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Postural Responses to Two Technologies for Generating Optical Flow

Abstract

The perception and control of stance are frequently studied in virtual environments, where computer-generated videographic displays are used to simulate the optical consequences of body sway. Generally, the intent of such studies is to understand how posture is controlled outside of virtual environments (i.e., in daily life). Accordingly, the validity of such studies will depend upon the extent to which postural responses to videographically generated optical flow resemble postural responses to optical flow that is generated in other ways. We conducted a direct test of postural responses to optical flow generated using two technologies: physical displacement of the visible surroundings (using a moving room), and videographic projection of computer-generated graphics. We attempted to make the two displays as similar as possible in terms of visual angle, optical texture, and the amplitude and frequency of oscillation. The results revealed several significant differences in postural responses to the two types of stimuli. This raises questions about the extent to which postural control in virtual environments can be generalized to postural control in the real world.

1 Postural Responses to Two Technologies for Generating Optical Flow

Computer-based simulations and virtual environments are becoming pervasive parts of many areas of basic research on human perception and action. Researchers often use simulations as a means to understand behavior in the actual (i.e., unsimulated) environment. That is, the main interest of this research is not how perception and action work in simulated environments, per se. Rather, the simulation is used as a tool for understanding basic (i.e., general) behavioral phenomena. In some areas simulations have become the principal means for presenting experimental stimuli. One such area is the study of relations between vision and the control of stance, in which computer-generated optical flow is displayed using videographic projection systems (e.g., Van Asten, Gielen, & Denier van der Gon, 1988; Dijkstra, Schöner, Gielen, 1994; Bardy, Warren, & Kay, 1996; Warren, Kay, & Yilmaz, 1996; Bardy, Marin, Stoffregen, & Bootsma, 1999; Marin, Bardy, Baumberger, Flückiger, & Stoffregen, 1999). The computer-generated flow is intended to resemble, in some parameters, the optical flow that naturally is generated by body sway. In this sense, the computer-generated flow is a simulation of the optical conse-

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quences of body sway. Researchers measure postural responses to this computer-generated simulation as a means of testing theories relating vision to stance.

In these and other studies researchers are not interested in postural responses to simulations, as such. Rather, the results are believed to generalize to situations in which optical flow is not generated by computer simulation. However, in relating vision to the control of standing posture, there has been no direct comparison of different methods of generating optical flow.[1] In this article, we report the results of such a comparison. The data revealed significant differences in postural responses to optical flow generated using different technologies. These differences raise questions about the extent to which postural research conducted in virtual environments may generalize to postural control in daily life.

1.1 Optical Flow and the Control of Stance

In ordinary stance, body sway is characterized by oscillatory displacements of the body (primarily in the anterior-posterior or AP axis) that are of low frequency and low amplitude. In adults, sway is concentrated below 0.4 Hz, with a peak at approximately 0.2 Hz, and amplitude (at the head) of about 4 cm (Bensel & Dzendolet, 1968). This gives rise to optical flow that, while global, is very subtle. Many studies have shown that vision has a powerful influence on the perception and control of body sway. One way to study relations between vision and posture is to simulate the optical consequences of body sway, that is, to create a display of optical flow, and to measure postural responses to the simulation.

In most studies of relations between vision and postural control, optical flow has been generated using one of two technologies. One way to simulate the optical consequences of body sway is by using a "moving room." A moving room is an enclosure that can be moved relative to the floor. For persons standing inside the room (on the stationary floor), room movement can produce optical flow that resembles the flow generated by body sway (e.g., Lee & Lishman, 1975; Stoffregen, 1985, 1986; Schmuckler, 1997; Stoffregen & Smart, 1998; Oullier, Bardy, Stoffregen, & Bootsma, 2002, 2004). Another way to simulate the optical consequences of body sway is through a combination of computer simulation and videographic projection (e.g., Van Asten et al., 1988; Dijkstra et al., 1994; Bardy et al., 1996; Bardy et al., 1999; Warren et al., 1996). Each of these methods of generating optical flow is known to induce robust postural responses. Typically, body sway becomes coupled to the imposed optical oscillations, with the body moving in the same direction as the stimulus, with approximately the same frequency and timing.

1.2 Spatial and Temporal Resolution

The optical flows created by moving rooms and computer-based videographics differ in a number of ways (e.g., Stoffregen et al., 2003; cf. Hochberg, 1986). One of these is the visual angle of the optical flow that is presented to subjects. Moving rooms create optical flow that surrounds the subject, whereas most video projection systems present optical flow only in the fronto-parallel plane. While this may influence behavioral responses to the two technologies, it was not a motivation for the present study. Our interest was focused on two other factors, spatial and temporal resolution.

In contemporary virtual environments, the spatial resolution of display imagery is constrained by the resolution of video display technology. In most video projection systems, spatial resolution is limited by the size of the pixels and raster lines. No such constraint oper-

1. An open question concerns whether moving rooms constitute virtual environments (Stoffregen, Bardy, Smart, & Pagulayan, 2003). The moving room used in the present study can be considered to be a virtual environment because it presents a simulation of body sway, and because the visual display (i.e., room motion) is generated and controlled by a computer. On the other hand, the optical flow generated by the moving room does not arise from computer graphics or videographic projection. There is no widely accepted, precise definition of virtual environment (Blade & Padgett, 2002), and so it is difficult to reach a clear conclusion about the status of the moving room. If the moving room is considered to be a virtual environment, then the present study is an evaluation of the relative characteristics of two virtual environment technologies. On the other hand, if the moving room is not considered to be a virtual environment, then the present study is a contrast between perceptually guided action in virtual and nonvirtual environments.

ates in the physical environment, where the optic array can have unlimited spatial resolution. This distinction is easily demonstrated by walking toward an image on a video projection screen. With decreasing distance detail is lost; the image breaks up and the underlying pixels become visible. By contrast, when walking toward a wall the surface becomes clearer and new details emerge.

