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A Metric to Quantify Virtual Scene Movement for the Study of Cybersickness: Definition, Implementation, and Verification

Abstract

This paper presents a metric to quantify visual scene movement perceived inside a virtual environment (VE) and illustrates how this method could be used in future studies to determine a cybersickness dose value to predict levels of cybersickness in VEs. Sensory conflict theories predict that cybersickness produced by a VE is a kind of visually induced motion sickness. A comprehensive review indicates that there is only one subjective measure to quantify visual stimuli presented inside a VE. A metric, referred to as *spatial velocity* (SV), is proposed. It combines objective measures of scene complexity and scene movement velocity. The theoretical basis for the proposed SV metric and the algorithms for its implementation are presented. Data from two previous experiments on cybersickness were reanalyzed using the metric. Results showed that increasing SV by either increasing the scene complexity or scene velocity significantly increased the rated level of cybersickness. A strong correlation between SV and the level of cybersickness was found. The use of the spatial velocity metric to predict levels of cybersickness is also discussed.

1 Introduction

1.1 Background

Motion sickness with virtual environments (VEs) has been referred to as *cybersickness* (McCauley & Sharkey, 1992) and has been the subject of many studies. A review of the literature indicates that the effects of variables related to the tasks, apparatus, and participants as well as methods to measure cybersickness have been studied. Examples of task-related variables that have been studied include duration of exposure (Cobb, Nichols, Ramsey, & Wilson, 1999; Stanney & Kennedy, 1998), habituation (Howarth & Hill, 1999; Regan, 1995), recovery period (Stanney, Kennedy, Drexler, & Harm, 1999), navigation velocities (So, Lo, & Ho, 2000b), methods of navigation (Howarth & Finch, 1999; Stanney & Hash, 1998), and viewing posture (Ehrlich, Singer, & Allen, 1998; Regan, 1995). Factors related to the apparatus and participants have also been studied. Examples include the display's field of view (DiZio & Lackner, 1997), types of display (Cobb et al., 1999; Howarth & Costello, 1997), use of stereoscopic presentation (Ehrlich, 1997; Mon-Williams, Plooy, Burgess-Limerick, & Wann, 1998), interpupillary distance mismatch (Regan, 1995), image update lags (DiZio & Lackner, 1997; Regan, 1995; So, 1994),

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gender, age, and pre-exposure stability (Kolasinski, 1995; Kolasinski & Gilson, 1999), and drug treatment (Regan, 1995).

A review of these studies indicates both agreement and disagreement among the reviewed studies. Examples of agreement include those studies on the effects of exposure duration: many studies have confirmed that moving in a VE for more than ten minutes will cause significant increases in nausea ratings (So, 1994; Regan, 1995; Howarth & Costello, 1997; Stanney & Kennedy, 1998; Stanney et al., 1999; Wilson, 1996; Wilson, Nichols, & Haldane, 1997). Examples of disagreement include those studies on the effects of time lags: So (1994) reported that an imposed lag of 280 ms did not significantly affect the nausea ratings generated by a 20 min. virtual flight-simulation session. Although this finding agrees with the results reported by Regan (1995), it disagrees with the findings in DiZio and Lackner (1997). Regan reported that there were no significant difference in malaise ratings when the effects of updated lag were maximized by increasing head movements and speed of interactions, whereas DiZio and Lackner reported that sickness severity increased monotonically with increasing lags up to 200 ms. The differences in the results reported by So (1994) and DiZio and Lackner (1997) could be due to differences in factors such as the visual content of the VE, the nature of the tasks, or the types and speeds of head movements. For example, the head movements reported by So (1994) were slow (0.02Hz oscillation with an amplitude of 24 deg. r.m.s.) and continuous (sinusoidal motion), whereas the head movements of DiZio and Lackner (1997) were discrete with large amplitudes (18 deg. to 180 deg.).

This example illustrates the difficulty in comparing results of cybersickness studies that use different virtual scenes and tasks. One possible solution to reduce this problem would be to identify a metric for quantifying the visual scene movement that a user is exposed to inside a VE. Furthermore, a review of literature identifies that forty out of fifty studies on cybersickness have used the Simulator Sickness Questionnaire (SSQ) (Kennedy, Lane, Berbaum, & Lilienthal, 1993) to measure the levels of cybersickness. Although the commonly used SSQ has facilitated the comparison of sickness responses among studies, it is unfortunate that there is as yet no common method to quantify the scene movement exposure among different experiments.

1.2 Importance of Visual Stimuli

The use of the sensory conflict theory (Reason & Brand, 1975), the sensory rearrangement theory (Reason, 1978), and the motion cue mismatch theory (Benson, 1984) as explanations for cybersickness has been widely discussed (Cobb et al., 1999; Hettinger & Riccio, 1992; Oman, 1993; Regan, 1995; Kennedy, Lanham, Drexler, Massey, & Lilienthal, 1995; McCauley & Sharkey, 1992; So, 1994; Stanney et al., 1998). Reason and Brand (1975) and Reason (1978) proposed the sensory rearrangement theory, which predicts that, when two or more sensory cues disagree or are at variance with the expected experience, symptoms of sickness can occur. As pointed out by Oman (1993): “No sensory conflict neuron or process has yet been physiologically identified” (p 373). Sensory conflict therefore remains a hypothetical parameter that cannot be measured directly. As a consequence, sensory conflict theory cannot be proved or disproved through direct measurements. A similar conclusion was reached by Griffin (1990) who searched for a theory to explain seasickness. In his book, Griffin (1990) presented the benefits of studying the conflict of sensory “stimuli” rather than the conflict of senses. The former can be measured readily, but the latter cannot be measured. This is consistent with the shift of research focus from sensory mismatch to motion cue mismatch as suggested by Benson (1984). The observer theory model on sensory conflict proposed by Oman (1982, 1993) also focuses on stimulus conflicts rather than on sensory conflicts. Cybersickness experiments should, therefore, focus on the relationship between the relevant sensory stimuli and their associated sickness levels and symptoms. In the case of VR simulation, one of the major sensory stimuli to the users will be the visual stimulus.

When an observer views a moving scene with a wide field of view, illusory self-motion (vection) in the direction opposite to the moving scene may be generated

(Griffin, 1990). This experience can be nauseogenic. A common conclusion found in cybersickness literature is that cybersickness is mainly due to this visually induced self-motion illusion (vection) that is inappropriate to the physical motion of the participant (Hettinger & Riccio, 1992; McCauley & Sharkey, 1992; Regan, 1995). This type of motion-cue mismatch has been identified previously in studies of cinerama sickness and simulator sickness (Benson, 1984). In the case of cybersickness, participants may receive visual cues to induce an illusion of body motion while their bodies are physically stationary. This causes discord between their visual and vestibular cues and, hence, sickness. The occurrence of vection in stationary participants has been associated with symptoms of nausea and sickness in many studies (for example, studies with VR systems: Cobb et al. (1999), McCauley & Sharkey (1992); studies with an optokinetic drum: Dichgans and Brandt (1978), Kennedy, Hettinger, Harm, Ordy, and Dunlap (1996); Stern, Hu, Leblanc, & Koch (1993); studies with a non-VR simulator: DiZio & Lackner (1991), Kennedy & Frank (1984)). Although these studies used different apparatus to present visual cues to the participants, they have one common characteristic: participants were exposed to visual scene movements.

Consequently, scene movement may be an important contributing factor in cybersickness, and the ability to measure and quantify scene movements is an important and interesting research topic. Such research is also consistent with the effort to identify and prioritize the sensory-motor discord that drives cybersickness (a research direction proposed by 26 leading experts in the field of cybersickness research (Stanney et al., 1998)).

1.3 Previous Studies on Measuring and Quantifying Scene Movements for the Study of Cybersickness

A review of literature reveals only four studies that have investigated the effects of scene movements on the level of cybersickness. Slater, Linakis, Usoh, and Kooper (1996) asked the participants to perform manual manipulation tasks (chess games) in VEs with different textural backgrounds. Both performance and sickness were measured. Unfortunately, the sickness data were not reported. Prothero, Draper, Furness, Parker, and Wells (1999) demonstrated that viewing a rotating scene (25 deg. horizontal × 19 deg. vertical) projected on a dark background produced significantly higher levels of cybersickness than did viewing the same rotating scene augmented on top of normal vision. In the latter case, the ambient field of view corresponded appropriately with the participants' head orientation. Prothero and his colleagues attributed the results to the theory of the "rest frame". Unfortunately, there was no report of an objective method to identify and quantify a rest frame within a VE.

