INTERNATIONAL JOURNAL OF HUMAN–COMPUTER INTERACTION, *17*(4), 463–477

Effects of Duration of Immersion in a Virtual Reality Environment on Postural Stability

Atsuo Murata
Department of Computer and Media Technologies,
Faculty of Information Sciences, Hiroshima City University

Few studies have been carried out to examine the relation between postural stability and subjective reports or feelings of motion sickness. Two views seem to exist on the relation between immersion in a virtual reality (VR) environment and subjective feelings of motion sickness. One predicts that the immersion induces both postural instability and motion sickness. Another view is that preimmersion postural instability predisposes people to motion sickness. However, these views are not supported by empirical research. Longer immersions in a VR environment may induce higher levels of postural instability and symptoms of motion sickness. In this study, effects of long-hours immersion in a VR environment on postural stability were examined to approach the underlying mechanism of postural instability and motion sickness using force platform measurement and self-reported questionnaire on motion sickness. As a result, it was suggested that longer immersion in a VR environment induced postural instability and symptoms of motion sickness.

1. INTRODUCTION

Postural stability refers to the ability to maintain balance and postural control. A postural control system is ruled by visual, somatosensory, and vestibular inputs that are coordinated by the central nervous system. The output of the system corresponds to postural steadiness or body sway. Integration of information from sensory inputs allows people to maintain balance and postural control. Conflict between vestibular and visual input might cause dysfunctions in a postural control system that lead to postural instability and motion sickness (Stanney, Kennedy, Drexler, & Harm, 1999). This conflict would produce a false sensation of movement of the body or environment that would induce postural instability and motion sickness.

There seem to be few studies that have investigated the effects of immersion in a virtual reality (VR) environment on postural instability and motion sickness. The VR environment seems to create the perception of immersion and of being trans-

Requests for reprints should be sent to Atsuo Murata, 3–4–1, Ozukahigashi, Asaminami-ku, Hiroshima, 731–3194, Japan. E-mail : murata@cs.hiroshima-cu.ac.jp

ported without actually moving. It is to be expected, according to the sensory conflict theory (Money, 1970; Reason & Brand, 1975), that immersion in a VR environment would cause postural instability and motion sickness (Cobb, 1999; Kennedy & Lilienthal, 1995). In short, interaction with a VR environment makes the information from visual and vestibular inputs conflict. This consequently affects the natural correspondence between sensory inputs and causes motion sickness and postural instability.

A few studies have been carried out to examine the relation between postural instability measured by floor-based static and dynamic tests and subjective reports or feelings of motion sickness. Here, the static test means that the stability is measured in terms of how long a participant can hold a static posture. The dynamic test evaluates postural instability using performance while walking according to a predetermined method. Hamilton, Kantor, and Megee (1989), using a flight simulator task, reported that postural stability was improved on postimmersion tests, although the participants actually reported symptoms of postural instability and disorientation. Hamilton et al. could not identify a significant relation between postural instability and motion (simulator) sickness. In other words, Hamilton et al. found that the postural stability measures did not necessarily degrade when the symptoms of motion sickness increased. Regan and Price (1994), using a VR environment, investigated the effect of VR immersion on postural instability that was measured using static floor-based performance tests. Regan and Price found no significant differences on a postimmersion malaise scale between an instability-induced group and stability-kept groups. Kennedy, Fowlkes, and Lilienthal (1993) also investigated the relation between symptoms of motion sickness and postural stability measured using static and dynamic floor-based performance tests. The stability test included standing on a preferred or nonpreferred leg and walking on the floor with eyes closed. Kennedy, Fowlkes, et al. (1993) could not identify a systematic relation for all measures in which increasing motion sickness symptoms leads to postural instability. The floor-based static and dynamic performance tests seem to be insensitive to the postural instability induced by VR or flight simulator immersion.

Evidence exists that has shown that exposure to flight simulator environments produces postural instability (Kennedy & Lilienthal, 1995). Kennedy and Lilienthal, using a portable automated assessment system, identified significant changes of postural stability after long exposures to a flight simulator task. Kennedy and Lilienthal stated that postural instability might be induced to a greater extent if a VR experience task is used because VR systems are more visually elaborate than flight simulators and less likely to convey vestibular cueing. Kennedy and Stanney (1996) further developed a certification protocol to measure postural instability induced by VR exposure using head displacement recording in the *x, y,* and *z* plane. The effectiveness of body or head sway measurement using video or posturography techniques (Black, Polasky, Dopxey, Gasway, & Reschke, 1995; Paloski, Black, Reschke, Clakins, & Shupert, 1993) has been pointed out. However, there are few studies that have shown systematically the relation between motion sickness and postural instability. At present, although no quantitative and reliable definition of the magnitude of postural instability has been established that corresponds well with the subjective feelings or reports of motion sickness, it is gradually clarified that VR immersion induces postural instability if proper measurement techniques are used.

To drive a motorcycle safely, a sense of equilibrium (postural stability) is necessary. If users of a VR system had postural instability to a larger extent, they would pose serious consequences (e.g., fall down violently and be seriously injured) for safety as they performed subsequent activities such as driving vehicles or motorcycles (Kennedy & Lilienthal, 1995). From the results of the studies mentioned, at present, I cannot find any implications for the performance of postexposure activities. The establishment of useful measures to evaluate motion sickness and postural instability is very important so that one can avoid serious consequences induced by postural instability as a result of VR immersion and find some implications for the performance of post-VR immersion activities.