The limited spatial resolution of videographic systems has consequences for the depiction of motion. When motion is of low amplitude, videographic systems may produce images that jump from point to point (this effect is known as aliasing). Aliasing can limit the utility of videographic technologies for depiction of events that are characterized by motion of low frequency or low amplitude. The perceptual salience of aliasing is greatest for low-amplitude motions. This may help to explain why many video-based studies of posture often use large amplitudes of stimulus motion (e.g., Van Asten et al., 1988; Bardy et al., 1996; Bardy et al., 1999; Warren et al., 1996). A problem with this is that posture is characterized by small amplitudes of sway. This means that the larger amplitudes used in video-based studies are unrepresentative of optical flow created by natural sway (Dijkstra et al., 1994). When periodic optical flow is generated using a moving room, robust coupling is observed for stimulus amplitudes in the range of natural postural motion (e.g., Lee & Lishman, 1975; Stoffregen, 1985, 1986; Stoffregen & Smart, 1998; Oullier et al., 2002, 2004). To investigate this issue we varied the amplitude of stimulus motion across a range that both included and exceeded the amplitude of natural sway.

Aliasing will be influenced by the amplitude of displayed motion, but also by the size of texture elements in the display. For small texture elements (i.e., approaching the size of pixels), small excursions or slow motions will produce motion that is visibly "jerky." Larger images will be less affected. Hence, we would expect the size of visual texture elements to influence postural responses to videographically generated optical flow. Postural responses should be more robust when videographic projections have large texture elements, and less robust when displays have smaller texture elements. Similarly, we would expect the amplitude of stimulus motion to influence postural responses to videographically generated optical flow, with responses being more robust for larger amplitudes of simulated motion. The size of texture elements and the amplitude of stimulus motion should have no effect on postural responses to flow generated by a moving room.

1.3 Summary and Predictions

We compared postural responses to optical flow generated by movement of a physical surrounding (a moving room), and by video projection of computer-generated graphics. We varied the amplitude of optical oscillations, and the size of texture elements in the displays. We strove to ensure that all other aspects of the optical flow were as similar as possible. We predicted (a) that the cross-correlation and gain between body sway and optical flow would be stronger in the moving room, (b) that differences in cross-correlation and gain would be most pronounced at smaller amplitudes of stimulus motion, and (c) that differences in cross-correlation and gain would be more pronounced for displays having smaller texture elements. We also analyzed the relative phase of stimulus motion and body sway. We included this variable because it is widely used to characterize the dynamics of postural responses to imposed optical flow; however, we did not make any predictions about the phase data.

2 Method

The experiment was unusual in that data were collected in two laboratories. The division was necessary to gain access to the two types of apparatus that were the subject of the research. Participants in the moving-room group were tested at the University of Cincinnati, USA, while participants in the videographic group were tested at the University of the Mediterranean, Marseille, France. Aspects of apparatus and procedure that differed across the two laboratories are detailed separately below.

One aspect of the apparatus that was identical in the two laboratories was the means used to control the visual angle of stimulus displays. To equate the field of view across groups, participants wore a pair of goggles.

The goggles had opaque plastic frames that occluded the far periphery (in the moving-room group, the goggles occluded the side walls of the room). The lenses of the goggles were removed, allowing a clear view forward. The circular viewing apertures were 5 cm in diameter, providing a viewing angle of 68.17° for each eye. The same pair of goggles was worn by participants in both groups.

2.1 Moving-room Group

2.1.1 Participants. Fourteen undergraduate students from the University of Cincinnati were assigned to the moving-room group. There were six females and eight males, ranging in age from 18 to 21 years, with a mean of 19.1 years, and ranging in height from 157.5 cm to 188 cm, with a mean of 174.5 cm. Six participants wore corrective lenses (contact lenses). Participants received course credit for their participation. The participants all reported that they had no history of vestibular disease or malfunction of the vestibular apparatus nor history of postural instability, recurrent dizziness, or falls. Participants were naive to the purposes of the experiment.

2.1.2 The Moving Room. The moving room was a 2.4 m cube constructed of sheets of plywood fixed to a frame of aluminum beams (Figure 1). The room was mounted on wheels that ran along steel rails that were bolted to the concrete laboratory floor. The interior walls of the room were covered with a marble-pattern contact paper. Illumination was provided by a fluorescent tube mounted on the ceiling of the moving room (other laboratory lighting was turned off during experimental sessions). Motion was produced by a 6-horsepower electric motor under computer control. The maximum excursion of the room was ±30 cm. The position and movement of the room were controlled to a spatial resolution of 1 mm and a temporal resolution of 40 ms. The moving room was located at the University of Cincinnati.

2.1.3 Data Acquisition. Postural data were collected using a 6-df magnetic tracking system (Flock of Birds; Ascension, Inc.). An emitter created a low-intensity magnetic field. One receiver (bird) was attached to the room while the other bird was attached to the back of a lightweight bicycle helmet that was worn by each participant. The magnetic emitter was positioned on a stand within the moving room. Data were collected at 50 Hz and stored on disk for later analysis.