Kennedy, Berbaum, and Smith (1993) attempted to quantify visual features within a flight-simulator scene that were correlated with the level of simulator sickness. In their studies, visual features (such as the position of the horizon) were identified through visual inspection. In 1996, Kennedy and his colleagues proposed an automatic method to quantify the visual stimulus for cybersickness (Kennedy, Berbaum, Dunlap, & Hettinger, 1996). In their studies, simulation scenes were videotaped and viewed by a human observer who would then assign scores to the scenes. Cluster analyses were then conducted on the scores, and the resulting metrics for quantifying the visual stimulus were referred to as the "human judged kinematics cluster score" (HJKCS). This work by Kennedy represented an important step towards quantifying the visual stimulus in the study of cybersickness. Unfortunately, the proposed HJKCS is subjective, and its compilation is labor intensive. Currently, there is still no point-fine objective metric for quantifying the visual information viewed in a VE.

It should be noted that, although only a few studies have attempted to quantify scene movement in a VE for the study of cybersickness, there have been decades of studies in search of a quantitative metric for optical flow information and its relationship with the perception of self-motion in simulators (Gibson, 1947, 1950; Gibson, Olum, & Rosenblatt, 1955; Owen & Warren, 1982, 1987). In addition, there have been many publications in the field of neurophysiology on the understanding of vection generation (for example, the "two-visual system": Schneider, 1967; Leibowitz & Dichgans, 1980;

Leibowitz & Post, 1982). Furthermore, studies concerning vection-induced motion sickness with rotating optokinetic drums have also been numerous (Stern & Koch, 1991; Hu, Stern, Vasey, & Koch, 1989; Hu et al., 1997; Kennedy, Hettinger, et al., 1996). These studies are reviewed in sections 2.1 and 2.2 to form a theoretical basis for the proposed spatial velocity metric.

2 The Proposed Metric for Quantifying Scene Movement in a VE

2.1 The Proposed 'Spatial Velocity' and Its Theoretical Basis

2.1.2 Definition of the Proposed Spatial Velocity Metric. In this work, a metric called *spatial velocity* (SV) was developed to quantify visual stimuli for the study of cybersickness. This proposed SV metric has two components: a metric to measure the scene complexity of a VE along horizontal, vertical, and radial axes; and a metric to measure the velocities of navigation by the participant through the VE in fore-and-aft, lateral, vertical, pitch, yaw, and roll directions. These two components are multiplied to form the rate of luminance variation that is perceived by a participant when he or she navigates through a VE:

The rate

$$= \text{(average spatial frequency, SF, along that axis)}$$
$$\times \text{(scene movement velocity, V, along that axis)}$$

This rate is referred to as the *spatial velocity* (SV) for that axis. It combines the scene complexity of a visual scene (SF) and its movement (V) relative to the participant. The main differences between the proposed SV metric and the previously reported HJKCS (Kennedy, Barbaum, et al., 1996) are that the HJKCS involves subjective judgement whereas the SV metric is totally objective, and that the calculation of HJKCS is labor intensive whereas the SV metric can be calculated by computer programs. Because scene movements are common among VR simulation, the SV metric is a generic measure not restricted to a particular application.

Spatial velocities for all six motions (*x:* fore and aft; *y:* lateral; *z:* vertical, yaw, roll, and pitch) are calculated as

$$\begin{bmatrix} SV_x & SV_{roll} \\ SV_y & SV_{yaw} \\ SV_z & SV_{pitch} \end{bmatrix} = \begin{bmatrix} SF_{rad} & SF_{horiz} & SF_{vert} \end{bmatrix} \times \begin{bmatrix} V_x & V_{roll} \\ V_y & V_{yaw} \\ V_z & V_{pitch} \end{bmatrix}$$

where $SV_{x,y,z,yaw,roll,pitch}$ are the spatial velocities of the fore-and-aft, lateral, vertical, yaw, roll, and pitch motions; $SF_{horiz,rad,vert}$, are the spatial frequencies of scene components along the horizontal, radial, and vertical axes; and $V_{x,y,z,yaw,roll,pitch}$ are the scene movement velocities along the six axes.

The logic of mapping the appropriate spatial frequencies (SF) to the scene movement velocities (V) is straightforward except for in the case of SV_x. It is mapped to the radial spatial frequency (SF_{rad}) because the radial dimension of virtual objects in the scene will change according to the fore-and-aft movement of the scene relative to the subject. This is analogous to shining a flashlight at a screen: as the flashlight moves towards the screen, the spot of light will change its radial dimension.

Details on the development, measurement, and implementation of the SV metric are described in sections 2.2 to 2.5. In the rest of this section, literature concerning the effects of optical flow elements on the perception of self-motion in non-VR systems is reviewed to form the theoretical basis for the two-component structure of the SV metric.

2.1.2 Theoretical Supports. In section 1.2, the close association between illusory self-motion (vection) and cybersickness has been discussed. It has been reported that vection is a necessary precondition for simulator sickness (Hettinger, Berbaum, Kennedy, Dunlap, & Nolan, 1990) and cybersickness (Hettinger & Riccio, 1992). In the search for a measure to quantify scene movement for the study of cybersickness, it is logical to review literature on the self-motion illusion (vection).

The perception of self-motion as a result of viewing scene movement has been the subject of many classic studies concerning flight simulation training (Gibson, 1947). In particular, Gibson et al. (1955) quantified the optical flow patterns of visual objects perceived by a pilot during a flight-simulation session. The flow patterns were represented by a function consisting of the relative velocities between the objects of interest and the aircraft. The effects of these flow patterns and other optical variables on the perception of self-motion have subsequently been studied extensively (Owen & Jensen, 1981; Owen, Warren, Jensen, Mangold, & Hettinger, 1981; Owen, Hettinger, Pallos, & Fogt, 1985; Owen & Warren, 1987). The variables investigated include the optical flow rate (flight velocity divided by instantaneous altitude), optical acceleration (product of flight velocity and descent rate divided by the square of the difference between the initial altitude and altitude to be descended to), optical density (instantaneous altitude divided by ground texture size), and optical splay (rate of descent divided by altitude).

As reported by Owen and Warren (1987), these optical variables have been specific to flight simulation. In an attempt to generalize the measurement of optical flow, another two optical variables have been proposed: the optical flow rate accelerations (FRAs) in the fore-and-aft and vertical directions, and the edge rate acceleration (ERA) along the flight path. Owen and Warren (1987) used an analogy with road traffic to explain optical flow rate and edge rate: "Flow rate is analogous to measuring the speed at which vehicles pass (e.g., in km per hour), whereas edge rate is analogous to measuring the frequency with which vehicles pass (e.g., in number per hour)" (p. 45). In Owen's study, the optical FRA represents the perceived acceleration (unit distance/second^2) of a participant who is navigating through a flight-simulation environment, and the ERA represents the perceived acceleration in the number of contrasted edges on the ground that a participant will pass per unit time (for example, number of edges per second^2). In other words, the FRA is a pure acceleration measurement that is independent of scene complexity, whereas the ERA combines both the navigation speed as well as the scene complexity of the ground texture. Owen and Warren (1987) reported that ERA has a stronger influence on the perception of self-motion than does optical FRA. This suggests that ERA may be a better variable to describe optical flow than FRA.

Comparing the ERA proposed by Owen and Warren (1987) with the proposed spatial velocity variable (SV):

- Both the proposed SV and ERA have similar components: navigation speed or its derivative, and complexity of scene texture.
- SV considers speeds of navigation in all six motions, whereas the ERA considers only speed of navigation in the fore-and-aft direction. (ERA focuses on the fore-and-aft axis because that is the main axis of movement for an aircraft.)
- In ERA, scene complexity is measured using a unit customized for simulation environments with square-textured ground; in SV, scene complexity is measured by a generic unit of "spatial frequency" (more details in section 2.2.2).

In short, ERA and SV are composed of similar components, but SV is a more generic metric and ERA has been developed for the flight-simulation environment.

Hettinger, Owen, & Warren (1985) studied the perception of vection with different ERAs. In their study, the flight velocity was kept constant and the ERA was increased by increasing the density of the edges (that is, reducing the size of the squared texture on the ground so as to increase the number of edges per unit distance). The results indicated that, as the ERA increased, the perception of vection increased, peaked, and then reduced. In 1989, Hu et al. reported on a study investigating the level of vection generated by participants viewing an optokinetic drum rotating at different speeds. The results indicated that, as the speed increased, the level of vection increased, peaked, and then reduced—a pattern similar to that of Hettinger et al. (1985). Kennedy, Hettinger, et al. (1996) also reported that as the speed of optokinetic drum increased, the latencies for circular vection (CV) to occur reduced, bottomed, and then increased. These latencies have been recognized to inversely relate to the level of motion sickness. The agreement among these three studies suggests that an increase in scene velocity (reported in Hu et al., 1989 and Kennedy, Hettinger et al., 1996) may have an effect on the level of vection similar to that of an increase in scene complexity (reported by Hettinger et al., 1985). This supports the multiplication of the scene complexity term and the scene velocity term in the SV metric. In conclusion, the proposed SV metric is consistent with the previous literature on optical flow measurement (Owen & Warren, 1987), self motion perception in flight simulation (Hettinger et al., 1985) and vection generation with an optokinetic drum (Hu et al., 1989).