Two views seem to exist on the relation between immersion in VR environments and subjective feelings of motion sickness. One predicts that the immersion induces both postural instability and motion sickness based on the sensory conflict theory (Money, 1970; Reason & Brand, 1975). The other view is that preimmersion postural instability predisposes people to motion sickness based on ecological theory by Riccio and Stoffregen (1991). However, there has been no empirical research to successfully support these views.

The effects of immersion in a VR environment have been evaluated using a short-time experimental paradigm. Cobb (1999) used a 20-min experimental task and concluded that there were no remarkable effects on postural instability measured by static and dynamic floor-based performance tests as a result of immersion in a VR environment for such a short duration. Cobb used the Tandem Romberg Test as a static test and walking heel-to-toe around a 4-m long set path, walking on the floor eyes closed, and walking on a line eyes closed as dynamic tests. Cobb also used a sway magnetometry technique and measured path length of hip sway. Only this magnetometry measure was rather sensitive to the symptom of simulator sickness. Cobb also stated that under more provocative conditions and if proper measurement techniques are used, measurements of postural stability could provide enough data to indicate how severe the effects of VR immersion were. Based on experimental results, Kennedy and Lilienthal (1995) also claimed that the duration of exposure might be a causal factor in postural disequilibrium, and Kennedy and Lilienthal suggested that exposures of fewer than 3 hr would not cause any postural unsteadiness. It is essential to develop an evaluation method of postural instability and motion sickness induced by VR exposure using a longer immersion time and a more sensitive technique. Until now, few attempts have been made to evaluate postural instability using a posturography technique based on a force platform. Moreover, the comparison of postural instability and motion sickness symptoms between the VR immersion condition and the condition under which participants do not experience VR exposure has not been carried out.

Longer immersions in a VR environment may induce higher levels of postural instability and symptoms of motion sickness. Therefore, the effects of duration of immersion in a VR environment on postural instability should be examined. In this study, I examined the effects of the duration of immersion in a VR environment on postural stability using a force platform measurement and a self-reported questionnaire on motion sickness. The change of postural stability measures with the increase of time was also compared between VR immersion and control (no VR immersion) conditions. On the basis of the results, I discuss the underlying mechanism of postural instability and motion sickness and the causal relation between these two items under longer immersion in a VR environment.

2. METHOD

2.1. Participants

Healthy undergraduate students (8 men), aged 21 to 23years, participated in the experiment as paid volunteers. All participants declared that their preferred foot was right.

2.2. Apparatus

Participants played an interactive TV game (Nintendo64, GOLDENEYE; Nintendo, Japan) wearing a monaural head mount display (HMD; Phillips, SCUBA; USA). The headset weighs 0.59 kg, and its image corresponds to 0.7 in. The HMD uses a TFT (thin film transfer) crystal panel with 180,000 pixels. This is equal to a 120-in. TV monitor placed 3 m in front of a participant. A joystick was used to play the TV game. The two crystal displays sustained a field of view of 60º by 46.8º with a 75% overlap. A participant could move his or her head freely throughout the game.

The Japan Kistler force plate (Kistler 9286; Japan) was used to measure postural steadiness (see outline of experimental setup in Figure 1). The signal of the force plate was amplified using eight Kistler 9865C1Y28 (Japan) charge amplifiers connected to the force plate. This force platform enables one to calculate horizontal (x- and y-axes) and vertical (z-axis) reaction forces separately on the basis of eight output signals. Using the horizontal and vertical reaction forces, the center of pressure (COP) is calculated as a location of the vertical reaction vector on the surface of a

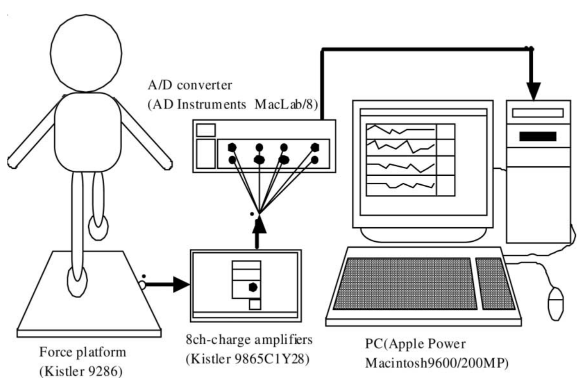

FIGURE 1 Outline of the experimental setup.

platform on which a participant stands. The COP reflects the orientation of body segments as well as the movements of the body to keep the center of gravity over a force platform (base of support). In such a way, the displacement of the COP is measured separately in the anterior–posterior (AP) and medial-lateral (ML) directions (Prieto, Myklebust, Hoffman, Lovett, & Myklebust, 1996). The outputs of the amplifiers were sent to a personal computer (Apple® Power Macintosh 9600/200MP; Apple Computer, USA) equipped with MacLab/8 (AD Instruments; Australia) for A/D (analog/digital) conversion. The MacLab/8 was adjusted to sample the eight charge amplifiers with a sampling frequency of 1 kHz.

2.3. Task

The participants played the three-dimensional (3-D) TV game for 3 hr while wearing an HMD.

2.4. Design and Procedure

The experimental setup is summarized in Figure 1. Before the experiment started and at 60, 120, and 180 min (immediately after the experiment finished) from the start of the experimental task, postural steadiness was measured using a force platform. Participants were also required to complete the Simulator Sickness Questionnaire (SSQ; Kennedy, Lane, Berbaum, & Lilienthal, 1993) before and after the task. In this study, sickness was not evaluated at each interval during the experiment (60 and 120 min) because it was judged that carrying out a questionnaire during the experiment would be time consuming and lead to the improved postural stability due to the rest of participants. To avoid the effect of circadian rhythm on the measured data, the experiment was carried out at 1:00 p.m. for all participants. The experimenter asked the participants to go to bed and wake up at the predetermined times on the experimental day. All participants observed this instruction. Therefore, it can be judged that the individual differences of a rhythm between participants would be minimal.

