over 500 university students, the prevalence rates for Hong Kong Chinese adults who rate themselves as not susceptible to motion sickness is $14 \pm 3\%$; slightly-to-moderately susceptible is $79 \pm 4\%$; and very-to-extremely susceptible is $7 \pm 2\%$ (So et al., 1999). In this study, all participants reported a rating of '0' at the start of each VR exposure. After the exposure to all conditions, one participant (i.e., 6%) reached a mean rating of more than '3', two participants (i.e., 13%) reached a mean rating of less than '1', and the rest of the 81% reported a mean rating between '1' and '3' (the mean rating was the mean of nausea ratings taken after 20 min of VR simulations with scene oscillations in all three rotational axes). This distribution (high–average–low: 6%–81%–13%) is similar to that of the prevalence rates of susceptibility to motion sickness reported previously (So et al., 1999: high-average-low: 7%–79%–14%).

3.4. The interaction effects between scene oscillation condition and participant

Among the three significant two-way interaction effects, the most interesting interaction is between the effects of participants and the scene oscillation conditions. Could it be that for some groups of participants, scene oscillation along a particular rotational axis will result in significantly higher levels of nausea? Mean nausea ratings of individual participants obtained at all time intervals within each condition were re-analyzed to identify a possible grouping of participants according to the effects of condition. It was observed that in 87% of the participants, the nausea ratings obtained in the no oscillation condition were the lowest among the 4 conditions. The rest of the 13% reported a *near-zero* rating in all four conditions. This suggests that the absence of scene movement can reduce the level of nausea and is consistent with the first hypothesis. The pattern of interaction between the effects of the presence/lack of scene oscillation and the effects of participant is illustrated in Fig. 3. Inspection of Fig. 3 indicates that the 16 participants reported different levels of increase in nausea rating with the presence of scene movement. Is it possible that the interaction effects between scene oscillation condition and participant are

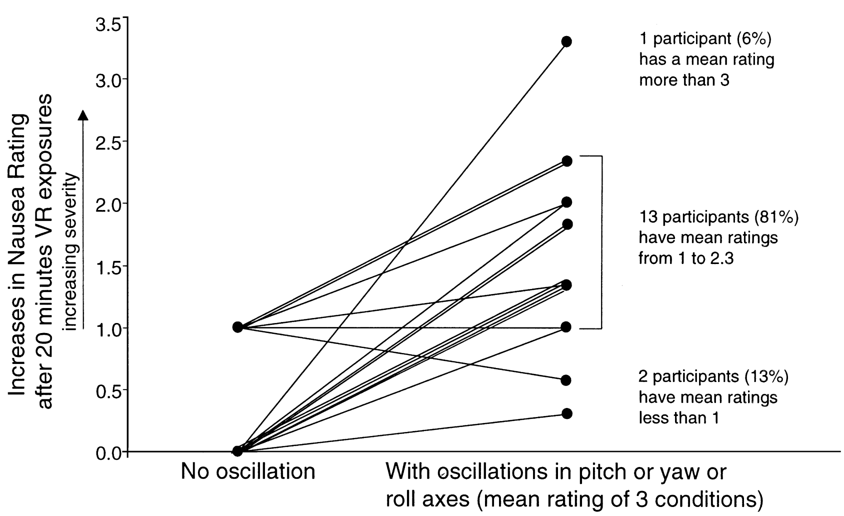

Fig. 3. An interaction plot illustrating the interactions between the effects of with/without scene oscillation and participants on the increase in mean nausea ratings after a 20 min VR simulation.

totally caused by the interaction effects between the presence/lack of scene oscillation and participant? In other words, would there be no interaction between the effects of scene oscillation axis and participant? A second ANOVA was conducted on data obtained only from the three conditions with scene oscillations. Results indicated that there was still a significant interaction between the effects of scene oscillation and participants. Further analyses showed that among the 16 participants, the percentages of participants reporting the highest ratings in the presence of scene oscillation along the pitch, yaw, and roll axes were: 31, 25, and 31%, respectively (Table 4). The rest of the 13% reported the highest rating with scene oscillation in both yaw and roll axes (6.5%) or both pitch and roll axes (6.5%). It was hypothesized that the order in which a condition was presented might have some effect on the ranking. Correlation tests were performed between the mean (for all time intervals) of nausea ratings and their positions in the sequence (first, second, third, and fourth) presented to the participant. Results indicated no significant correlation ($p > 0.2$). In order to investigate whether the participants were consistent in their ranking of nausea, the condition(s) with the highest nausea rating, highest SSQ's nausea sub-score, and highest nausea symptom reported by the same participants were compared (Table 4). Inspection of the table indicates that the most common condition for the nausea rating was about 50 and 75% consistent with that for the SSQ nausea sub-score and SSQ nausea symptom respectively. The lower match between the rankings according to the nausea ratings and the nausea sub-score is expected because the latter comprises symptoms of nausea as well as other symptoms such as *general discomfort* and *difficulty concentrating*. The 75% match between the ranking according to the nausea ratings and ranking according to the SSQ nausea symptoms suggests only that participants had been consistent in their ranking. Kolasinski (1996) reported a model to predict SSQ scores as functions of different subject-related variables such as age, gender, mental rotation ability, and pre-exposure stability. In this study, the 16 participants were of the same gender and similar ages, and yet they reported different nausea susceptibilities to VR simulation involving scene oscillations along different rotational axes. Further studies are needed to investigate the reason behind the interaction pattern between the effects of scene oscillation axis and participant.

