PERCEIVED SELF MOTION IN VIRTUAL ACOUSTIC SPACE FACILITATED BY PASSIVE WHOLE-BODY MOVEMENT

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ABSTRACT

When moving sound sources are displayed for a listener in a manner that is consistent with the motion of a listener through an environment populated by stationary sound sources, listeners may perceive that the sources are moving relative to a fixed listening position, rather than experiencing their own self motion (i.e., a change in their listening position). Here, the likelihood of auditory cues producing such self motion (*aka* auditory-induced vection) can be greatly facilitated by coordinated passive movement of a listener's whole body, which can be achieved when listeners are positioned upon a multi-axis motion platform that is controlled in synchrony with a spatial auditory display. In this study, the temporal synchrony between passive whole-body motion and auditory spatial information was investigated via a multimodal time-order judgment task. For the spatial trajectories taken by sound sources presented here, the observed interaction between passive whole-body motion and sound source motion clearly depended upon the peak velocity reached by the moving sound sources. The results suggest that sensory integration of auditory motion cues with whole-body movement cues can occur over an increasing range of intermodal delays as virtual sound sources are moved increasingly slowly through the space near a listener's position. Furthermore, for the coordinated motion presented in the current study, asynchrony was relatively easy for listeners to tolerate when the peak in whole-body motion occurred earlier in time than the peak in virtual sound source velocity, but quickly grew to be intolerable when the peak in whole-body motion occurred after sound sources reached their peak velocities.

1. INTRODUCTION

Display systems that are used to reproduce virtual events in highly realistic virtual environments are naturally expected to produce the most convincing results when stimuli presented via multiple sensory modalities are well synchronized [1]. A great deal of attention has been paid to coordinated display within the auditory and visual modalities, but even the best of such bimodal simulations may fail to produce satisfying results when the user is intended to move through a virtual world. Developers of multimodal display technology should be reminded of the following point, stated quite succinctly by Brenda Laurel in a 1993 interview [2]:

> "When we enter a virtual world,
> we bring our bodies with us."

The implications of this statement are quite important to the success of virtual reality applications, primarily because most applications of multimodal display technology present a mismatch between modalities that can break the illusion of reality. The result is a degrading of the observer's sense of presence in the simulated world. In contrast, when multisensory stimulation is coordinated within a more comprehensive simulation, a multimodal display can become so entirely convincing that it can create an experience of the observer's travel through a virtual environment, though observers may be well aware that they are maintaining a relatively fixed position within a reproduction environment while being presented with illusions of self motion.

In the study reported in this paper a pair of virtual sound sources were displayed via a multichannel loudspeaker array for a listener positioned upon a multi-axis motion platform that could be controlled in synchrony with the spatial auditory display. Although the sources could be perceived as moving in relation to the listener's position, listeners could be induced to experience their own self motion by a small but forceful passive movement of their whole bodies. Previous work has shown that such passive movement can interact strongly with visual cues known to dominate the perception of linear self motion [3]. Despite the dominance of visual cues, however, there are situations in which auditory cues alone are available to induce perceived self motion in observers, such as the case in which observers are displaced away from a sound source that is positioned behind them, outside of their field of view (as was done in [4]). And although auditory induction of self motion is relatively weak, auditory information alone has been observed to produce vection, creating both illusions of self rotation [5] and illusions of linear self motion [6]. There is also evidence that simple vibrotactile stimulation can exert an influence on auditory-induced vection [7]. Readers wishing to become more familiar with the literature in this area are referred to the recently published Doctoral Thesis of Aleksander Väljamäe entitled "Sound for Multimodal Motion Simulators" [8].

So in the current study, the motivation was to determine whether passive whole-body movement could be used to facilitate auditory-induced vection for a blind-folded listener. More specifically, the study focused upon the importance of synchrony between the auditory stimulus and the whole-body movement that could be presented via a motion platform upon which listeners were positioned. The amount of motion that could be created was quite small, and did not actually change the overall position of the listeners, who always ended up exactly where they started by the time the coordinated auditory stimulus was terminated. In fact, the motion created both a strong angular acceleration and a strong linear acceleration at a focused point in time, but this was preceded by slower anticipatory movement, and followed by a slow return to the original position and orientation. Thus it might be said that the listener positioned upon a multi-axis motion platform was

indeed "traveling without moving," and only the virtual sources presented via spatial auditory display were actually moving relative to the listener's position in a manner that matched the stimulus expected when that listener moved through an environment populated by stationary sound sources.