When measuring postural steadiness using a force platform, the participants were required to stand quietly in a comfortable stance near the center of the force platform for about 2 min. The measurement duration was 20 sec for each standing posture. There were three standing positions: standing on both feet with eyes closed (SBF), standing on the left foot with eyes closed (SLF), and standing on the right foot with eyes closed (SRF). The order of the measurements in the three positions was randomized across the participants. Between measurements for each posture, participants were allowed to take a rest of about 10 to 20 sec. The independent variable was computed as the COP. As a control condition, all of the participants were also measured for the similar physiological and psychological data while not playing 3-D TV games or being involved in a VR environment for 3 hr. In other words, all of the participants also took part in the control experiment. The measurement for the control condition was carried out on another day. The VR and control conditions were counterbalanced for order across the participants. During the 3-hr control experiment, participants were allowed to perform their favorite activities such as reading a book and doing their assignments so long as the activity did not include playing TV or computer games. They were forbidden to use computers. I describe the details of these measurements in the next section.

3. MEASURES OF POSTURAL STABILITY

The COP is a bivariate distribution jointly defined by AP and ML coordinates (Murata & Iwase, 1998; Prieto et al., 1996). N is the number of data points (time series of AP and ML body sway calculated using eight force platform outputs) and corresponds to 20,000 because the force platform measured the data with a sampling frequency of 1 kHz. T is the period of time selected for analysis and equals 20 sec. First, the following notations are defined:

$AP_o[n]$: AP displacement of the COP
$ML_o[n]$: ML displacement of the COP
AP_m: Mean of $AP_o[n]$
ML_m: Mean of $ML_o[n]$

The AP and ML time series are referenced to the mean COP as follows:

$$AP[n] = AP_0[n] - AP_m \quad (1)$$
$$ML[n] = ML_0[n] - ML_m \quad (2)$$
$$RD[n] = RD_0[n] - RD_m \quad (3)$$

In this study, the following measures were used to assess postural steadiness by computing the time series of AP and ML using the output signals of the force platform amplifiers. RD stands for resultant distance. The mean distance M_{RD} represents the mean distance from the mean COP and is given by

$$M_{RD} = \sum_{i=1}^{N} \frac{RD[n]}{N} \quad (4)$$

The mean distance M_{AP} represents the mean AP distance from the COP and is given by

$$M_{AP} = \sum_{i=1}^{N} \frac{|AP[n]|}{N} \quad (5)$$

The mean distance M_{ML} represents the mean ML distance from the mean COP and is given by

$$M_{ML} = \sum_{i=1}^{N} \frac{|ML[n]|}{N} \quad (6)$$

The mean velocity (MVL) of the COP is given by

$$MVL = \sum_{i=1}^{N} \sqrt{\frac{\left(AP[n+1] - AP[n]\right|^2 + \left(ML[n+1]\right) - ML[n]\right|^2 \Big)}{T}} \tag{7}$$

The mean velocity of the COP in the AP direction MVL_{AP} is given by

$$MVL_{AP} = \sum_{i=1}^{N-1} \frac{\left|AP[n+1] - AP[n]\right|}{T} \tag{8}$$

The mean velocity of the COP in the ML direction MVL_{ML} is given by

$$MVL_{ML} = \sum_{i=1}^{N-1} \frac{\left|ML[n+1] - ML[n]\right|}{T} \tag{9}$$

The sway area (SW) is dependent on the distance from the mean COP and the distance traveled by the COP and can be conceptualized as proportional to the product of mean distance and mean velocity. This measure $AREA_{SW}$ is given by

$$AREA_{SW} = \sum_{i=1}^{N-1} \frac{\left|AP[n+1]ML[n] - AP[n]ML[n+1]\right|}{(2T)} \tag{10}$$

4. RESULTS

The changes of the mean ML (Equation 6), AP (Equation 5), and RD (Equation 4) distance with time are plotted in Figures 2, 3, and 4, respectively. The change of the mean sway area $AREA_{SW}$ (Equation 10) with time is shown in Figure 5. The changes of the mean velocity of the COP in the ML, AP, and resultant directions are shown in Figures 6, 7, and 8, respectively. In Figures 2 through 8, the data for the control condition are also plotted. Using a normal probability sheet, I checked whether the data in Figures 2 through 8 were normally distributed or not. As a result, the data plotted on the normal probability sheet were nearly on the straight line. The correlation coefficients of the regression line were highly significant and more than .95 for all of the seven measures.

The mean and standard deviation of the seven measures were compared as a function of task condition, standing posture, and block (Table 1). The results of a

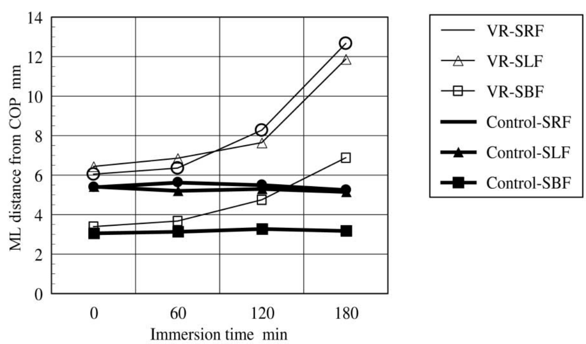

FIGURE 2 Change of mean medial-lateral (ML) distance with the increase of immersion time. VR = virtual reality; SRF = standing on right foot condition; SLF = standing on left foot condition; SBF = standing on both feet condition.