2.2 Methods to Measure Scene Complexity

2.2.1 The Proposed Method to Measure Scene Complexity. In this study, the scene complexity of a VE during a simulation session was measured by averaging the scene complexities of sampled snapshots taken during the simulation. The scene complexity of each snapshot was measured by three descriptions: the average spatial frequencies (SF) along the horizontal, vertical, and radial axes. (Details on how to measure SF is documented in section 2.2.3.) The average SFs along the horizontal and vertical axes were the means of the SFs across all pixel rows and columns, respectively. The average SF along the radial axis was the geometric mean of the average SFs along the horizontal and vertical axes. For example, if a snapshot had 640 columns and 480 rows of pixels, the SF along each of the 640 columns was measured, and the mean of these 640 dominant SFs was the average SF along the vertical axis of that snapshot. Similarly, the mean of the 480 SFs along each row was the average SF along the horizontal axis. Having stated the methods to measure scene complexity of a VE, three questions remain: Why was spatial frequency used? How was the SF of a row or column of pixels determined? How was the number of sampled snapshots determined? Sections 2.2.2 to 2.2.4 address these three questions.

2.2.2 Rationale for Using Spatial Frequency to Measure Scene Complexity. In this work, scene complexity was divided into two subcomponents: a luminance component and a chrominance component. These two components are the typical subcomponents of a television picture signal: the luminance component represents the spatial distribution of luminance intensity, and the chrominance component represents the spatial distribution of the color. The search for a suitable measure to quantify scene complexity for the study of cybersickness focused on these two aspects. It should be noted that the "meaning" aspect of the scene was purposely omitted. Although Kennedy, Berbaum, and Smith (1993) reported that the position of some specific visual elements such as the artificial horizon may influence the level of simulator sickness, the identification of such elements is application specific and can be subjective. Because the proposed SV is designated to be an objective generic metric, the subjective meaning behind the scene was not considered in the proposed SV metric.

In a study of visually induced linear vection with a simulated aerial view of a textured ground (random dot pattern), Previc, Varner, & Gillingham (1992) reported that neither color (instead of black-and-white graphics) nor perspective view affected the level of perceived vection. This suggests that the chrominance component of a scene may not have a strong influence on vection. In a literature review concerning cybersickness, Kolasinski (1995) also hypothesized that color would not have a direct effect on the level of cybersickness, although it might influence the level of graphical realism. The reported reason was that people use peripheral vision to detect movement, and peripheral vision is poorly sensitive to color. This agrees with Livingstone & Hubel (1988), who reported that there is consistent evidence in both physiological and psychophysical studies to show that the visual system that is responsible for movement perception is not sensitive to color and is also not used for shape discrimination. Without intending to rule out the influence of the chrominance component of a scene on the level of vection that can be generated, as an initial implementation, scene complexity was measured by its luminance component only. Future studies to compare VEs with isochronal or isolumiant colored mappings are desirable.

Previous work by Owen and his colleagues on quantifying optical flow measured the luminance density of scene complexity by counting the number of contrasted edges per unit distance (Owen & Warren, 1987). (See reviews in section 2.1.) In Owen's studies, the counting was possible because the scene of interest was a simulated ground with squared texture, and the edge density was simply worked out from the size of the squares (Tobias & Owen, 1984; Hettinger et al., 1985). The SV metric proposed here is intended to be applicable in environments containing different textures. Consequently, a more generic method of measuring luminance density is needed.

A review of the literature indicates that, in many studies concerning the visually induced self-motion illusion (vection), the patterns of luminance variations have been quantified in terms of spatial frequency (Brandt, 1973; Dichgans & Brandt, 1978; Henn, Cohen, & Young, 1980; Hu et al., 1989; Hu et al., 1997; Koch et al., 1990; Stern, Hu, Vasey, & Koch, 1989; Muller, Wiest, & Deecks, 1990). The unit for spatial frequency (SF) is defined as cycles of changes in luminance per unit visual angle, or cycles per degree (cpd). A *cycle* refers to a complete cycle of luminance variation. Experimental results have shown that approximately 50% of healthy participants manifest nausea symptoms when exposed to rotating black-and-white stripes with a horizontal SF of 1/15 cpd (Stern, Koch, Leibowitz, Shupert, & Stewart, 1985; Stern & Koch, 1991). Hu et al. (1997) studied the level of vection and sickness as functions of SFs. Hu varied the SFs of black-and-white stripes inside an optokinetic drum from 1/60 cpd to 16/60 cpd and reported that the level of vection and sickness increased, peaked, and then reduced. This suggests that the SFs of a moving scene have a significant influence on the level of vection and sickness. Hu et al. (1997) found that the level of vection peaked at 4/60 (that is, 1/15) cpd—a level of horizontal SF most often used in studies involving the optokinetic drums (Stern et al., 1985; Stern & Koch, 1991). In the SV metric, SFs along the horizontal, vertical, and radial axes were used to measure scene complexities.

Spatial frequency (SF) measures the frequency of spatial variations in luminance within a scene. However, it is an average value and does not indicate the exact details of shapes and patterns. In other words, a scene full of circular objects can have the same SFs as a scene full of rectangular objects. In 1990, Muller, Wiest, and Deecks studied the level of vection generated from viewing a moving scene of different patterns: black-and-white stripes, random dots, and a checkerboard pattern of similar spatial densities. Results showed that there was no significant difference among the levels of vection obtained from viewing the three patterns. This suggests that the shapes of patterns may not be important to the induced vection. In addition, Leibowitz, Shupert-Rodemer, & Dichgans (1979) reported that diopter refractive errors as large as those corresponding to legal blindness have no influence on vection generation. Lebowitz and Post (1982) concluded that changes to the fine details of patterns have little influence on the associated vection.

In conclusion, reviews of the literature indicate that, among luminance variation, chrominance variation, shapes, and patterns of a moving scene, the spatial variation of the luminance levels has the most influence on the level of vection generated. Although spatial variation in the luminance level has been measured using spatial frequency (SF) as well as using contrasted edges per unit distance, SF is a more generic metric. Consequently, scene complexity in the SV metric was measured using SF.

2.2.3 Methods to Determine the SF Across a Row or Column of a Snapshot. Having decided to measure the scene complexity of a VE by averaging the dominant SFs of the rows and columns of sampled snapshots, a question remains as to how to determine the dominant SF of a row or column of a snapshot. A row or column of a snapshot is likely to contain luminance variations at different SFs. The standard method to extract the distribution of luminance variation as a function of SF is to calculate a spatial frequency power spectral density (SFPSD). Standard spectral analysis algorithms such as the fast Fourier transform (FFT) can be used (Bendat & Piersol, 1986). The use of FFTs to calculate a SFPSD has long been a standard method in image processing (Schalkoff, 1989). However, there is no standard method to determine the dominant SF from a SFPSD. This study applied three methods to calculate the dominant SFs: the mean method, the mode method, and the combined method. The mean method calculates the average SF according to the PSD distribution, whereas the mode method calculates the SF at which the amount of luminance variation peaked. The combined method calculates the dominant SF according to the following equation:

Dominant SF

= Average of all frequencies at which the SFPSD

$> \frac{1}{2}\,(\mathrm{SFPSD})_{max}$

All three methods were used to reanalyze data from two previously reported experiments. The results are documented in section 3.4.

2.2.4 The Number of Sampled Snapshots to be Taken. The purpose of taking sampled snapshots is to estimate the "average" scene complexity of the whole VE as perceived by a user during a typical navigation. As with any sampling problem, an optimized number of samples is a compromise between the level of statistical accuracy and the resources available. Because the development of the proposed SV is still in its initial stage and the aim of this study is to determine the benefits of SV rather than to optimize the implementation of SV measurement, oversampling was used. (Future research to optimize the number of samples is proposed in section 5.)

In this study, sampled snapshots were taken twice per second over a simulation session of 30 min., yielding 3,600 snapshots. Fortunately, the calculation of the proposed SV has been computerized. In the two experiments whose data were reanalyzed in section 3, the navigation velocities have most of their energy below 0.4Hz. For navigation velocities with frequencies below 0.4Hz, a sampling rate of two snapshots per second (that is, 2Hz) is well above the Nyquist sampling frequency of 0.8Hz (0.4Hz × 2). Hence, oversampling was employed (Oppenheim, Willsky, & Nawab, 1997).