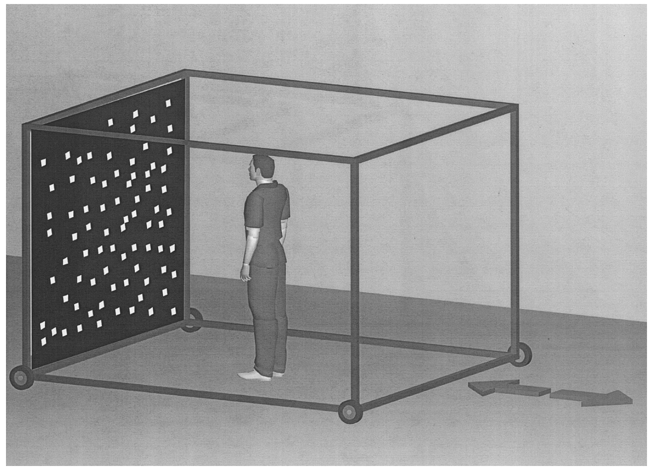

Figure 1. *The moving room (not drawn to scale).*

2.1.4 Stimuli. Two 183 cm by 183 cm sheets of rigid foam board, covered with matte black paper, served as the targets. On the "large-texture display" 2.5 cm by 2.5 cm white squares were mounted on the black paper. The "small-texture display" consisted of 0.5 cm by 0.5 cm white squares mounted on the black paper. For each display the white squares were prepared to cover 26% of the area of the black background. The white squares were arranged randomly on the black background. This was done by sifting the squares over the black paper by hand. The orientation of the squares varied randomly. Due to the sifting procedure some squares partially overlapped one another, so that the squares covered slightly less than 26% of the black background. The squares were secured with a clear spray adhesive after which clear contact paper was applied to the entire surface of each display.

The displays were mounted on wooden frames that could be rigidly attached to the center of the front wall of the moving room. For a person 174.5 cm tall at a viewing distance of 0.8 m, each display subtended a visual angle of 97.67° horizontal by 86.1° vertical. This meant that during trials, when the goggles were worn, the display could fill the field of view.

2.1.5 Procedure. The participants removed their shoes and donned the goggles and the bicycle helmet. They faced the front wall of the moving room so that their line of sight was along the axis of room motion, with their heels on a strip of black tape that was 0.8 m from the displays.[2] They viewed the displays while adopting one of three postures: hands placed in the front pockets, hands clasped in front, or hands clasped behind. Participants were instructed to adopt a comfortable stance without attempting to stand rigidly, and to refrain from extraneous motions. They were asked to maintain their gaze within the edges of the display surface, and to orient their head so that the display surface filled the field of view. There was no fixation point.

Each experimental session consisted of 20 experimental trials. Trials were 70 s in duration, and room motion was always at 0.2 Hz. There were five different amplitudes of room motion: 2, 7, 12, 17, and 22 cm. Each amplitude was presented twice for each display, for a total of 10 trials per display. Amplitudes were presented in blocks of five, in which each amplitude appeared once. Within blocks, the order of the presentation of amplitudes was randomized for each participant. The two displays were presented in blocks of ten trials each. Seven participants began with the small-texture display, and seven began with the large-texture display.

During the first 10 s of each trial, motion amplitude ramped up from 0 to the appropriate level for that trial. For this reason, data were collected only for the latter 60 s of each trial. After ten trials were completed with the first display, the experimenter replaced it with the second display.

2. Because of the existence of body sway, we could not fix the distance between the head and the displays. In research relating optic flow and body sway, the position of the subject relative to the display is often approximate (e.g., Lee & Lishman, 1975; Stoffregen, 1985; Dijkstra et al., 1994).

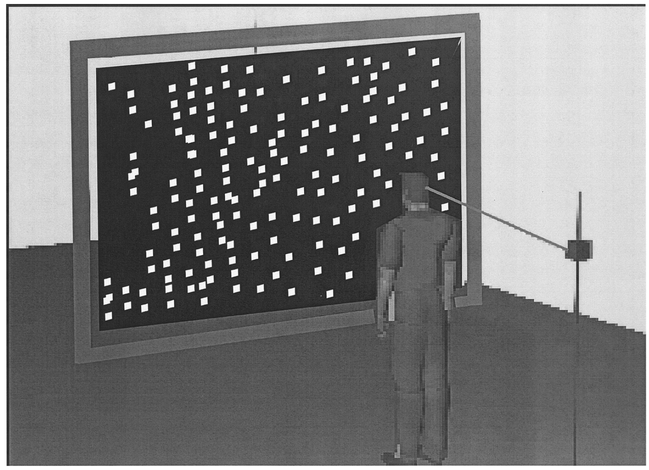

Figure 2. *The videographic projection system (not drawn to scale).*

2.2 Videographic Group

2.2.1 Participants. Fifteen students at the University of the Mediterranean in Marseille, France participated on a volunteer basis, ranging in age from 19 to 26 years (mean = 22), and in height from 156 to 182 cm (mean = 173). Seven participants were female and eight participants were male. The participants all reported that they had no history of vestibular disease or malfunction of the vestibular apparatus nor any history of postural instability, recurrent dizziness, or falls. Participants were naive to the purposes of the experiment. Seven participants wore corrective lenses (contacts).

2.2.2 Videographic Display. A videographic display was used to generate optical flow (Figure 2). Raster displays were generated on a Silicon Graphics INDY 4600 XZ workstation. These displays were projected at a full-frame rate of 30 Hz onto the screen with an Electrohome Marquée 7500 video projector with a 30 Hz refresh rate. The delay between image generation (in the computer) and image presentation (on the projection screen) was 90 ms. Image resolution was 1350 (horizontal) by 1100 (vertical) pixels. Participants stood at a distance of 0.8 m from a flat rear-projection screen (3 m horizontal by 2.25 m vertical). For a person 173 cm tall standing at this distance, the screen subtended a visual angle of 123.86° horizontal by 98.2° vertical;

thus, when the goggles were worn, the display could fill the field of view. The videographic display system was located in the Department of Sport Sciences, University of the Mediterranean, Marseille, France.

2.2.3 Data Collection. Head position was tracked using a locometer (Bessou, Montoya, Dupuis, & Pages, 1989; cf., Stoffregen, 1985, 1986; Oullier et al., 2002). Each participant wore a cap with a string attached to the back of it. This string traveled over the axle of a stand-mounted potentiometer (the potentiometer was at head height, so that the string extended horizontally from the cap). The string was wrapped twice around the potentiometer, and a 40 g weight (applying a maximum tension of .04 DaNs) was attached to the far end, which hung vertically from the axle. Changes in head position in the anterior-posterior axis caused changes in the position of the potentiometer axle (Bessou et al., 1989). The stand was positioned 140 cm behind the participant.