Table 4
Condition(s) of scene oscillation with the highest nausea rating (mean of all time intervals), highest changes in SSQ nausea sub-scores (post-exposure scores — pre-exposure scores), and highest nausea symptoms in the SSQ checklist

Participant No.	Condition(s) with the highest scores / level		
	Nausea rating	Nausea sub-score	Nausea symptom
1	Roll	Roll	Roll
2	Roll	Roll	Roll
3	Pitch and Roll	Pitch and Roll	Pitch and Roll
4	Yaw	All equal	Yaw
5	Yaw	Yaw	Yaw
6	Yaw	Roll	Roll
7	Roll	Roll	Roll
8	Pitch	Pitch and Yaw	Pitch
9	Pitch	Yaw	Yaw and Pitch
10	Yaw and Roll	Roll	Roll
11	Roll	Roll	Roll
12	Pitch	Pitch	Pitch
13	Pitch	Pitch	Pitch
14	Yaw	Roll	Yaw
15	Roll	Pitch	Pitch
16	Pitch	All equal	Pitch
% of ranking among the 16 participants	31% pitch ranked 1st 25% yaw ranked 1st 31% roll ranked 1st	19% pitch ranked 1st 13% yaw ranked 1st 43% roll ranked 1st	31% pitch ranked 1st 19% yaw ranked 1st 38% roll ranked 1st

3.5. The main effects of scene oscillation

Firstly, we look at the effects of the presence and absence of scene oscillation. Post-hoc analyses using Student–Newman–Kuels (SNK) tests of the ANOVA results in Table 2 are shown in Table 5. Inspection of Table 5a and the interaction plots in Figs. 2 and 3 indicates that (i) nausea ratings obtained without scene oscillation were significantly lower than those obtained with scene oscillations ($p < 0.05$, Table 5a), (ii) in the absence of scene oscillation, nausea ratings increased at a lower rate with exposure duration (Fig. 2), and (iii) 87% of the participants reported higher nausea ratings when exposed to scene oscillations, although the level of sickness might vary with individuals (Fig. 3). Similar findings were also deduced from the four SSQ scores. In other words, it can be reported that the level of cybersickness in the absence of scene oscillation was significantly lower than in the presence of scene oscillations ($p < 0.05$). This supports the first hypothesis and suggests that scene oscillation is one of the major contributing factors of cybersickness, consistent with sensory conflict theory which predicts that wide field-of-view scene movement can introduce a sense of self-motion illusion (vection), which can then cause symptoms of cybersickness in the absence of appropriate body movement (Reason and Brand, 1975; Griffin, 1990; Oman, 1993).

Secondly, we look at the effects of scene oscillation axis. Nausea ratings with scene oscillations along the pitch, yaw, and roll axes are shown in Fig. 2. It can be observed that after 20 min of exposure, the mean nausea ratings with oscillations along three different axes are

Table 5
Student–Newman–Kuels (SNK) tests indicating the effects of (a) scene oscillation conditions, (b) duration, and (c) participants on nausea ratings (Alpha = 0.05, means with the same letter are not significantly different)

(a) SNK groupings on the effects of scene oscillation conditions (General Linear Model Procedure)

SNK grouping					Mean	*N*	Scene oscillation conditions
A					1.00	80	Pitch axis
A					0.98	80	Roll axis
A					0.88	80	Yaw axis
			B		0.2	80	No oscillation

(b) SNK groupings on the effects of Duration (General Linear Model Procedure)

SNK grouping					Mean	*N*	Duration (min)
A					1.27	64	20
	B				1.13	64	15
		C			0.92	64	10
			D		0.52	64	5
				E	0.00	64	0

(c) SNK groupings on the effects of Participants (General Linear Model Procedure)