Although the virtual sound sources by themselves did not create a strong sense of self motion, an illusory experience of linear self motion was created for some listeners under some conditions when a short-duration whole-body movement was presented in close temporal proximity with the display of two virtual sound sources that simulated movement along paths beginning in front of the listening position, moving close to the listener' head, and terminating behind the listening position. In order to quantitatively measure the extent to which synchrony of the multimodal stimuli influenced this phenomenon, the relative intermodal timing of the displayed components was varied over a range of 500 ms, and listeners were asked to judge which of the two displayed events occurred first, the auditory event or the whole-body motion event. The auditory event was focused in time by having the virtual sound sources reach their peak velocity just as they passed by the listening position, traveling from front to rear as they passed on either side of the listener's position. The whole-body motion event was focused in time by having the platform reach its maximum displacement via a very rapid motion to this peak and back, with much slower platform motion throughout the remainder of an 8-second stimulus presentation.

That listeners were able to make successful judgments of the temporal order of these two events across modalities can be observed in the experimental results reported in this paper. But this observation in itself is not particularly interesting. A more interesting question to be answered here was that regarding the relative timing of the displayed multimodal components: Would asynchrony be easier for listeners to tolerate when the peak in whole-body motion occurs at an earlier time, when compared to an arrival later in time than the time at which the peak in virtual sound source velocity occurs? Another question of interest was that regarding the influence of sound source velocity on the temporal order judgments: Would discrimination performance show that intermodal delays in whole-body movement are more poorly resolved as virtual sound sources are moved at decreasing speeds through the space near a listener's position? The results could have implications for the hypothesis that sensory integration of auditory motion cues with small, forceful passive whole-body movement depends both upon time order of the multimodal components and upon the simulated sound source velocities.

Although the results of this study may be of interest in general to those engaged in research on multimodal interaction, there are also practical applications that call for the investigation that is reported in this paper. In particular, there is growing interest in developing effective multimodal displays that can make distinctions between virtual sound source motion and listener motion, especially under conditions in which the spatial auditory cues alone do not provide a strong basis for such distinctions. An application is envisioned in which a listener is immersed in a virtual acoustic environment and is provided with strong multimodal cues that produce an experience of that listener moving through an environment populated by stationary sound sources. This is in contrast to the typical results of virtual acoustic rendering along, in which listeners often perceive that the sources are moving relative to a fixed listening position, rather than experiencing their own self motion.

2. METHODS

This section describes both the stimulus generation methods and the response method used in the experimental sessions. First, an overview of the employed auditory display and motion control system is presented, along with a description of the selected bimodal stimuli.

2.1. Auditory Display System

The auditory display system employed a 5-channel audio system driving an array consisting of 5 low-frequency drivers and 5 higher-frequency drivers. Although 5 full-range loudspeakers could have been used, the specialized hardware employed here had several advantages, primarily having to do with the planar wavefront that was created by the higher-frequency drivers, which were dipole radiating panels featuring the "Planar Focus Technology" of Level 9 Sound Designs, Inc. of British Columbia. The low-frequency drivers (with cross-over frequency set at maximum) were Velodyne SPL-1000R powered subwoofers placed at positions just below the higher-frequency drivers at the standard angles used in surround sound reproduction (the speaker angles in degrees relative to the median plane were –135, -45, 0, 45, and 135). The speakers in the array were positioned at a two-meter radius from the listening position, and the array was located in a relatively dry room with specially designed acoustical treatment that diffused the early reflections within the reproduction environment. The loudspeaker reproduction utilized only a subset of those composing a spherical array that is located in the Multimodal Shared Reality Lab, a newly constructed laboratory space within McGill University's Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT). This lab features a motion platform that is flush mounted with a raised floor, and is described in the following section.

2.2. Motion Platform System

The passive whole-body movement was created using a motion platform that was capable of moving an observer with three Degrees of Freedom (3DOF) in a home theater setting. The motion was controlled by the Odyssée™ system, commercially available from D-BOX Technology of Quebec. The Odyssée™ system [9] uses four coordinated actuators to enable control over pitch and roll of the platform on which the observer's chair was fixed. When all four actuators move together, observers can be displaced linearly upwards or downwards, with a very quick response and with considerable force (the feedback-corrected linear system frequency response is flat to 50 Hz). The magnitude of motion that was typically presented could be measured a number of ways, but for the current study it should suffice to report the maximum RMS value presented in the vertical direction. This peak in acceleration was measured at the observer's foot position to be 1.3 m/sec^{2,} (using a B&K Type 4500 accelerometer and a Type 2239B controller).
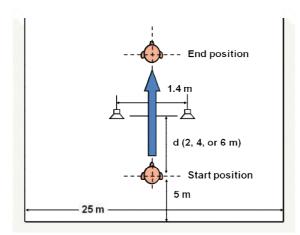
Figure 1. *Graphic showing the simulated path taken by the listener through a virtual room, and passing between two virtual sources (which are indicated by the loudspeaker symbols in the graphic). The listener's path began at a "Start position" that was either 2, 4, or 6 meters from the plane containing the two sound sources, and the listener's position was smoothly varied along a straight line over an eight-second period until the listener reached an "End position" (that was also 2, 4, or 6 m from the two sound sources). The delay, gain, and angle of three simulated reflections were based upon the changing position of the listener relative to the two side walls and the one rear wall of the virtual room (and no reflections were simulated for the front wall, ceiling, or floor).*