2.3 Implementations to Measure Spatial Frequency

With a specific task, most VR training applications have a typical navigation path; examples include a recommended flight path in flight-simulation training (Wells, Venturino, & Osgood, 1989) and a predetermined route in driving simulation (Bayarri, Fernandez, & Perz, 1996). A program to capture views along the path at a rate of two snapshots per second was written. The captured pictures were stored in Portable Gray Map (PGM) format so that the grayscales of all the pixel elements could be extracted as a matrix (255 is white and 0 is black). The PGM format is supported by common graphics programs such as xv in UNIX (or IRIS) and Paintshop-Pro in Windows 98, and the grayscale matrix can be viewed as a text file. The grayscale value of each pixel element represents its luminance level.

Figure 1 illustrates the measurement of the dominant SF of a row within a visual scene. Inspection of the figure shows that the luminance information (that is, grayscale) of each pixel in the row is extracted as a series of numbers. The power spectral density (PSD) of this grayscale series is then calculated using the FFT operation available in common signal processing software (such as MATLab and PC-DAT) (Bendat & Piersol, 1986). The result is the SFPSD. From the SFPSD, the average dominant frequency is determined by the three methods as explained in section 2.2.3. The unit of the dominant SF is the number of cycle changes in luminance level per degree (cpd). This process is repeated for every row in the captured scene, and the dominant SF of all rows are averaged to give the average horizontal spatial frequency (SF_{horiz}). Similarly, the average vertical spatial frequency (SF_{vert}) can be obtained. The radial spatial frequency (SF_{rad}) is defined as the geometrical sum of SF_{horiz} and SF_{vert} (that is, $SF_{rad} = [SF_{horiz^2} + SF_{vert^2}]^{1/2}$).

As illustrated in figure 1, the power spectral density method was used to determine the dominant spatial frequency along a row or column of a captured scene (Bendat & Piersol, 1986). A possible alternative approach is to use the Michelson contrast (C_m) instead of spatial frequency (Boff and Lincoln, 1988). This will involve the calculation of the Michelson contrast (C_m)

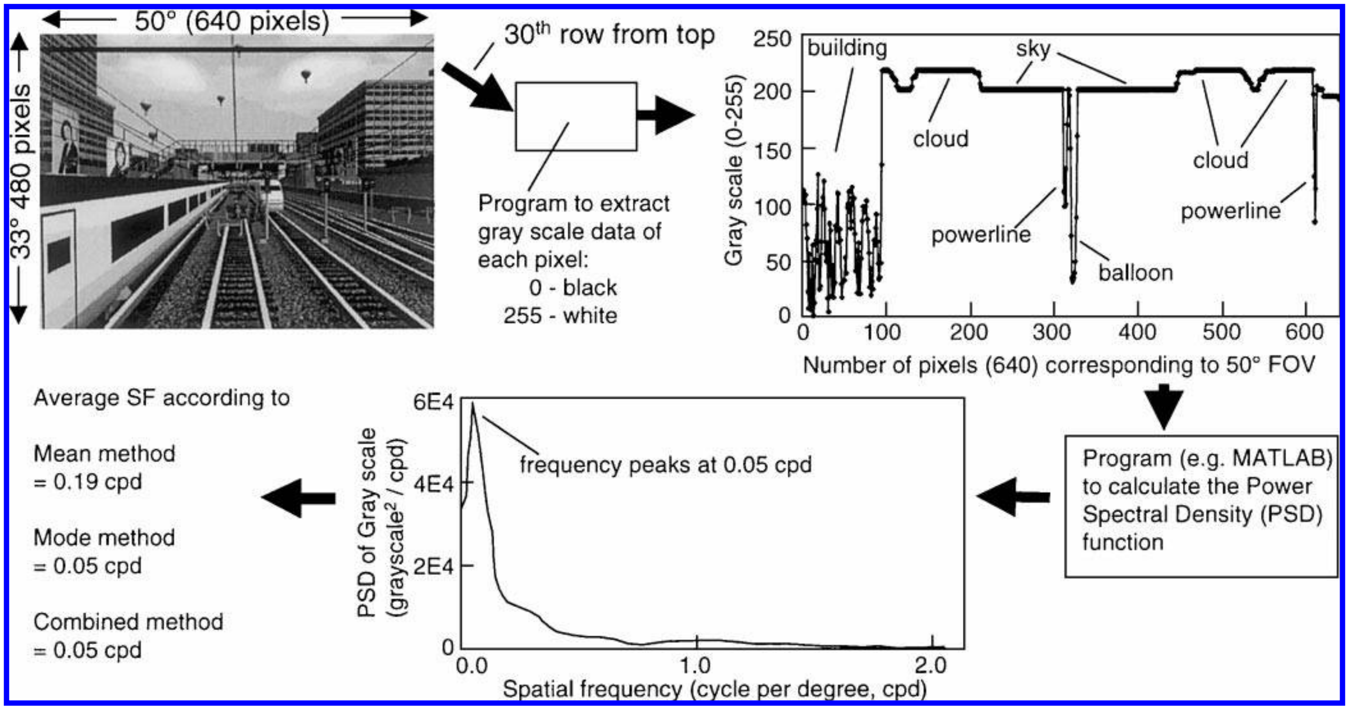


Figure 1. *An illustration of how spatial frequency power spectral density of a row is measured.*

for each row and column of a captured scene (modified from Boff and Lincoln (1988)):

$$C_m = (G_{max} - G_{min})/(G_{max} + G_{min})$$

where

G_{max} is the maximum grayscale value along a row or column

G_{min} is the minimum grayscale value along a row or column

Although the Michelson contrast (MC) approach requires much less calculation than does the spatial frequency (SF) approach, the later was chosen because MC accounts for only the two pixels with the maximum and the minimum grayscale value along a row or column. Unlike the MC, the SF accounts for the frequency of variation and amplitude of the grayscale values of all the pixels along a row or column. Consequently, SF was considered to provide more information than MC and was used in this study. A series of simulations was conducted to determine the effects of different windowing (for example, Hanning, Hamming, or rectangular) and the length of FFT (for example, 64, 128, 256) on the accuracy of a SFPSD. Results indicated that using a rectangular window introduced distortion and both Hanning and Hamming produced similar SFPSDs. With a display resolution of 640 × 480 and a field of view of 48 deg. by 33 deg., an FFT length of 256 was used to produce a spatial frequency resolution of 0.05 cpd. Figure 2 illustrates the spatial frequencies of two different pictures. The first one is a pattern of black-and-white stripes, and the second one is a snapshot taken in a VE used in a previous study on cybersickness (So, Lo, & Ho, 2000a).

2.4 Implementation to Measure the Scene Movement Velocity (V)

In a typical VE, the scene presented on a display is a view of the VE from a certain viewpoint. This view-

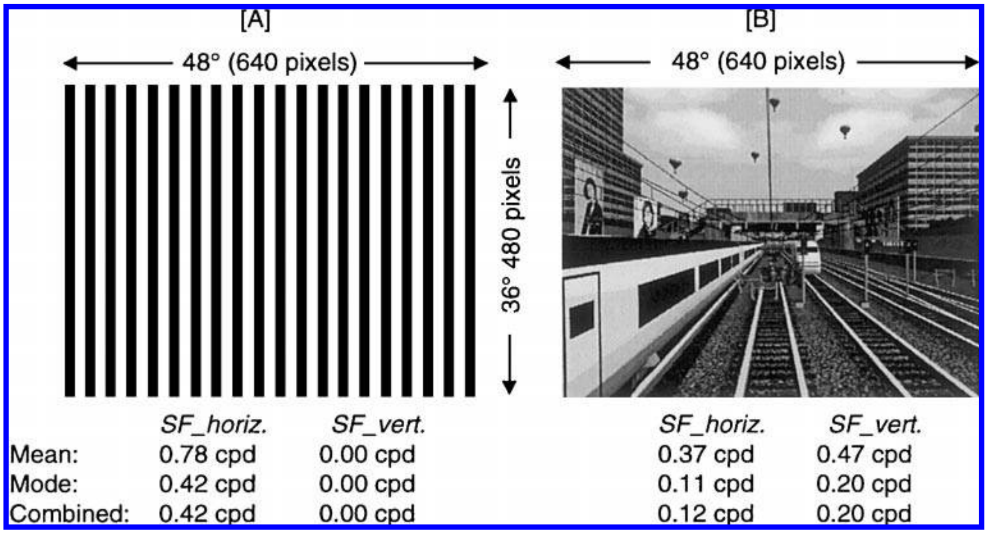


Figure 2. *Spatial frequencies of two examples: "A" a black-and-white strip pattern; "B" a sampled scene from a virtual environment (field of view: 48 deg. horizontal × 36 deg. vertical; 640 × 480 pixels).*

point acts as a virtual video camera that captures and projects images of virtual 3-D objects onto a 2-D screen. The pointing direction of this viewpoint can be preprogrammed as well as controlled, in real time, by the head orientation and navigation devices (such as a joystick). This viewpoint is usually represented within a VE simulation program as a vector containing *x-y-z* position coordinates and yaw, roll, and pitch orientations. As this viewpoint coordinate changes, the scene presented on the display changes accordingly. By recording these viewpoint coordinates in a file, the scene movement displacement time histories in all six axes can be measured. The displacement time histories can then be differentiated to obtain the time histories of the velocities (relative to the user) from which the r.m.s. scene velocities in six axes can be calculated. The r.m.s. velocities are referred to as the *scene movement velocities* (V). The coordinate system used to measure the direction component of navigation velocities is adapted from a previous study (So et al., 2000b). The coordinate system is called the *viewer-centered coordinate* and defines the fore-and-aft, lateral, vertical, pitch, yaw, and roll directions with respect to the instantaneous pointing direction of the participant's head.