SNK grouping					Mean	*N*	Participant number (S1–S16)
A					1.25	20	S9
A	B				1.10	20	S2
A	B	C			1.05	20	S11
A	B	C			1.00	20	S1
	B	C	D		0.90	20	S15
	B	C	D	E	0.80	20	S12
	B	C	D	E	0.75	20	S6
	B	C	D	E	0.75	20	S14
		C	D	E	0.70	20	S7
		C	D	E	0.70	20	S8
		C	D	E	0.65	20	S4
		C	D	E	0.65	20	S16
			D	E	0.65	20	S13
			D	E	0.55	20	S10
				E	0.45	20	S5
				E	0.40	20	S3

similar. Another ANOVA on nausea data obtained in the three conditions with scene oscillation was performed. Results indicated that scene oscillations along different axes did not produce a significant main effect on nausea ratings ($F_{2,120} = 1.6$, $p > 0.15$) and there was no significant interaction between the effects of axis and duration. However, as discussed in Section 3.4, the effects of axis had significant interaction with the effects of participants. Inspection of Table 4 indicates that the participants could largely be divided into three groups according to the axes of scene oscillations that were associated with the highest level of reported nausea. Nausea ratings within each group of participants were analyzed with non-parametric Friedman two-way ANOVAs to study the effects of axis of scene oscillation. Non-parametric tests were used because, after separating the data into three different groups according to their highest ranked axis of scene oscillation, the data within each group failed the normality test. Results of the Friedman two-way ANOVAs indicated that, in all three groups of participants, the effect of axis has a significant effect on nausea ratings ($p < 0.01$). This suggests that individuals could have different susceptibilities to scene oscillation along the pitch, yaw, and roll axes. However, it is also true that the resultant effects of scene oscillation axis on the average level of nausea obtained from the whole group of participants was not significant ($p > 0.15$), which is consistent with the SNK analyses as shown in Table 5a. Further analyses on the nausea sub-scores indicate similar results — while individuals had different susceptibilities to scene oscillation along the pitch, yaw, and roll axes, the resultant effects of scene oscillation axis were not significant. The absence of significant difference among the resultant effects of scene oscillation disagrees with the second hypothesis, which predicts that the effects of scene oscillation along the yaw axis would be less. However, inspection of the pattern in Table 4, with oscillation along the yaw axis consistently less associated with highest sickness reports, supports the second hypothesis. Similarly, the rankings of mean nausea ratings in Table 5a are also consistent with the second hypothesis — among scene oscillations along the three axes, the yaw axis scene oscillation had the lowest mean nausea rating.

3.6. The profile of SSQ scores

In this study, the mean post-exposure Total Sickness (TS) score was 35 in the presence of scene oscillation, which is comparable to the published data (19–55) documented in Kennedy and Stanney (1997). The profiles of the mean SSQ scores before and after the exposure are shown in Fig. 4. The scores of the three conditions with scene oscillation along different axes were averaged, inspection indicates that the profiles of the post-exposure sickness sub-scores (Nausea (N), Oculomotor (O) and Disorientation (D)) are consistently $O > D > N$ in the three conditions with scene oscillations. This profile is different from the $D > N > O$ pattern reported by Kennedy and Stanney (1997) and the $D > N > O$ and $D > O > N$ patterns reported by Ehrlich and Kolasinski (1998), but it is similar to that reported in 3 out of the 9 experiments reported in Cobb et al. (1999). Since different simulation and display apparatus, virtual environments, and tasks were used in these studies, it is difficult to clearly explain the differences in sickness sub-score profiles. Kennedy and Stanney (1997) reported that sickness data from non-Virtual Reality simulators have a sickness sub-score profile of $O > N > D$, which is closer to that found in this experiment, whereas a profile of $O > D > N$ is similar to that of alcohol induced discomfort (Kennedy et al., 1994a). Indeed, Kennedy and Lilienthal (1994) report that the level of cybersickness can be measured by postural stability which has a well established relationship with the equivalent Blood Alcohol Concentration (BAC) level. In this study, the high level on the oculomotor sub-score (O) was mainly due to the high level of fatigue and eye-strain symptoms,which may be related to the weight of the helmet (0.94 kg), the short focal length of the projected imagery, the slight optical distortion of images around the edge of the HMD lens, and the low-resolution images. It is worth noting that, even before the exposure, the pre-exposure oculomotor sub-score was consistently the highest among the three sub-scores for all the conditions. In order to minimize the pre-exposure biases, further ANOVAs and SNK analyses were conducted on the differences between the post-exposure and the pre-exposure scores. Results indicated that both the statistics and the profiles remained similar to the previous analyses using pre- and post-exposure scores.