Voltage potentials from the potentiometer were converted into measurements of position in centimeters. The voltage data were calibrated by pulling the thread to various distances from the potentiometer and inputting the distance values that corresponded to the voltage that was registered. At the beginning of each day, the experimenter positioned the cap at 110 cm and 209 cm from the potentiometer, and position was calibrated from the corresponding voltage. The position of the potentiometer axle was sampled at 50 Hz. To negate the 90 ms delay between image generation and image presentation (see above), on each trial, the trigger that initiated data collection from the potentiometers was delayed by 90 ms, relative to the beginning of image generation. Thus, the net delay between image presentation and collection of corresponding postural data was 0 ms.

2.2.4 Stimuli. Displays were modeled on those used in the moving room. To begin, measurements of the texture elements in the moving room were used to determine the appropriate expansion and contraction dimensions for the texture elements in the videographic displays. Two displays were used, each consisting of white squares arranged randomly on a black background. The large-texture display consisted of squares measuring 2.5 cm on a side at the midpoint of the oscillation. The small-texture display consisted of squares measuring 0.5 cm on a side at the midpoint of the oscillation. The small squares covered less than three pixels and, accordingly, were subject to substantial aliasing effects. As with the displays in the moving room, the random distribution of squares resulted in some squares partially overlapping others, so that the net density of white elements (relative to the black field) was slightly less than 26%. Because the projection screen was larger than the display board used in the moving room, the absolute size of the videographic stimulus was larger than that of the moving room stimulus. However, the use of the goggles ensured that the effective visual angle of the stimuli in the two laboratories was identical.

2.2.5 Procedure. Participants removed their shoes and donned the cap, to which the thread was already attached. They were then positioned with their heels on a strip of tape 0.8 m from the projection screen. Participants were instructed to view the displays while adopting one of three postures: hands placed in the front pockets, hands clasped in front, or hands clasped behind. Participants were instructed to adopt a comfortable stance without attempting to stand rigidly, and to refrain from extraneous movements. They were asked to maintain their gaze within the edges of the display surface, and to orient their head so that the display surface filled the field of view. There was no fixation point. Trials lasted 65 s. For technical reasons, data collection began 5 s after the beginning of stimulus motion; thus, data were recorded only for the latter 60 s of each trial. The conditions, the number, and the sequence of trials were the same as for the moving-room group.

2.2.6 Data Analysis and Variables. Before conducting descriptive or inferential analyses, data from individual trials were screened for completeness. Some trials were found to have gaps in the data stream. In the moving-room group these gaps were caused largely by noise in the magnetic signal, while in the videographic group, gaps resulted primarily from hard disk problems of the desktop computer used to store data in real time. Individual trials were deleted if they contained fewer than 3000 data points (60 s at 50 Hz). On this basis, 135 trials were deleted from the videographic group, leaving 165 for analysis. Ten trials were deleted from the moving-room group, leaving 270 for analysis. For both groups, the deleted trials appeared to be distributed randomly across participants and conditions.

The time series of body sway exhibited low-frequency drift and high-frequency noise. Inspection of the power spectra obtained using a Fast Fourier Transform (FFT) indicated that the drift was due to frequencies below 0.08 Hz. Data were therefore processed using a customized filter based on decomposition and reconstruction of the time series after FFT (Oullier et al., 2002, 2004).

We analyzed three dependent variables. These were (1) the maximum cross-correlation for motion between postural motion and display motion in the AP axis ($R_{Display\text{-}head}$), (2) the gain of head amplitude relative to stimulus amplitude ($Gain_{Display\text{-}head}$), and (3) the relative phase of stimulus and head oscillations ($\phi_{Display\text{-}head}$). We used the point-estimate method to compute the stimuli-head relative phase (e.g., Zanone & Kelso, 1997; Bardy, Oullier, Bootsma, & Stoffregen, 2002). The cross-correlation and gain variables were subjected to separate one-between (group: videographic vs. moving room), two-within (stimulus amplitude, texture size) analyses of variance. Relative phase was analyzed using circular statistics (Batschelet, 1981), which do not permit multifactor analysis of variance; accordingly, we used Watson-Williams tests.

3 Results

Our planned analyses concerned behavior across the full duration of experimental trials, that is, zero to 60 seconds (00–60 s). These results are reported first. In addition, we conducted post hoc analyses comparing the first half (00–30 s) and second half (30–60 s) of the trials; these post hoc analyses are reported later.

3.1 Full Trials (00–60 s)

3.1.1 Maximum Display-head Cross-correlation ($R_{Display\text{-}head}$). Means are presented in Figure 3a. The mean $R_{Display\text{-}head}$ was .25 (SD = 0.16) for the videographic group, and .60 (SD = 0.43) for the moving-room group. A two-way ANOVA performed on the Fisher-transformed values of $R_{Display\text{-}head}$ revealed a significant main effect of the Group factor, $F(1,82) = 82.62$, $p < .05$, effect intensity (EI) = 10.28%. There was also a significant main effect of amplitude, $F(4,328) = 5.9$, $p < .05$, EI = 1.50%, indicating a change in coupling as the amplitude increased. The Group × Amplitude interaction was also significant, $F(4,328) = 5.0$, $p < .05$, EI = 1.28%; the relation between stimulus amplitude and cross-correlation was greater for the moving-room group (see Figure 3a). There were no significant effects involving texture size.