Navigation data have been successfully extracted with a number of popular VE development programs including World-Tool-Kit (WTK) from Sense8, dVISE from DIVISION, and RENDERWARE from Criterion. All of these software packages have built-in functions to extract and record the viewpoint coordinates (for example, WTK: 'WTviewpoint_getlastposition', 'WTviewpoint_getlastorientation'; dVISE: 'VCBody_GetData', 'VCTracker_GetData'; RENDERWARE: 'RwGetCameraPosition', 'RwGetCameraLTM').

3 Verifying the Proposed Metric

3.1 Objective and Hypothesis

Data from two previously reported experiments were reanalyzed to determine the effects of SV on the rated level of cybersickness. The aim was to demonstrate that SV significantly correlates with the level of cybersickness. The two previous experiments had been conducted before the development of the proposed SV metric and their original aims were to investigate the effects of scene velocity and scene complexity on cybersickness (So et al., 2000a). The current objectives of the reanalyses of those data were to identify any significant relationships between nausea ratings and spatial velocity, and SSQ total severity scores and SV. In addition, the three methods of calculating the dominant SF were compared. According to Hettinger et al. (1985), Hu et al. (1989), and Hu et al. (1997), the level of perceived self-motion will rise, peak, and then decline when either the SF or the scene velocity increases. It was, therefore, hypothesized that the level of cybersickness would also rise, peak, and decline as SV is increased by either increasing scene velocity (V) or scene complexity (SF). The hypothesis that the level of cybersickness will decline at high scene velocity is consistent with the limits on pursuit eye movements in fast-moving visual scenes (Cohen, Matsuo, & Raphan, 1977). Cohen et al. suggests that, as eye movement ceases to follow a fast moving visual scene, the level of vection would decline. In addition, this hypothesis is also consistent with the theory of the two-visual system, which states that the ambient visual mode responsible for spatial localization and orientation is not sensitive to luminance variations at high spatial frequencies (Held, 1970; Leibowitz & Dichgans, 1980).

3.2 Brief Details of the Previously Reported Experiment 1 Conducted to Study the Effects of Scene Velocity

Details and initial results of the original experiment have previously been reported by So et al. (2000a). Thirty-six healthy Chinese males participated in the experiment. They were exposed to the VE for 30 min. A duration of 20 min. to 30 min. has been commonly used in the studies of cybersickness (Draper, 1998; Howarth & Finch, 1999; Lampton et al., 1994; Kolasinski, 1995; Regan, 1995; Kennedy & Stanney, 1997). Three different navigation velocity conditions were used, and each condition had twelve participants. The same VE was used in the three conditions (that is, same average SFs across conditions), and the differences in SVs were due solely to the changes in navigation velocities.

Using the combined method, the SVs in the fore-and-aft direction for the three conditions were: 0.8, 1.1, and 2.3 cycles × meters/seconds × degrees. Table 1 summarizes the measured SVs in the three conditions. In all conditions, participants moved through the VE passively according to a predetermined path. The viewpoint was head-steered, and participants were asked to periodically turn their heads from side to side (rotating about the vertical axis) and to describe what they observed. This was done so that the participants would be more involved with the VE. The VE, presented on a 48×36 deg. VR4 head-mounted display, was generated using dVISE software running on a Silicon Graphics Onyx2 station. A Polhemus head tracker was used to maintain the correct orientation of the scene with respect to the head. The average frame rate was 30 frames per second and the head movement response lag was about 60 ms. Nausea ratings and SSQ scores were recorded. The nausea ratings were taken verbally at 5 min. intervals using a seven-point Likert scale used in previous work on cybersickness (So, 1994; Lo & So, 2000) and on motion sickness (Woodman & Griffin, 1997; Golding & Kerguelen, 1992).

3.3 Brief Details of the Previously Reported Experiment 2 Conducted to Study the Effects of Scene Complexity

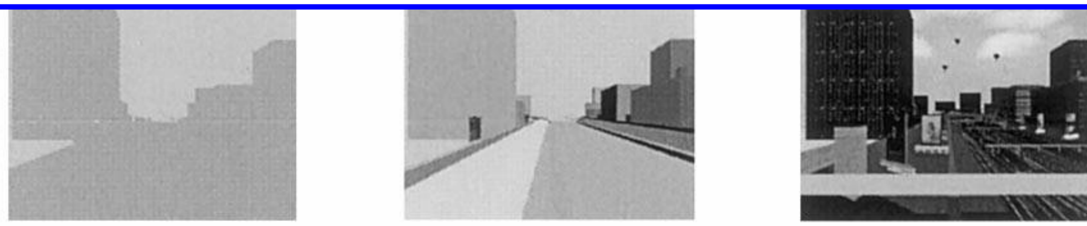
Details and the initial results of the original experiment have previously been reported by So et al. (2000a). There were three conditions: traveling through a VE with either a low, medium, or high level of scene complexity. Using the combined method of calculating SF, the low, medium, and high scene-complexity levels corresponded to average radial spatial frequencies of 0.01, 0.07, and 0.24 cpd, respectively. At the time of the experiments, the proposed SV metric had not yet been developed, and the three complexity conditions were selected by visual inspection. Examples of snapshots taken from the three conditions are shown in figure 3. The VEs making up the three complexity conditions contained similar polygons, and the adjustment in complexity level was achieved mainly by changing the texture of the mappings. The scene velocities were the same in the three conditions and participants were exposed to a 30 min. guided tour of a virtual city. As in experiment 1, participants made periodic head turns around the yaw axis. Each condition had 12 partici-

Table 1. *Spatial Frequencies (SF), Scene Velocities (V), and Spatial Velocities (SV) for the Three Conditions in Experiment 1 (The Three Conditions Differ in Their Scene Velocities) (SFs and SVs Calculated by the Mean, Mode, and Combined (Comb.) Methods Are Shown)*

		Three levels of scene velocities		
Medium		Low	Medium	High
Scene velocity r.m.s. (V)	Fore and aft (×) (metre/s)	3.3	4.3	9.5
	Lateral (y) (metre/s)	1.2	1.6	3.4
	Vertical (z) (metre/s)	0.2	0.3	0.6
	Roll (deg./s)	0.5	0.6	1.4
	Yaw (deg./s)	14.2 ⟨3.8⟩*	16.2 ⟨5⟩*	17.3 ⟨11⟩*
	Pitch (deg./s)	0.6	0.8	1.6
Spatial frequency (SF)	Horizontal (cycle/deg.)		0.79 (mean) 0.18 (mode) 0.21 (combined)	
	Vertical (cycle/deg.)		0.60 (mean) 0.09 (mode) 0.09 (combined)	
	Radial (cycle/deg.)		1.04 (mean) 0.21 (mode) 0.24 (combined)	
Spatial velocity (SV) using SFs by mean method	Fore and aft (×) (mc/ds)	3.43	4.47	9.88
	Lateral (y) (mc/ds)	0.95	1.26	2.69
	Vertical (z) (mc/ds)	0.12	0.18	0.36
	Roll (cycle/s)	0.52	0.62	1.46
	Yaw (cycle/s)	11.22 ⟨3⟩*	12.80 ⟨4⟩*	13.67 ⟨8.7⟩*
	Pitch (cycle/s)	0.36	0.48	0.96
Spatial velocity (SV) using SFs by mode method	Fore and aft (×) (mc/ds)	0.69	0.90	2.00
	Lateral (y) (mc/ds)	0.22	0.29	0.61
	Vertical (z) (mc/ds)	0.02	0.03	0.05
	Roll (cycle/s)	0.11	0.13	0.29
	Yaw (cycle/s)	2.56 ⟨0.7⟩*	2.92 ⟨0.9⟩*	3.11 ⟨2⟩*
	Pitch (cycle/s)	0.05	0.07	0.14
Spatial velocity (SV) using SFs by comb. method	Fore and aft (×) (mc/ds)	0.79	1.03	2.28
	Lateral (y) (mc/ds)	0.25	0.34	0.71
	Vertical (z) (mc/ds)	0.02	0.03	0.05
	Roll (cycle/s)	0.12	0.14	0.34
	Yaw (cycle/s)	2.98 ⟨0.8⟩*	3.40 ⟨1.1⟩*	3.63 ⟨2.3⟩*
	Pitch (cycle/s)	0.05	0.07	0.14

mc/ds: metre × cycle/degree × second

* Scene movements due to head movements in the yaw axis has been excluded.