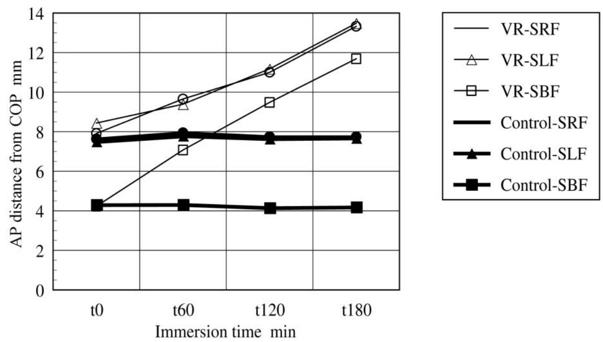

FIGURE 3 Change of mean anterior–posterior (AP) distance with the increase of immersion time. VR = virtual reality; SRF = standing on right foot condition; SLF = standing on left foot condition; SBF = standing on both feet condition.

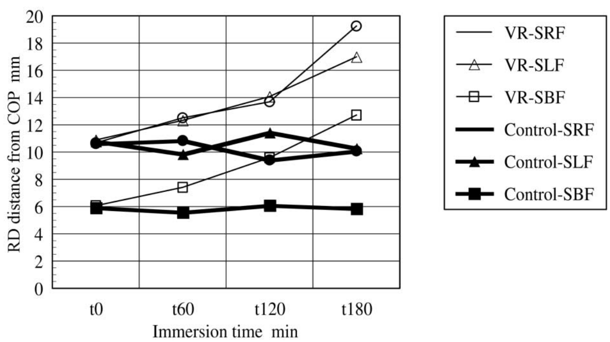

FIGURE 4 Change of mean RD (resultant distance) distance with the increase of immersion time. VR = virtual reality; SRF = standing on right foot condition; SLF = standing on left foot condition; SBF = standing on both feet condition.

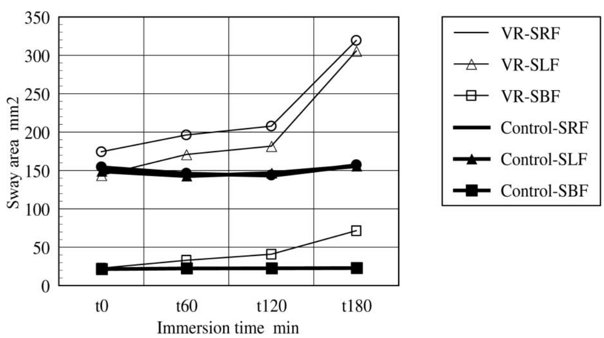

FIGURE 5 Change of mean sway area with the increase of immersion time. VR = virtual reality; SRF = standing on right foot condition; SLF = standing on left foot condition; SBF = standing on both feet condition.

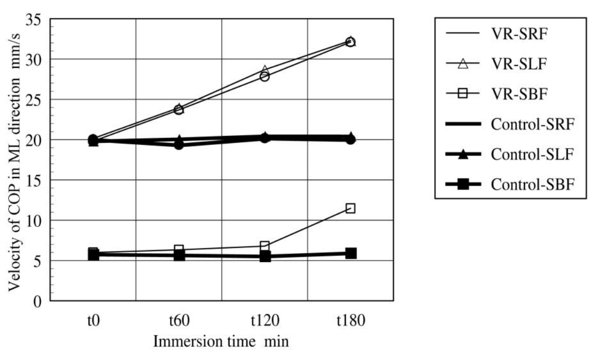

FIGURE 6 Change of mean velocity of the center of pressure (COP) in the medial-lateral (ML) direction with the increase of immersion time. VR = virtual reality; SRF = standing on right foot condition; SLF = standing on left foot condition; SBF = standing on both feet condition.

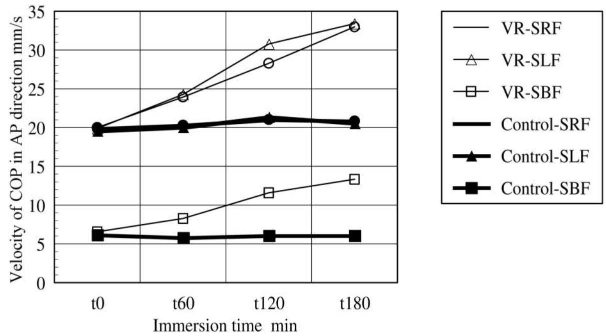

FIGURE 7 Change of mean velocity of the center of pressure (COP) in the anterior–posterior (AP) direction with the increase of immersion time. VR = virtual reality; SRF = standing on right foot condition; SLF = standing on left foot condition; SBF = standing on both feet condition.

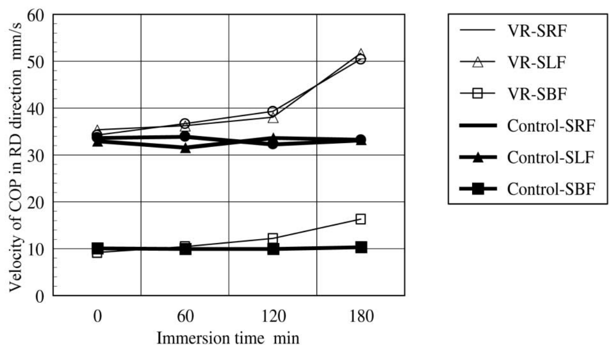

FIGURE 8 Change of mean velocity of the center of pressure (COP) in RD (resultant distance) direction with the increase of immersion time. VR = virtual reality.; SRF = standing on right foot condition; SLF = standing on left foot condition; SBF = standing on both feet condition.

three-way (Task Condition × Standing Posture × Block) analysis of variance performed on the seven measures are summarized in Table 2.