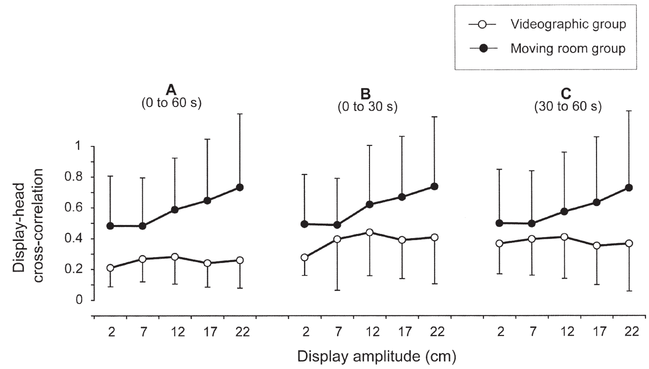

Figure 3. *Display-head maximum cross-correlation ($R_{Display\text{-}head}$).* a) Full trials (00–60 s). b) The first half of trials (00–30 s). c) The second half of trials (30–60 s).

3.1.2 $Gain_{Display\text{-}head}$. Means are presented in Figure 4a. Overall mean values of $Gain_{Display\text{-}head}$ were 0.24 (SD = 0.33) for the moving-room group, and 0.17 (SD = 0.33) for the videographic group. The main effect of group was not significant. There was a significant main effect of amplitude, $F(4,328) = 51.51$, $p <$ .05, EI = 2.90%, indicating a decline in gain with increasing stimulus amplitude. There was also a significant interaction between group and amplitude, $F(4,328) =$ 11.73, $p < .05$, EI = 0.66%. There were no significant effects involving texture size.

3.1.3 Relative Phase ($\phi_{Display\text{-}head}$). Mean values of phase are presented in Figure 5a. For each condition, displacement of the head followed the stimulus

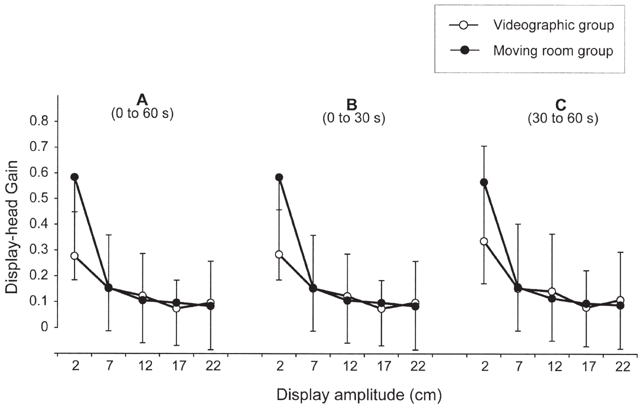

Figure 4. *Display-head Gain ($Gain_{Display\text{-}head}$).* a) Full trials (00–60 s). b) The first half of trials (00–30 s). c) The second half of trials (30–60 s).

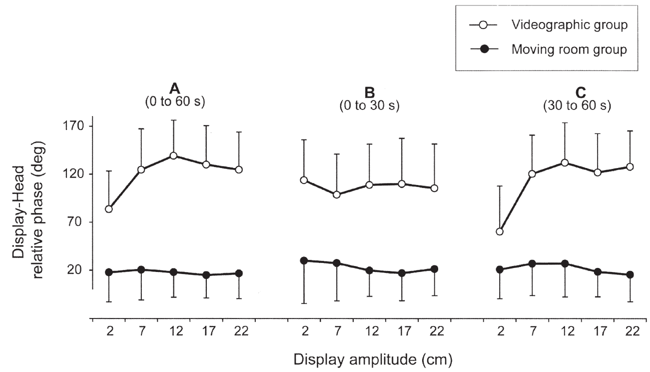

Figure 5. *Display-head relative phase ($\phi_{Display\text{-}head}$).* a) Full trials (00–60 s). b) The first half of trials (00–30 s). c) The second half of trials (30–60 s).

motion, and the relative-phase values were clustered around a mean (significant Raleigh test for nonhomogeneity, $p < .05$), indicating a preferred phase angle. The mean value of $\phi_{Display\text{-}head}$ was 121.03° (SD = 44.31°) for the videographic group, and 18.72° (SD = 27.15°) for the moving-room group; the difference was significant, $F_{Watson\text{-}Williams}$ (1,298) = 492.52, $p < .05$. In addition, $\phi_{Display\text{-}head}$ differed significantly from 0° for each group, as indicated by the 95% confidence interval for $\phi_{Display\text{-}head}$, which did not contain 0° for the videographic group (114.0° $< \phi_{Display\text{-}head} <$ 128.06°), or for the moving-room group (14.38° $< \phi_{Display\text{-}head} <$ 23.06°). For the videographic group, Watson-Williams tests revealed that in the 2 cm condition $\phi_{Display\text{-}head}$ different significantly from each of the other amplitudes (Table 1). There were no significant effects involving texture size.

3.2 Development of Coupling (00–30 s and 30–60 s)

For the videographic group, the cross-correlation (mean = 0.25) between stimulus motion and body sway was lower than has been reported in other studies examining postural responses to videographic optical flow. For example Bardy et al. (1996) found a mean cross-correlation of 0.48 for participants viewing a depicted wall that moved at a frequency of 0.2 Hz and an amplitude of 24 cm. Dijkstra et al. (1994) reported cross-correlation values ranging from 0.62 to 0.82 in response to frequencies of 0.2 Hz and amplitudes that ranged from 1 cm to 10 cm. Van Asten et al. (1988) reported cross-correlation values that ranged from 0.32 to 0.63 when viewing a depicted wall at a frequency of 0.2 Hz and an amplitude of 1.2 m. Warren et al. (1996) found a mean cross-correlation value of 0.67 in the anterior-posterior direction when participants viewed a depiction of a wall moving at a frequency of 0.25 Hz and an amplitude range of 8.5 to 16.4 cm. Similar differences exist across studies in the relative phase of stimulus and body motion; the phase observed for the videographic group was larger than has been reported in previous studies.