	Low scene complexity			Medium scene complexity			High scene complexity		
	SF_horiz.	*SF_vert.*	*SF_radial*	*SF_horiz.*	*SF_vert.*	*SF_radial*	*SF_horiz.*	*SF_vert.*	*SF_radial*
Mean:	0.07 cpd	0.07 cpd	0.10 cpd	0.15 cpd	0.07 cpd	0.17 cpd	0.71 cpd	0.61 cpd	0.93 cpd
Mode:	0.02 cpd	0.01 cpd	0.03 cpd	0.02 cpd	0.02 cpd	0.04 cpd	0.05 cpd	0.16 cpd	0.17 cpd
Combined:	0.02 cpd	0.02 cpd	0.03 cpd	0.02 cpd	0.02 cpd	0.04 cpd	0.07 cpd	0.17 cpd	0.18 cpd

Figure 3. *Spatial frequency measurements for sampled snapshots of a VR guided tour with low, medium, and high scene-complexity levels (field of view: 48 deg. horizontal × 36 deg. vertical, 640 × 480 pixels).*

pants, and a total of 36 participants were used. Table 2 summarizes the spatial frequencies, scene velocities, and the spatial velocities of the three conditions. The apparatus used was the same as that used in experiment 1. The average frame rates and response lags of the three VEs had been carefully matched. The average frame rate was 30 frames per second and the head movement response lag was about 60 ms.

3.4 Results of the Reanalyzed Data

The nausea ratings and the increases in SSQ total sickness scores (postexposure scores − preexposure scores) recorded at the end of the 30 min. VR simulations are shown in figures 4 and 5 as functions of SVs in the fore-and-aft and yaw directions, respectively. The SVs calculated by the three methods—mean, mode, and combined—are shown for comparison. Each data point represents the mean of data from twelve participants. Only SVs in these two axes are shown because the predetermined navigation path did not have much energy in the other axes.

3.4.1 Comparing the Three Methods Used to Calculate SVs. Inspection of tables 1 and 2 shows that SVs calculated using the mode and the combined methods are similar, but the SVs calculated by the mean method are higher. A possible reason is that most snapshots are dominated by graphics with low SF so that the SFPSD distributions are skewed. An inspection of figure 3 indicates that both nausea ratings and SSQ total scores increased with increasing SV as calculated by all three methods and do not offer enough evidence to dismiss any method of calculating SVs.

The theory of the two visual systems was again applied to determine which method is most suitable for calculating SVs. Leibowitz et al. (1979) have reported that the level of vection generated from viewing a moving scene is not affected by the introduction of a diopter lens. They concluded that the visual system that is responsible for spatial orientation and vection is not sensitive to high-frequency changes in luminance variation (that is, patterns with high spatial frequencies), which is a finding that is consistent with the theory of the two visual systems. A series of simulations was conducted to examine the values of SVs after introducing some blurring effects into the 3,600 sampled snapshots. This blurring effect was to simulate the visual effects of a diopter lens. The hypothesis was that, if the level of vection is not affected by blurring the fine details of the moving scene, then an appropriate measure of SV should also be independent of the blurring effects. The blurring effect was introduced using photo-editing software (Printshop-Pro). Different levels of blur were available by selecting the radius of blur (the larger the radius, the more severe the blurring effect). Examples of a snapshot before and after applying the blurring effects with a radius of 0, 1, 2, and 4 are shown in figure 6 (radius of 0 means no blurring).

Table 2. *Spatial Frequencies (SF), Scene Velocities (V), and Spatial Velocities (SV) for the Three Conditions in Experiment 2 (The Three Conditions Differ in Their Spatial Frequencies, That Is, Scene Complexities) (SFs and SVs Calculated by the Mean, Mode, and Combined (Comb.) Methods Are Shown)*

		Levels of scene complexity		
Medium		Low	Medium	High
Scene velocity r.m.s. (V)	Fore and aft (×) (metre/s)		9.5	
	Lateral (y) (metre/s)		3.4	
	Vertical (z) (metre/s)		0.6	
	Roll (deg./s)		1.4	
	Yaw (deg./s)		17.3 ⟨11⟩*	
	Pitch (deg./s)		1.6	
Spatial frequency (SF)	Horizontal (cycle/deg.)	0.03 (mean)	0.22 (mean)	0.79 (mean)
		0.01 (mode)	0.06 (mode)	0.18 (mode)
		0.01 (comb.)	0.07 (comb.)	0.21 (comb.)
	Vertical (cycle/deg.)	0.02 (mean)	0.08 (mean)	0.60 (mean)
		0.00 (mode)	0.02 (mode)	0.09 (mode)
		0.00 (comb.)	0.02 (comb.)	0.09 (comb.)
	Radial (cycle/deg.)	0.04 (mean)	0.24 (mean)	1.04 (mean)
		0.01 (mode)	0.06 (mode)	0.21 (mode)
		0.01 (comb.)	0.07 (comb.)	0.24 (comb.)
Spatial velocity (SV) using SFs by mean method	Fore and aft (×) (mc/ds)	0.38	2.28	9.88
	Lateral (y) (mc/ds)	0.10	0.75	2.69
	Vertical (z) (mc/ds)	0.01	0.05	0.36
	Roll (cycle/s)	0.06	0.34	1.46
	Yaw (cycle/s)	0.52 ⟨0.3⟩*	3.81 ⟨2.4⟩*	13.67 ⟨8.7⟩*
	Pitch (cycle/s)	0.03	0.13	0.96
Spatial velocity (SV) using SFs by mode method	Fore and aft (×) (mc/ds)	0.10	0.57	2.00
	Lateral (y) (mc/ds)	0.03	0.20	0.61
	Vertical (z) (mc/ds)	0.00	0.01	0.05
	Roll (cycle/s)	0.01	0.08	0.29
	Yaw (cycle/s)	0.17 ⟨0.1⟩*	1.04 ⟨0.7⟩*	3.11 ⟨2.0⟩*
	Pitch (cycle/s)	0.00	0.03	0.14
Spatial velocity (SV) using SFs by comb. method	Fore and aft (×) (mc/ds)	0.10	0.67	2.28
	Lateral (y) (mc/ds)	0.03	0.24	0.71
	Vertical (z) (mc/ds)	0.00	0.01	0.05
	Roll (cycle/s)	0.01	0.10	0.34
	Yaw (cycle/s)	0.17 ⟨0.1⟩*	1.21 ⟨0.8⟩*	3.63 ⟨2.3⟩*
	Pitch (cycle/s)	0.00	0.03	0.14

mc/ds: metre × cycle/degree × second

* Scene movements due to head movements in the yaw axis has been excluded.

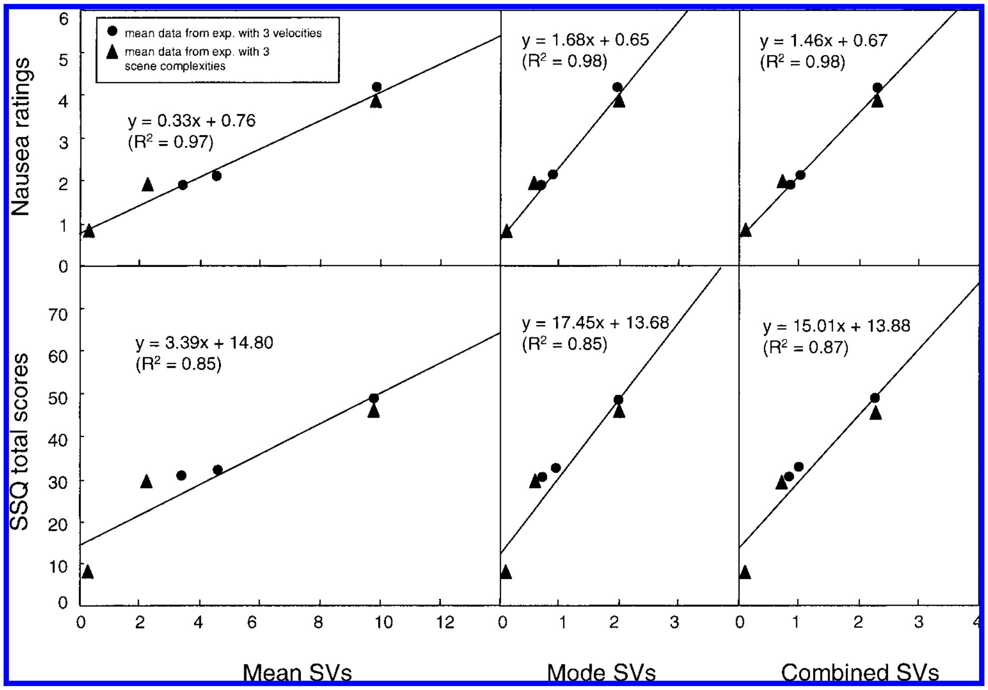


Figure 4. *Mean nausea ratings and SSQ total scores obtained after a 30 min. VR simulation as functions of spatial velocity (SV) in the fore-and-aft direction calculated using three different methods (cycles × meters/degree × second). Data reanalyzed from two experiments previously reported by So et al. (2000a).*