All of the measures tended to increase as the duration of immersion increased. It is clear that a decrease in postural equilibrium is induced to a larger extent after 180-min immersion in a VR environment. The measures for the standing on one foot (SLF or SRF) were larger than those standing on both feet (SBF). The increments in measurements induced by VR exposure were more outstanding for the one-foot condition than for the both-feet condition. The body sway tended to be smaller for the both-feet condition, indicating that the one-foot condition was more sensitive to postural instability. As a result of a post hoc test (Fisher's protected significant difference), the differences in these measures between the SLF and SRF were not significant, although the preferred foot was right for all participants. In the range of this experiment, whether the measurement was done with a preferred foot or not did not affect the measured values. These data indicated that VR immersion had some effects on the postural control system and gave rise to postural instability and that measures collected under the one-foot condition were more sensitive to postural instability. The mean values of the seven measures in the pretask control condition were nearly equal to those for the pre-VR immersion conditions. The seven measures for the control condition were nearly constant irrespective of the duration of experiment. This means that no remarkable postural instability was induced during the measurement before VR exposure. In the range of this experi-

Table 1: Mean and Standard Deviation of Seven Measures Compared as a Function of Task Condition, Posture, and Time.

	VR immersion			*Control*		
Time	*SRF*	*SLF*	*SBF*	*SRF*	*SLF*	*SBF*
M_{AP}[a]						
0 min	7.91 ± 1.97	8.43 ± 1.96	4.23 ± 1.05	7.63 ± 1.61	7.51 ± 1.31	4.31 ± 1.43
60 min	9.65 ± 1.41	9.38 ± 1.37	7.07 ± 0.95	7.95 ± 1.75	7.80 ± 1.42	4.32 ± 1.23
120 min	11.00 ± 1.13	11.17 ± 1.22	9.48 ± 0.93	7.75 ± 1.78	7.65 ± 1.75	4.16 ± 1.13
180 min	13.32 ± 1.37	13.48 ± 1.25	11.68 ± 0.95	7.75 ± 1.73	7.68 ± 1.43	4.20 ± 1.26
M_{ML}[a]						
0 min	6.05 ± 1.05	6.44 ± 0.97	3.39 ± 0.71	5.41 ± 1.64	5.44 ± 1.50	3.08 ± 1.31
60 min	6.35 ± 1.50	6.85 ± 1.56	3.67 ± 1.40	5.65 ± 1.60	5.23 ± 1.73	3.16 ± 0.73
120 min	8.27 ± 1.38	7.64 ± 1.67	4.75 ± 1.14	5.51 ± 1.52	5.32 ± 1.43	3.30 ± 0.95
180 min	12.67 ± 2.93	11.87 ± 2.54	6.88 ± 1.74	5.26 ± 1.43	5.17 ± 1.46	3.20 ± 1.10
M_{RD}[a]						
0 min	10.67 ± 2.41	10.88 ± 2.15	6.06 ± 1.87	10.62 ± 2.43	10.80 ± 2.13	5.92 ± 1.54
60 min	12.51 ± 2.61	12.32 ± 2.01	7.41 ± 2.34	10.85 ± 2.43	9.86 ± 2.58	5.58 ± 1.90
120 min	13.68 ± 2.54	14.07 ± 2.35	9.58 ± 1.56	9.42 ± 2.34	11.45 ± 1.98	6.10 ± 0.86
180 min	19.25 ± 3.16	16.98 ± 2.95	12.71 ± 2.13	10.08 ± 2.24	10.28 ± 1.98	5.86 ± 2.54
MVL_{AP}[b]						
0 min	20.01 ± 6.53	19.87 ± 5.12	6.55 ± 3.15	19.88 ± 6.61	19.58 ± 5.87	6.17 ± 3.64
60 min	23.93 ± 6.87	24.27 ± 7.72	8.27 ± 4.15	20.31 ± 6.99	20.06 ± 6.41	5.82 ± 2.98
120 min	28.28 ± 8.10	30.77 ± 8.87	11.58 ± 5.13	21.04 ± 7.33	21.38 ± 6.18	6.08 ± 4.16
180 min	32.98 ± 9.11	33.40 ± 9.74	13.33 ± 5.68	20.85 ± ?.25	20.57 ± ?.36	6.08 ± 3.10
MVL_{ML}[b]						
0 min	19.80 ± 6.82	20.13 ± 5.98	5.98 ± 2.56	20.03 ± 6.89	19.86 ± 7.13	5.80 ± 4.56
60 min	23.68 ± 9.14	23.95 ± 8.60	6.32 ± 2.34	19.36 ± 5.43	20.11 ± 6.87	5.70 ± 2.15
120 min	27.81 ± 10.44	28.67 ± 8.72	6.78 ± 4.21	20.18 ± 7.19	20.48 ± 6.05	5.57 ± 2.17
180 min	32.10 ± 10.18	32.28 ± 8.70	11.47 ± 3.21	20.01 ± 7.19	20.47 ± 6.05	5.96 ± 1.56
MVL[b]						
0 min	34.25 ± 9.13	35.37 ± 12.71	9.18 ± 3.14	33.75 ± 11.42	33.06 ± 9.87	10.18 ± 5.41
60 min	36.68 ± 13.06	36.25 ± 15.41	10.43 ± 4.35	34.00 ± 11.36	31.68 ± 12.56	10.06 ± 2.98
120 min	39.31 ± 10.85	38.06 ± 11.36	12.18 ± 3.65	32.37 ± 11.36	33.75 ± 9.20	10.06 ± 4.15
180 min	50.43 ± 17.11	51.68 ± 14.28	16.31 ± 2.75	33.25 ± 11.27	33.37 ± 13.54	10.43 ± 1.87
$AREA_{SW}$[c]						
0 min	174.37 ± 58.15	143.75 ± 35.74	22.75 ± 8.76	154.75 ± 63.03	149.62 ± 70.10	22.25 ± 13.54
60 min	196.25 ± 75.83	170.87 ± 60.38	33.00 ± 14.21	146.50 ± 59.40	143.50 ± 63.25	23.12 ± 5.43
120 min	207.75 ± 68.71	181.62 ± 79.01	40.87 ± 24.16	144.12 ± 59.28	147.25 ± 65.12	23.25 ± 10.14
180 min	319.37 ± 102.35	305.62 ± 123.57	71.50 ± 58.71	157.50 ± 54.31	156.50 ± 61.20	23.62 ± 7.85