In seeking to understand the differences between the videographic group and previous studies, we considered variations in methodology across studies. In studies that use moving rooms and videographically generated optical flow, the treatment of data commonly differs. When videographically generated flow is used, data collection (or data analysis) commonly begins at some interval after the onset of stimulus motion. For example, Dijkstra et al. (1994), Bardy et al. (1996, 1999, 2002), and Warren et al. (1996) began data collection 20 s after the onset of stimulus motion. The rationale for these delays was "to allow the participant to achieve a steady state," (Warren et al., 1996, p. 822, see also Bardy et al., 1996,

Table 1. *Watson-Williams Tests on $\phi_{\text{Display-head}}$, Contrasting the 2 cm Stimulus Amplitude Against Each of the Other Four Amplitudes, for the Videographic Group*

Videographic group (00–60 s)	df	F	p	R1	R2
2 cm vs. 7 cm	58	12.48	<.05	23.57	22.75
2 cm vs. 12 cm	58	26.69	<.05	23.57	24.34
2 cm vs. 17 cm	58	16.77	<.05	23.57	23.32
2 cm vs. 22 cm	58	13.71	<.05	23.57	23.7

Table 2. *Watson-Williams Tests on $\phi_{\text{Display-head}}$, Contrasting the 2 cm Stimulus Amplitude Against Each of the Other Four Amplitudes During the Second Half of Trials (30–60 s), for the Videographic Group*

Videographic group (30–60 s)	F	p	df	R1	R2
2 cm vs. 7 cm	22.7	<.05	58	21.27	23.39
2 cm vs. 12 cm	30.95	<.05	58	21.27	23
2 cm vs. 17 cm	23.74	<.05	58	21.27	23.38
2 cm vs. 22 cm	30.55	<.05	58	21.27	24.22

p. 274). By contrast, when a moving room is used, data collection begins at the onset of room motion (e.g., Lee & Lishman, 1975; Stoffregen, 1985, 1986; Schmuckler, 1997; Stoffregen & Smart, 1998). Given that trials typically are less than 90 s long, the 20 s difference between the two technologies is substantial.

As noted above, in the present study, data collection began 5 s after the onset of stimulus motion for the videographic group, and 10 s after stimulus onset for the moving-room group. Thus, we were not able to analyze postural responses at the onset of stimulus motion. However, we could test for changes over time in the data that were collected. To investigate possible changes in coupling as a function of the time elapsed following stimulus onset, we conducted post hoc analyses contrasting the first 30 s (00–30 s) and last 30 s (30–60 s) of data collected for each trial. New analyses of variance were conducted on the cross-correlation and gain variables, including time (00–30 s vs. 30–60 s) and amplitude of stimulus oscillation (2, 7, 12, 17, and 22 cm), as within-subjects variables, and group (videographic vs. moving room) as a between-subjects variable. Phase was again analyzed using circular statistics. Because texture size had no effect in our initial analyses, it was not included in the post hoc analyses.

3.2.1 Maximum Cross-correlation ($R_{\text{Display-head}}$). The means are presented in Figure 3b and c. The main effect of time was not significant. The interaction between time and amplitude was significant, $F(4,328) = 3.20$, $p < .05$, EI = 0.25%. There were no other significant effects involving time. Repeating our earlier analysis, the main effects of group and amplitude were significant, group: $F(1,82) = 42.37$, $p < .05$, EI = 12.65%, amplitude: $F(4,328) = 7.02$, $p < .05$, EI = 3.87%. There were no other significant effects.

3.2.2 $\text{Gain}_{\text{Display-head}}$. The means are presented in Figure 4b and c. The main effect of time was not significant, and none of the interactions involving time was significant. Repeating our earlier analysis, the main effect of amplitude was significant, $F(4,328) = 59.91$, $p < .05$, EI = 21.93%, as was the group × amplitude interaction, $F(4,328) = 9.92$, $p < .05$, EI = 3.63%.

3.2.3 Relative Phase ($\phi_{\text{Display-head}}$). The means are presented in Figure 5b,c. For the videographic group, phase in the 2 cm condition differed between the two time periods (00–30 s vs. 30–60 s), $F_{\text{Watson-Williams}}(1, 58) = 17.35$, $p < .05$. In this condition, phase lag decreased during the second half of trials. Also for the videographic group, $\phi_{Display\text{-}head}$ in the 2 cm condition during the second half of trials (30–60 s), differed from $\phi_{Display\text{-}head}$ in each of the other stimulus amplitudes (Table 2). Taken together, these results indicate that $\phi_{Display\text{-}head}$ changed over time for the videographic group, but only in the 2 cm condition. There were no other significant effects.

Our post hoc analysis revealed that, with one exception, coupling of body sway with stimulus motion was stable over time for the moving-room group and for the videographic group. The exception occurred in the videographic group for the 2 cm stimulus amplitude. In this condition, cross-correlation and phase were observed to change over time, with the synchrony between body sway and room movements increasing over time.

4 Discussion

Oscillating optical flow was created using a moving room, and using computer graphics presented via video projection. Separate groups of standing subjects were exposed to each type of optical flow. Within groups, we varied the size of texture elements in the optic-flow displays, and we varied the amplitude of optic flow oscillations. We characterized postural responses to imposed optical flow in terms of the cross-correlation, gain, and phase of body motion relative to stimulus motion. We found significant differences in postural responses to optical flow created by the moving-room and the videographic system. Cross-correlation was higher for the moving-room group than for the videographic group. Both groups exhibited a significant phase lag, relative to the stimulus motions; however, the phase lag for the videographic group was significantly greater than for the moving-room group. The gain of postural responses differed for the two groups, but only for the smallest amplitude of stimulus motion (2 cm), where gain was greater for the moving-room group. Contrary to our predictions, variation in the size of texture elements had no effects on postural responses.