Results of the simulations indicated that, when blurring is introduced, SVs calculated using the mean method were significantly reduced ($p < 0.001$), but there was no significant change in SVs calculated by the mode and combined methods ($p > 0.15$). Consequently, the simulation results suggest that the mode and combined methods are more appropriate than the mean method. The rest of the analyses will focus on data associated with SVs calculated by the mode and combined methods.

Although the effects of blurring did not have a significant effect on the SFs (hence, SVs) calculated by the mode and combined methods, an inspection of figure 6 indicates that the mode and combined SFs were reduced slightly by the introduction of blurring. This suggests that the level of vection (hence, cybersickness) may not be related to the level of SVs as closely as expected. Future studies to investigate the effects of blurring on cybersickness are desirable (such as repeating the Leibowitz et al. (1979) study in a VE).

3.4.2 Effects of SVs in the Fore-and-Aft Direction. As shown in figure 4, as SVs increased in the fore-and-aft axis, both the nausea rating (NR) and the total sickness score (TS) increased. Results of ANOVA tests showed that the increases were significant ($p < 0.001$). The hypothesis predicts that, as SV increases, the level of cybersickness will increase, peak, and then decline. In these two experiments, both nausea ratings and SSQ scores continued to increase with increasing SVs. A possible reason is that the range of SVs used in experiment 1 was not high enough so that the level of cybersickness was still in the increasing range. In the previous study by Hu et al. (1997), the SVs used ranged from 1 cps to 16 cps in the yaw direction (scene with SFs from 1/60 cpd to 16/60 cpd rotating at

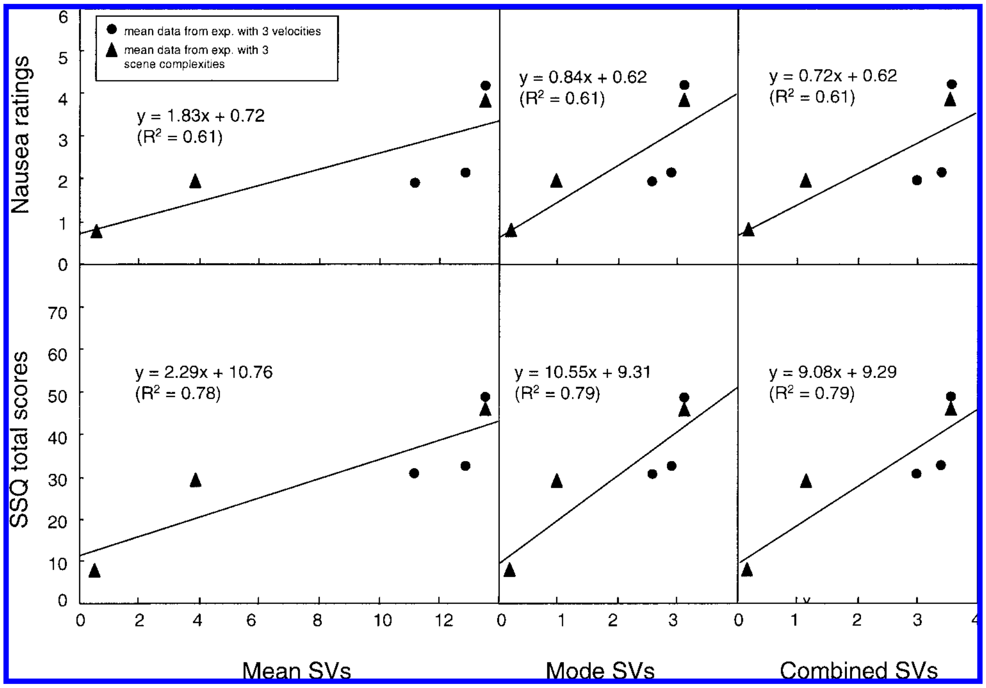


Figure 5. *Mean nausea ratings and SSQ total scores obtained after a 30 min. VR simulation as functions of spatial velocity (SV) in the yaw direction calculated using three different methods (cycles/degree). Data reanalyzed from two experiments previously reported by So et al. (2000a).*

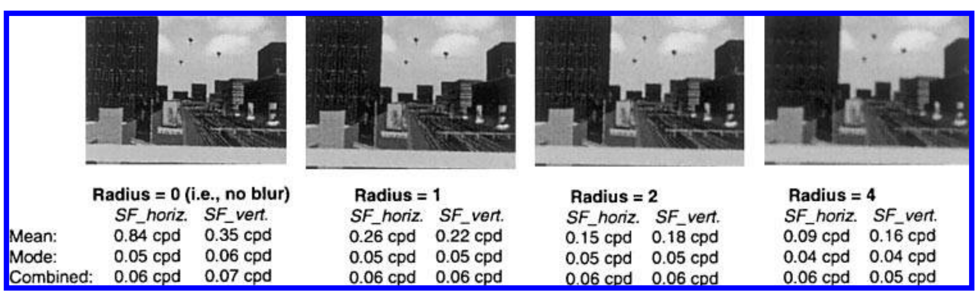


Figure 6. *Spatial frequency measurements for a sample snapshot with and without blurring effects (blurring radius of 0, 1, 2, and 4 using the software Printshop-Pro; field of view: 48 deg. horizontal × 36 deg. vertical, 640 × 480 pixels).*

60 deg./s), and the sickness peaked at 4 cps. In this study, the maximum SVs in the yaw axis calculated by the mode and combined methods were 3.1 and 3.6 cps, respectively.

Obviously, there is much difference between the scene presented by Hu et al. (1997) and the two experiments documented by So et al. (2000a). The former consisted of alternating vertical black-and-white stripes on the inside of an optokinetic drum rotating around the yaw axis, and the latter consisted of colored VEs moving mainly in the fore-and-aft and yaw directions. Acknowledging that there are many factors that will affect this comparison (such as, context of the scene and axis of scene movement), nonetheless, we argue that the possibility of quantifying the scene movement of these two studies (So et al., 2000a; Hu et al., 1997) using the same metric is a vivid demonstration of the benefits of the SV metric.

Correlation tests between SVs and nausea ratings and between SVs and SSQ total scores were conducted. Results indicated that SVs in the fore-and-aft direction were significantly correlated with both nausea ratings and SSQ total scores ($p < 0.001$). Regression models of mean nausea ratings and SSQ total scores as a linear function of SVs are shown in figure 4. An R^2 of >0.97 and >0.85 were obtained between combined SVs and mean nausea ratings and between combined SVs and mean SSQ scores, respectively.