Note. VR = virtual reality; SRF = standing on right foot; SLF = standing on left foot; SBF = standing on both feet. M_{AP} = mean anterior–posterior (AP) distance; M_{ML} = mean medial–lateral (ML) distance; M_{RD} = mean resultant distance; MVL_{AP} = mean velocity (MVL) in the AP direction; MVL_{ML} = MVL in the ML direction; $AREA_{SW}$ = the product of mean distance and MVL in the sway area. The blank area shows no statistical significance.

[a]Unit = mm. [b]Unit = mm/s. [c]Unit = mm^2.

Table 2: Results of a Three-Way (Task Condition × Posture × Block) Analysis of Variance Carried Out on Seven Measures.

Measure	*Task F(1, 7)=*	*Posture F(2, 14) =*	*Block F(3, 21) =*	*Task × Posture F(3, 21) =*	*Task × Block F(3, 21) =*	*Posture × Block F(6, 42) =*	*Task × Posture × Block F(6, 42) =*
M_{AP}	54.17*	44.17*	28.39*		5.57*		
M_{ML}	38.58*	27.05*	18.39*		25.35*	6.34*	
M_{RD}	57.86*	52.24*	19.99*		18.75*	6.56*	
MVL_{AP}	85.64*	215.62*	67.89*	26.41*	65.15*	11.78*	
MVL_{ML}	63.38*	193.38*	45.63*	55.72*	72.45*	8.42*	
MVL	114.96*	234.31*	75.19*	22.93*	134.34*	11.95*	
$AREA_{SW}$	62.18*	123.32*	60.82*	21.97*	88.71*	16.78*	

Note. M_{AP} = mean anterior–posterior (AP) distance; M_{ML} = mean medial–lateral (ML) distance; M_{RD} = mean resultant distance; MVL_{AP} = mean velocity (MVL) in the AP direction; MVL_{ML} = MVL in the ML direction; $AREA_{SW}$ = the product of mean distance and MVL in the sway area. The blank area shows no statistical significance.

ment, all of the seven measures sensitively reacted to VR exposure, and it is impossible to determine the best measure.

In Figure 9, the SSQ scores for nausea, oculomotor, disorientation, and total severity are plotted for preexposure and postexposure. The data for the control condition are also plotted. The postcontrol in this figure denotes the measurement of SSQ after the completion of the 3-hr control experiment. For the VR immersion condition, the nausea, oculomotor difficulty, disorientation, and total score at postexposure were all greater than those at preexposure. In accordance with this, the postural instability after VR immersion for 3 hr increased as compared with that under preimmersion (Figures 2 through 8). The data were analyzed using a nonparametric Wilcoxon test. The total severity was significantly greater after the VR immersion than before the VR immersion ($z = -2.536$, $p < .05$). The nausea ($z = -2.271$, $p < .05$), oculomotor ($z = -2.521$, $p < .05$), and disorientation ($z = -2.201$, $p < .05$) were all significantly greater at the posttask condition than at the pretask condition. The SSQ scores for the control did not differ significantly between pretask and posttask condition.

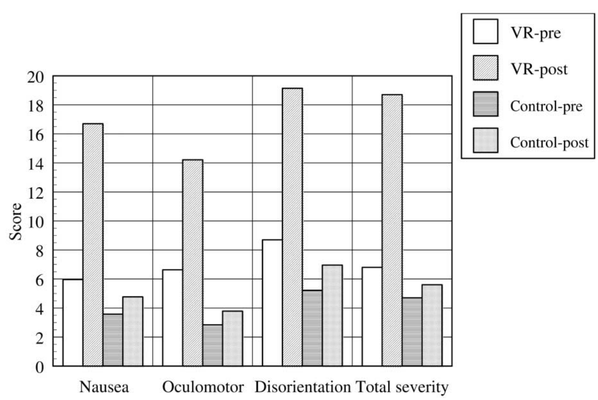

FIGURE 9 Simulator Sickness Questionnaire scores compared between precondition and postcondition. VR-pre = before start of 3-hr VR immersion; VR-post = after finish of 3-hr VR immersion; Control-pre = before start of 3-hr control experiment; Control-post = after finish of 3-hr control experiment.