Coupling of body sway with stimulus motion in the videographic group was weaker than has been reported in several studies using videographic projection. To better understand the divergence of our findings from the literature, we conducted a complementary analysis, in which we compared the first 30 s of collected data with the final 30 s. This analysis revealed that in the moving room, postural responses were stable over time. For the videographic group, postural responses changed over time for the 2 cm stimulus amplitude condition, but were stable for all other stimulus amplitudes. Overall, the results raise questions about the extent to which different means of generating optical flow produce equivalent information about relations between vision and the control of stance.

The results suggest substantial differences in postural responses to the two technologies for generating optical flow. However, results from the videographic group differ from previous studies using video projection of computer-generated imagery. The interpretation of differences between the current study and previous studies will strongly influence the interpretation of differences between groups within the current study.

4.1 Group Differences

Postural responses to the two methods of generating optical flow differed, with significant main effects and/or interactions in each of the three dependent variables. Our prediction that the cross-correlation between body sway and optical flow would be stronger in the moving room was confirmed by the significant main effect of group and the higher cross-correlation values for the moving-room group (Figure 3). The main effect of group on gain was not significant, and so our prediction that gain would be greater for the moving-room group was not confirmed. Our prediction that group effects on cross-correlation would be most pronounced at smaller amplitudes of stimulus motion was not confirmed; in fact, the groups differed most at larger stimulus amplitudes. Our prediction that group effects on gain would be most pronounced at smaller amplitudes of stimulus motion was confirmed. Finally, our predictions regarding relations between display type and the texture size of display elements were not confirmed: The size of texture elements did not yield significant effects for cross-correlation, gain, or phase. This null result indicates that aliasing related to texture size was not a factor in postural responses to optic flow in the videographic group.

The fact that some of our predictions were confirmed while others were not is less important than the fact that the data revealed that the different types of optical flow were associated with several differences in postural responses to optical flow. Postural responses to optical flow clearly were different for the videographic group and the moving-room group. In the context of relations between posture and vision, this general finding is consistent with our hypothesis that with existing technologies, the presentation of optical flow through video projection of computer-graphics may not be representative of other technologies for generating optical flow. This raises the possibility that current virtual environment systems may not provide a representative simulation of posture-related optical flow, in general.

4.2 The Moving-room Group

For the moving-room group, cross-correlation increased with stimulus amplitude. This result resembles a finding of Fouque and Bardy (1997). Using the same moving room and the same set of five movement amplitudes, Fouque and Bardy observed a U-shaped relation between cross-correlation and stimulus amplitude. The lowest coupling occurred at the 7 cm stimulus amplitude. However, as in the present study, coupling increased steadily from the 7 cm condition to the 22 cm condition. The increase in cross-correlation with increasing stimulus amplitude might be interpreted as an effect of stimulus strength or salience, but such an interpretation would run counter to the facts of natural sway amplitude, which is on the order of 4 cm. An alternative explanation is that at higher stimulus amplitudes, greater coupling facilitated clear vision of the walls (cf., Si, Schneider, & Bierkan, 2001).

The gain data closely resembled those reported by Fouque & Bardy (1997) for the same stimulus amplitudes. The decline in gain with increasing stimulus amplitude reflects the fact that the absolute displacement of the body was approximately constant across conditions.

Our analyses indicated that responses did not change over time. This is consistent with the common practice, when using a moving room to generate optical flow, of beginning data collection at the start of room motion. Our finding, and the common methodological practice, implies that in moving rooms, coupling of body sway with imposed optical flow begins almost immediately.

The phase data have interesting relations to findings of Oullier et al. (2002), who used the same moving room. The moving-room group (mean phase = 18.72°) exhibited relative-phase values similar to those observed in a condition of Oullier et al., in which participants were instructed to use intentional head movements to track motion of the room (24.2°), but differed from a condition in which participants were asked (as they were in the present experiment) simply to look at the front wall (49.4°). One major difference between the two studies is that Oullier et al. varied frequency, while in the present study we varied amplitude. Another was the difference in visual angle: Oullier et al. exposed participants to the entire moving room, while in the present study participants could not see the side walls.

4.3 The Videographic Group

Overall, cross-correlation was only weakly influenced by stimulus amplitude, as shown by the small percentage of variance accounted for by the main effect of stimulus amplitude, and by the significant group × amplitude interaction. The weak relation between stimulus amplitude and cross-correlation echoes a finding of Bardy et al. (1999), who found no relation between stimulus amplitude and cross-correlation. Interestingly, this was true despite a substantial difference in tasks; as in one task in the Oullier et al. (2002) study, Bardy et al. instructed participants to use intentional head movements to track motion of a visual target, whereas in the present study, participants were asked simply to look at the motion stimulus.

For the larger amplitudes of stimulus motion, responses were stable over time, that is, responses during the first 30 s of data did not differ from the last 30 s. This suggests that the common practice, when using videographically presented optical flow, of beginning with an "adaptation period" may be unnecessary. By contrast, in the 2 cm stimulus amplitude condition the synchrony of body sway and stimulus motion improved over time, with an increase in cross-correlation, and a decrease in phase. The generally weak effects of the amplitude of stimulus motion on body sway suggest that (as with our variation of texture size) aliasing was not a significant factor in the results.

The cross-correlation between display motion and body sway for the videographic group was lower than has been reported in other studies that have examined postural responses to videographic optical flow (Van Asten et al., 1988; Dijkstra et al., 1994; Bardy et al., 1996, 1999; Warren et al., 1996). Relative phase between head and stimulus motion was also higher. Both differences were observed even for the second half of trials, which were more directly comparable to previous studies. In previous studies, mean cross-correlations have ranged from 0.32 (Van Asten et al., 1988) to 0.70 (Bardy et al., 1996), and phase has been about 8°. The difference in coupling to videographically presented optical flow between the present study and previous studies might suggest some type of artifact in the present data.