3.4.3 Effects of SVs in the Yaw Direction. Inspection of figures 4 and 5 indicates that the regression analyses with SVs in the yaw direction reported lower values of R^2 (>0.61 and >0.78) than those with SVs in the fore-and-aft direction (>0.97 and >0.85). Further investigations indicated that the SVs in the yaw direction had included scene movements introduced by the head turns of the participants. During the study, participants were asked to turn their heads periodically to the left or right to observe some objects in the VE. This resulted in additional scene movement in the yaw direction. According to the sensory conflict theory, these additional scene movements were associated with appropriate physical head movements and, hence, should not cause a conflict between the vestibular cue and visual cue. As a result, SVs in the yaw axis have been recalculated to exclude the additional scene movements introduced by the head movements. This was possible because the head positions and orientations were measured during the studies. The results are shown in tables 1 and 2 in brackets. Figure 7 illustrates the nausea ratings and SSQ total scores as a function of the revised SVs in the yaw direction. Regression analyses indicated that both the nausea ratings and SSQ total scores increased linearly with revised SVs in the yaw direction ($R^2 = 0.99$ and >0.88, respectively (figure 7)). Similar to the effects of SVs in the fore-and-aft direction, this result only partially agrees with the hypothesis that predicts that both nausea ratings and SSQ total scores will

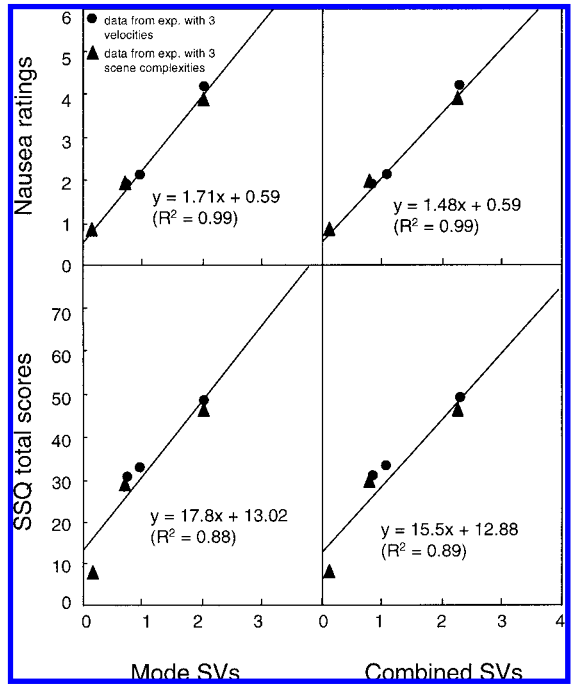


Figure 7. *Mean nausea ratings and SSQ total scores obtained after a 30 min. VR simulation as a function of spatial velocity (SV) in the yaw direction calculated using the mode and combined methods (cycles/degree). Scene movements in response to head yaw movements of the participants have been excluded from the calculation of SVs. Data reanalyzed from two experiments previously reported by So et al. (2000a).*

increase, peak, and then decline as SVs increase. A possible reason has been discussed in section 3.4.2.

After removing the scene movement introduced by the yaw axis head movements, the maximum SV in the yaw axis was reduced to 2.3 cpd (using the combined method). This further supports the argument that the values of SV studied were within the range in which cybersickness would increase with increasing SVs.

The reanalyzed results indicated that increasing SV by increasing either the scene velocity (first experiment) or the scene complexity (second experiment) leads to significant increases in both nausea rating and SSQ total scores ($p < 0.001$, ANOVAs). Because scene velocity and complexity are the two key components of the proposed SV metric, this suggests that

SV can be an appropriate measure to quantify visual scene stimuli for the study of cybersickness. It is acknowledged that this is only the beginning and that there are still many research questions to be answered. Nonetheless, the proposed SV metric should advance the continuous quest to quantify the visual stimuli in the study of cybersickness.

4 Discussion: Benefits of the 'Spatial Velocity' Metric

With the SV metric, it is now possible to quantify the visual stimuli inside a VE, and experiments can be conducted to establish the relationship between the level of visual stimuli (as measured by SV) and the level of cybersickness. Because cybersickness is a type of visually induced motion sickness (Hettinger & Riccio, 1992), studying the relationship between visual stimuli and cybersickness may yield important knowledge about the cause of cybersickness. In addition, the availability of an objective method to measure and quantify the visual stimuli during a VE simulation represents a large step toward meaningful comparison among cybersickness studies using different VEs.

At present, calculation of the SV metric is implemented as a MATLab batch file. The authors intend to make this routine available on the Internet so that researchers from all over the world can upload snapshots of their VEs and obtain the average SF_horiz, SF_vert, and SF_radial via email. It is hoped that this will spur the quest for the cause of cybersickness as well as the continuous development and refinement of the proposed SV metric.

With the ability to meaningfully compare different cybersickness studies, it may be possible to develop a dose value formula to predict the severity of cybersickness. A review of the literature on the motion (sea) sickness dose value (MSDV) indicates that at the center of the MSDV there is a basic unit: ship acceleration along the vertical axis. This acceleration quantifies the heave that is mainly responsible for the generation of seasickness (Griffin, 1990; British Standards Institution, 1987). The MSDV has the following form (Griffin, 1990):

$$\mathrm{MSDV} = \left[\int_0^{T} (\text{frequency-weighted ship acceleration along the vertical axis})^2 dt\right]^{1/2}$$

where T is the duration of a voyage.

Likewise, the SV metric, which quantifies scene movement that is contributing to the generation of cybersickness, could be used as the basic unit for a cybersickness dose value (CSDV). For example, a simple CSDV could consist of an integration of the SV measurements over the duration of exposure (T):

$$\int_0^{T} \mathrm{SV}\ dt$$

In MSDV, the ship acceleration is frequency-weighted. With the proposed CSDV, the hypothesis that cybersickness will increase, peak, and then decline as SVs increase also calls for some sort of weighting function so that SV can be used as a better predictor variable for cybersickness. Future experiments to determine the need and characteristics of the possible frequency weighting function(s) would be beneficial.

It is acknowledged that, besides the SV and the duration of exposure, other factors also contribute to the level of cybersickness: for example, subject-related factors (Cobb et al., 1999; Kolasinski, 1995), types and styles of control (Howarth & Finch, 1999; Stanney & Hash, 1998), display parameters (DiZio & Lackner, 1997; Mon-Williams & Wann, 1998), and time delay (DiZio & Lackner, 1997; Regan, 1995; So, 1994). In 1992, Kennedy and his colleagues used regression analyses to formulate a dose value to predict the level of blood alcohol level based on a number of different measurements (Kennedy, Turnage, & Dunlap, 1992). Similar methodologies can be applied in future studies to extend the proposed CSDV to include the effects of other contributing factors.

It should be noted that, similar to seasickness, there exists a large individual variation in the occurrence and severity level of cybersickness (for example, seasickness: Griffin, 1990; cybersickness: Lo & So, 2000; Kolasinski, 1995). It is not easy to predict the severity of cybersickness for an individual. Even the MSDV does not predict the severity of seasickness for an individual. Rather, it predicts the percentage of passengers who will feel sick after a particular voyage of known duration and ship motion acceleration (Griffin, 1990; British Standards Institution, 1987). Although individual predictions of cybersickness cannot be ruled out—especially there have been some promising studies (such as Kolasinski & Gilson (1999))—the primary future of the SV metric is in formulating a cybersickness dose value (CSDV) to predict the percentage of users who will report a certain level of SSQ score after exposure to a VE with known SV values and for a known duration. When this is available, the CSDV can then be combined with the complementary research on individual effects by Kolasinski and others.

5 Conclusions, Limitations and Future Research

A metric called *spatial velocity* (SV) has been developed for quantifying visual scene movement in a VE. A review of the literature indicates that this SV metric is the first objective metric developed to quantify the visual scene movement in a VE. With such a metric, future experiments could be conducted to establish a generic relationship between visual scene movement in a VE and the rated level of cybersickness. The SV metric consists of two components: spatial frequency, which quantifies the spatial variation of luminance information in a VE, and the r.m.s. navigation velocities of the viewers through the VE. The literature indicates that the SV metric is consistent with the theory of two visual systems, as well as studies on vection perception in the presence of optical flow and studies with optokinetic drums.

The fast Fourier transform has been used to calculate SVs, and the methods to determine the dominant spatial frequency across a row or column of a picture have been selected based on studies related to the two visual systems theories.

Data from two previously reported experiments were reanalyzed to determine the relationship between SV and the level of cybersickness. The results showed that both the level of nausea and SSQ total scores increased with increasing SV. Significant correlations were found between SVs and nausea ratings as well as between SVs and SSQ total scores. This verifies that the spatial velocity (SV) measure is a significant predictor of cybersickness and can, therefore, be a suitable quantifying unit for visual scene movement in a virtual environment.

The potential use of this SV unit to establish a cybersickness dose value (CSDV) has also been presented.

Despite the successful introduction of an objective quantifying metric for virtual scene movement, the research is limited in several respects. First, the two previously reported experiments used only male participants. Studies to include female participants are desirable. Second, the range of SVs verified was limited. It has been hypothesized that, as SV increases, the level of cybersickness will increase, peak, and then decline. Yet, data from the two reported experiments verified only that, as SV increased from 0 to 2.3 meters $\times$ cycles per degree $\times$ second in the fore-and-aft direction (using the combined method of calculation), both nausea ratings and SSQ total severity scores increased. Future research should extend the range of SVs investigated.

In this study, two snapshots per second were sampled during the navigation tour in the VE to calculate the SVs. Further simulations are desirable to determine the optimal number of sample snapshots. In addition, it would be of academic interest to isolate the contributions of the SVs in different axes.

It is planned to post the SV calculation program on the Internet so that other researchers in the field can use it to calculate SVs for their VR simulations. An initial grant for setting up this Website has been obtained, and an announcement will be made when the site is ready.

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