5. DISCUSSION

For the three standing postures, the effects of longer immersion in a VR environment on the postural stability measures were clear. Moreover, the extent of postural instability was greater in the standing with one foot (SRF and SLF) condition than in the SBF condition. As shown in Figure 9, in accordance with these tendencies, the SSQ scores on the nausea, oculomotor disturbances, disorientation, and total severity increased significantly after 3-hr exposure to a VR environment. From the results of this study, the body sway measured using a force platform seems to be promising for the evaluation of postural instability.

Comparing the results of 3-hr immersion in a VR environment to those of the control under which no immersion was imposed on the participant, the effects of the longer immersion in a VR environment can be pointed out with more confidence. When the participant was not engaged in a VR task with an HMD, the postural stability measures described by Equations 4 through 10 did not change with an increase in time. The values remained nearly constant irrespective of the time (Figures 2 through 8). The SSQ score for the control condition also did not differ between pretask and posttask conditions. The mean values of the seven measures at 0 immersion time (before the experimental session starts) for the control condition were nearly equal to the corresponding values during VR immersion. These data show that VR immersion gradually degraded the postural control system. The significant Task Condition × Block interaction, which must have occurred mainly because the patterns of change of postural stability measures as a function of time were different between the VR immersion and control conditions, validates the result. In other words, under the control condition, the measures were nearly constant across time, whereas the measures increased with time under the VR immersion condition. This result supports the idea that longer immersion in a VR environment induces postural instability.

On the preceding discussion, one can conclude that 3-hr immersion in a VR environment reduced postural control both psychologically and physiologically. The duration of exposure to a VR environment is a crucial factor for producing postural instability. At the 180-min measurement, the postural instability was the largest, and the symptoms of motion sickness such as nausea, oculomotor, and disorientation were induced to a larger extent as compared with the preimmersion condition. The exposure to a VR environment for more than 3 hr would be sufficient to induce detriment in postural stability. One can conclude that longer immersion in VR environments will surely induce more severe postural instability and more symptoms of motion sickness as compared with the preexperiment state and the control (no VR immersion) condition and induce more severe postural instability (body sway) than the shorter immersion condition. Future research will be required to investigate the postural instability and symptoms of motion sickness in many VR environments in addition to 3-D TV games to establish a duration standard for VR environment use. The recovery process after longer immersion in VR environments should also be explored to propose and recommend a satisfactory recovery time.

Integration of information from sensory inputs, such as the visual, somatosensory, and vestibular, provides information about orientation that would allow one to maintain postural stability through compensatory reflective movements. The conflict between visual and vestibular input produces false sensations of movement of the body or environment by transmitting inappropriate signals to the central nervous system where vestibular and visual input are integrated (Cobb, 1999). At present, it is generally believed that conflicting information from the five sensory inputs rather than specific information from any one input may cause motion or simulator sickness and postural instability (Money, 1970; Reason & Brand, 1975).

The ecological theory of motion sickness and postural instability (Riccio & Stoffregen, 1991) insists that postural instability itself causes sensory conflict, which in turn produces motion sickness. In fact, there is a certainty that the interaction with VR systems alters the natural correspondence between sensory inputs, although the causal relation between postural instability and motion sickness or between postural instability and sensory conflict has not been clarified. In other words, this model hypothesizes that postural instability before immersion in VR is a necessary precursor to motion sickness.

To verify the ecological theory, it would be necessary to use an experimental paradigm in which the degree of postural instability is controlled before immersion experience in some way and to investigate whether such a difference would lead to various degrees of motion sickness. Grouping of participants with high and low instability would be a key to the success of verifying the hypothesis. If the symptoms of induced motion sickness differed between the two groups, an ecological explanation might be validated. As pointed out by Cobb (1999), an experimental paradigm that enables one to measure postural stability during an experimental session would also be necessary to verify this theory systematically and definitely.

The measures described by Cobb (1999), static or dynamic, might have effects on learning. In Hamilton et al. (1989), with findings that differ from this study, an increase of postural instability was not reported. The dynamic floor-based performance measures addressed by Cobb are uncertain in the measurement itself due to the necessity of learning how to perform a test and are susceptible to learning effects. As Hamilton et al. suggested, with the test trial proceeding, a learning effect was observed. In Cobb (1999), the learning effect of the performance test, that is, a significant effect of test trial, was also reported. It is possible that such a learning effect masks any reduction in performance data for the evaluation of postural instability. On the other hand, the postural stability measures based on the force platform are more objective and less susceptible to learning effects than floor-based performance tests done by Cobb and Hamilton et al. because it is not necessary to learn how to perform the test. Participants only stand on a force platform with the predetermined posture during the measurement.

In this study, I also conducted the control conditions under which no VR experience was made during the experiment to investigate the change of postural instability as a function of immersion time and to compare the degree of instability when there was no VR immersion to that when VR immersion was used. As shown in the results, all measures during VR immersion increased as the immersion time increased, indicating that postural instability was, to a larger extent, induced. Postural instability was observed less before immersion and under the control experiment. Therefore, the data do not indicate that the preimmersion postural instability predisposes participants to motion sickness. Rather, it would be reasonable to assume that the immersion experience induced both postural instability and symptoms of motion sickness, which supports the sensory conflict hypothesis. At present, it is not clear whether postural instability is a cause of motion sickness or not. In the range of this study, it is impossible to identify the causal relation between these two phenomena. I can only point out that these phenomena are the effects of immersion experience in VR.