However, there do not appear to be any directly comparable studies, due to variations in methodology. Bardy et al. (1996) and Warren et al. (1996) studied body sway during walking on a treadmill. Coupling could be increased during walking, due to biomechanical changes (cf., Fouque & Bardy, 1997). Dijkstra et al. (1994) presented 3D simulations of the optical consequences of body sway, as compared to the 2D simulations used in our videographic conditions.[3] Van Asten et al. (1988) used a variety of stimulus amplitudes, with the smallest being 1.2 m, as compared to the 22 cm maximum amplitude used in the present study.

Differences in experimental design make it difficult to compare results of the present study with results of previous studies using videographic projection of optical flow. It is possible that our videographic data were influenced by some type of artifact, such as a flaw in the simulation or in projection. But it is also possible that these data represent the real behavior of the subjects, i.e., that they are not artifactual. More research is needed to resolve this issue.

In addition to differences in design, studies using videographic projection of optical flow often are characterized by differences in the selection of experimental participants. When optical flow is presented via videographic projection, a routine outcome is that approximately 30% of subjects exhibit no coupling of body sway with optical flow (Warren et al., 1996). In some studies, participants who do not respond are replaced, so that published data reflect only those participants who exhibited robust coupling. By contrast, in studies using a moving room, subjects have not been replaced; the published data reflect all participants. Published cross-correlation values for moving-room and videographic studies are of similar magnitude. The use of inclusion criteria for videographic studies therefore suggests that for cross-correlation, the population mean for videographic displays may be lower than for moving-room displays.

It is common in studies of relations between vision and posture for participants to include individuals who are familiar with the expected outcome of the research. For example, in the study of Dijkstra et al. (1994, p. 481), there were four participants and "three of the subjects were familiar with the purposes of the experiment." In a later study from the same laboratory, Dijkstra et al. (1994, p. 495) wrote that three of the six participants "were familiar with the purpose of the experiment," and "four subjects had participated in a previous study." In the studies of Van Asten et al. (1988), all of the participants were researchers or students; the article does not indicate whether these included the authors or others who were familiar with the experimental hypotheses. Warren et al. (1996, p. 821), "set a criterion that overall postural sway be significantly correlated with the oscillatory visual display before a participant's data were analyzed in more detail." In addition, "the four *most responsive* participants from Experiment 1 . . . were used in Experiments 2 and 3" (Warren et al., 1996, p. 829, emphasis added). These practices suggest that the coupling reported in previous studies using videographic flow may be artifactually elevated relative to levels that would be found in naive samples. In the present study, the videographic group included only persons who were not familiar with the experimental hypotheses, and participants were not excluded from data analysis on the basis of their performance. This may account for the fact that values of cross-correlation were lower in the present study (videographic group) relative to earlier studies, even when considering only the latter 30 s of trials.

3. Dijkstra et al. (1994) stated that similar results were obtained using a 2D simulation; however, no data were reported.

4.4 Is Behavior Fooled by Simulation?

It is widely assumed that users of virtual environments do not distinguish the depiction from the real world (e. g., Slater, Usoh, & Steed, 1994). However, there have been few direct tests of this assumption (Lathan, Tracey, Sebrechts, Clawson, & Higgins, 2002; for an example in the cognitive domain, see Wilson, Foreman, & Tlauka, 1997). One question that can be asked about virtual environments is whether users experience the simulation per se, or whether they experience an illusion that the simulation is the "real thing." A second question, which is the focus of the present investigation, is whether behavior in virtual environments resembles behavior in the simulated environment. Such a resemblance might be expected if users of virtual environments could not distinguish them from the corresponding real environment. Stoffregen et al. (2003; Stoffregen, 1997) have suggested that virtual environments are specified as such. That is, they have suggested that behavior in virtual environments gives rise to patterns of ambient energy (e.g., in the optic, acoustic, and/or global arrays; Stoffregen & Bardy, 2001) that differ from the patterns produced by behavior in real environments (e.g., Edgar & Bex, 1995). If this is true, and if users detect these differences, then virtual environments could be perceived as such. Perception of virtual environments as such could lead to differences in perceptually guided behavior in virtual and real environments. In the present study, this appears to have been true; that is, the action fidelity (Riccio, 1995; Stoffregen et al., 2003) of the videographic display appears to have been low. Stoffregen et al. noted that the ideal way to assess differentiation of real and simulated environments is to expose participants alternately to paired real and simulated environments (without prior knowledge of which is which). Both subjective (i.e., conscious reports) and objective (i.e. perception-action) data will be relevant.

One implication of our study is that there is a need for direct, experimental comparison of perception and action in virtual environments and in the corresponding real environments (cf., Stanney, Mourant, & Kennedy, 1998; Stanney & Zyda, 2002). Such research is often difficult to perform, but it will be essential if we are to understand the perception and action in both types of environments. In particular, direct comparisons will be needed to support any claim that perception and action in a given virtual environment can be considered to be representative of perception and action in the corresponding real environment.

Our study examined postural control, and it should not be assumed that our findings with posture would generalize to other perception and action tasks. However, our findings suggest that additional research is needed to contrast perceptual-motor performance across a variety of perception-action tasks in the context of virtual and real environments.

An additional qualification to the present study arises from ongoing changes in the technology of computer graphics and video projection. One aspect of technological development will be improvements in both spatial and temporal resolution. These improvements in simulation technology may reduce differences of the type found in the present study. However, this is an empirical question.

5 Conclusion

We observed several differences between postural responses to optical flow generated by a moving room and via computer graphics. Differences in cross-correlation, gain, and phase all suggest that technology used to generate optic flow plays a strong effect on the coupling of body sway to the flow. In addition, our finding that coupling developed over time in one condition for the videographic group is consistent with the fact that studies employing computer-generated optical flow typically delay the start of data collection for up to 30 s after the start of stimulus motion. However, the interpretation of these differences will be influenced by the fact that postural responses to computer-generated optical flow in the present study differed from responses to similar displays in previous studies. Methodological differences among studies make it difficult to interpret the differences between our studies and the literature.

Thus, the proper interpretation of the present results can be realized only through additional research.

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