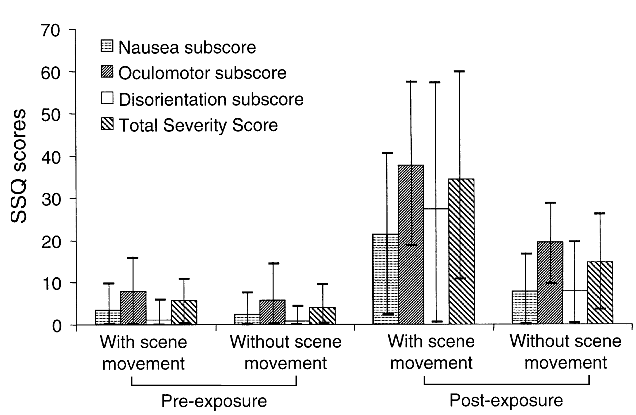

Fig. 4. Mean sickness scores before and after a 20 min simulation with and without scene oscillation (± one standard deviation are shown).

3.7. Implications of the main effects and interaction effects

This study provides evidence that the presence of scene oscillation (30°/s) along any of the pitch, yaw, and roll axes in a Virtual Reality (VR) simulation will significantly increase the symptoms of sickness. In particular, the rate of increase of nausea symptoms with increasing exposure duration significantly accelerates in the presence of scene oscillations. This suggests that scene oscillation is one of the major contributing factors of cybersickness, that has a multiplicative effect with duration of exposure from 0 to 20 min (data beyond 20 min were not collected in this study). The authors acknowledge that, besides scene oscillations and duration of exposure, there are other known contributing factors to cybersickness. Nonetheless, the finding of this paper is valuable because the evidence that the presence of scene oscillation can significantly increase nausea symptoms supports the statement that cybersickness is a type of vection-induced motion sickness (Hettinger and Riccio, 1992). The finding is consistent with the logic that vection is generated through the viewing of scene oscillation and, in the absence of appropriate physical motion, the vection sensation causes symptoms of sickness (sensory re-arrangement theory: Reason and Brand, 1975).

Results from this study indicate that there are consistent differences in individual susceptibilities to nausea induced by scene oscillations along different axes. However, the results also indicate that scene oscillations along any of the pitch, yaw, or roll axes could produce similar average levels of cybersickness among a group of 16 randomly selected male participants. This suggests that, while knowing the presence of scene oscillations (in any rotational axes) in a VR simulation may prove useful in predicting the *average* severity level of cybersickness amongst for example, 100 male participants, it may be necessary to know the axes of scene oscillations if the severity level of cybersickness of an *individual* is to be predicted.

This study compared VR simulation sessions with and without scene oscillations and reported significant differences in the rated levels of cybersickness. In other words, scene oscillation has been studied as a discrete variable with two levels: with and without. Further studies to identify methods to measure and quantify scene oscillations are desirable so that scene oscillation can be studied as a continuous variable.

4. Conclusions and future work

Scene oscillations along the pitch, yaw, and roll axes within a virtual environment have been shown to significantly increase the rated level of nausea and Simulator Sickness Questionnaire (SSQ) scores. Experimental data indicate that, all other things being equal, scene oscillations along different rotating axes will have similar effects on the average level of cybersickness of a group of randomly selected male participants. This suggests that there is not a dominant rotational axis of virtual scene movement contributing towards cybersickness. Nonetheless, individual differences in sickness susceptibilities towards scene movements along a single rotational axis are also found.

In the presence of scene oscillations, exposure to a virtual environment for a period longer than five minutes will cause significant increases in nausea ratings. In the absence of scene oscillation, viewing a stationary virtual environment for up to 15 min is not likely to cause any significant increase in the nausea level. In this study, all participants were asked to keep their heads still. Further experiments investigating the interactions between scene oscillations and head movements are desirable. Also, only male participants were used in this study. Further studies with female participants are needed to extend the results.

This study supports the idea that scene movement in a virtual environment can cause significant increases in cybersickness and that its presence will significantly accelerate the increase of nausea ratings with the duration of exposure. This suggests that if the scene movement in a virtual environment can be measured and quantified, it may become a useful predictive variable in estimating the levels of cybersickness associated with a particular VR simulation.

Kennedy et al. (1992), reported a dose equivalent equation to predict the blood alcohol level in an individual. Kennedy's dose equation comprises several performance measures that are correlated with the blood alcohol level. In a similar way, it should be possible to develop a regression equation comprising the various contributing factors of cybersickness so as to predict the level of cybersickness associated with a specific VR simulation. These factors should include the duration of exposure, amount of scene oscillation, degree of control over scene movement (Stanney and Hash, 1998), display parameters (field-of-view: Dizio and Lackner, 1997; stereoscopic presentation: Wann and Mon-Williams, 1997; image update lags: Dizio and Lackner, 1997, Cobb et al., 1999), subject-related variables (Kolasinski, 1996), and amount of head movement (Regan, 1995). Studies in this direction would be rewarding. The successful development of the Motion Sickness Dose Value (MSDV) to predict the severity level of sea sickness could provide a valuable road map for the proposed future studies (BSI, 1987; Griffin, 1990).

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