Figure 10 summarizes the preceding discussion. The effects of immersion experience in VR must be pursued from multiple perspectives. In the evaluation of how immersion experience affects people, the contents of VR systems or tasks—which might be passive, active, 2-D, or 3-D—would need to be taken into account along with the duration of immersion, the reliability of measurements for evaluating postural stability, and the learning effects of measures mentioned previously (floor-based dynamic tests used by Hamilton et al., 1989, and Cobb, 1999). The sensitivity to motion sickness, which might be characterized by the degree of postural instability before an immersion experience or by the Motion History Questionnaire proposed by Kennedy et al. (1992) must also be considered. The combination of a sensory conflict and an ecological model might be appropriate to evaluate the effects of immersion in VR. From this experiment, it is not possible to draw any definite and strong conclusion on the relation between motion sickness and postural instability and generalize the results to propose a useful guideline until someone designs a more generalized VR experiment taking into account factors listed in Figure 10.

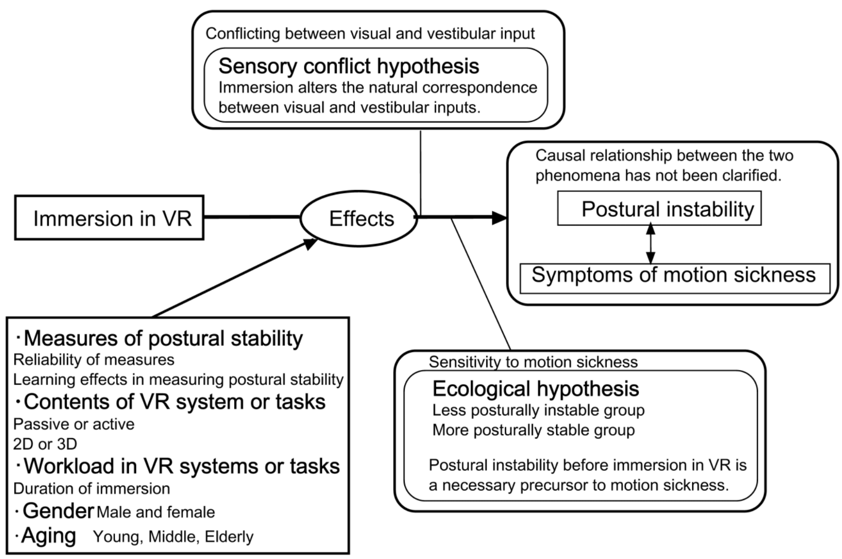

FIGURE 10 Modeling of how immersion in virtual reality (VR) induces postural instability and symptoms of motion sickness. Two explanations (sensory conflict theory and ecological hypothesis) are listed. 2D = two dimensional; 3D = three dimensional.

REFERENCES

Black, F. O., Paloski, W. H., Dopxey, B., Gasway, D. D., & Reschke, M. F. (1995). Vestibular plasticity following orbital spaceflight: Recovery from postflight instability. *Acta Oto-Laryngologia*, *(Suppl. 520(II))*, S450–454.

Cobb, S. V. G. (1999). Measurement of postural stability before and after immersion in a virtual environment *Applied Ergonomics*, *30*, 45–57.

Hamilton, K. M., Kantor, L., & Megee, L. E. (1989). Limitations of postural equilibrium test for examining simulator sickness. *Aviation Space Environmental Medicine, 59,* 246–251.

Kennedy, R. S., Fowlkes, J. E., & Lilienthal, M. G. (1993). Use of a Motion Sickness History Questionnaire for prediction of simulator sickness. *Aviation Space Environmental Medicine, 63,* 588–593.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology, 3,* 203–220.

Kennedy, R. S., & Lilienthal, M. G. (1995). Implications of balance disturbances following exposure to virtual reality systems. In *Proceedings of Virtual Reality Annual International Symposium '95* (pp. 35–39). Los Alamitos, CA: IEEE Computer Society Press.

Kennedy, R. S., & Stanney, K. M. (1996). Postural stability induced by virtual reality exposure: Development of a certification protocol. *International Journal of Human–Computer Interaction*, *8,* 25–47.

Money, K. (1970). Motion sickness. *Physiological Review, 50,* 9–17.

Murata, A., & Iwase, H. (1998). Chaotic analysis of body sway. *Proceedings of 20th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 20,* 1557–1560.

Paloski, W. H., Black, F. O., Rescheke, M. F., Clakins, D. S., & Shupert, C. (1993). Vestibular ataxia following shuttle flights: Effects of microgravity on otolith-mediated sensorimotor control of posture. *American Journal of Otology*, *14*(1), 9–17.

Prieto, T. E., Myklebust, J. B., Hoffman, R. G., Lovett, E. G., & Myklebust, B. M. (1996). Measures of postural steadiness: Differences between healthy young and elderly adults. *IEEE Transactions on Biomedical Engineering, 43,* 956–966.

Reason, J. T., & Brand, J. J. (1975). *Motion sickness.* London: Academic.

Regan, E. C., & Price, K. R. (1994). The frequency of occurrence and severity of side-effects of immersion virtual reality. *Aviation Space Environmental Medicine, 65,* 523–530

Riccio, G. E., & Stoffregen, T. A. (1991). An ecological theory of motion sickness and postural instability. *Ecological Psychology, 3,* 195–240.

Stanney, K. M., Kennedy, R. S., Drexler, J. M., & Harm, D. L. (1999). Motion sickness and proprioceptive aftereffects following virtual environment exposure. *Applied Ergonomics, 30,* 27–38.