2.3. Multimodal Stimulus Generation

The two virtual sound sources (bowed violin sounds with vibrato) were treated as stationary sound sources and were processed to match the auditory cues that would be available to localize them relative to a listener who moved through a virtual acoustic environment. The two sound sources were separated in musical pitch by a minor third at A3 (220 Hz) and C4 (262 Hz). The two input dry sound signals were processed using a custom sound spatialization algorithm simulating time and level differences, and source-velocity-dependent Doppler shift effects. A detailed description of the algorithm is beyond the scope of this paper, but can be though of as a partial implementation of the "spatial reverberation" algorithm described first in [10]. The implementation can be described briefly as follows: To the dry direct sound was added diffuse late reverberation and three simulated early reflections, the delay, gain and simulated spatial angle of which were computed using a simple image source method. Thus, each individual reflection also had the appropriate Doppler shift associated with the modulation of their delay times based upon the model virtual room, and furthermore varied in level based upon the inverse square law, just as did the level of the source as the length of the path of propagation was varied.

Figure 1 shows the simulated path taken by the listener through a virtual room (see figure caption for details). The A3-sound source was moving on a path that came close to a position just to the left of the listener, while the C4-source was moving just to the right of the listener. Figure 2 shows the source velocity functions over time for the three simulated paths that varied also

in the simulated distance traveled (solid lines, in blue). The maximum sound pressure level (SPL) reached by the stimuli during the course of their presentation was measured at each of the three simulated stimulus velocities. Using a RadioShack model 33-2055 sound level meter in the A-weighting, fast-response mode, the maximum SPL was found for all three stimuli to be 85 dBA at the listening position. Upon these three temporal profiles is superimposed the temporal profile for the angular deflection of the motion platform, plotted using the (red) dashed line. As can be seen from the degree values labeling the right side of the plot in Figure 2 (also in red), the amount of angular deflection was quite minimal, reaching a peak value of one degree. This peak value was shifted forward or backward in time by 125 or 250 ms relative to the plotted sound source velocity profiles to create four other intermodal-delay conditions. A controlled amount of linear motion of the listener's head was associated with the plotted angular deflection, since the pivot point of the motion platform was near the level of the listeners' feet, rather than their heads. In order to reduce the chance that listeners would use mechanical noise of the motion platform in their judgments, a small upward and downward vibration was added to platform motion. To generate this vibration, low-pass filtered white noise was used. The cutoff frequency was 50 Hz. The maximum amplitude of this vibration was 0.06 cm (7/320 inch).
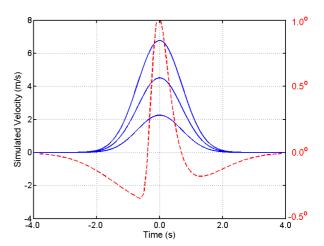

Figure 2. *The temporal profiles of presented multimodal stimuli. The solid lines (in blue) plot simulated sound source velocity (m/s) as a function of time (s). Velocity values for the y-axis are labeled on the left side of the plot. Note that the peak in sound source velocity occurs at "Time Zero" for all three sound source paths that were presented, and that simulated velocity was only substantial during four of the eight seconds of the sound stimulus duration. The dashed line (in red) plots the angular deflection (degrees) of the motion platform over time with the degree values labeled on the right side of the plot (also in red). Due to the alignment of the peak angular deflection with the peak velocities, the plotted case was nominally regarded as "synchronized." The other four conditions were created by shifting the angular deflection profile to present intermodal delay values that differed from this case by 125 or 250 ms.*

2.4. Time Order Judgments

The method of constant response was utilized to estimate the point of subjective simultaneity (PSS) with regard to the intermodal delay between auditory and whole-body motion stimuli. The procedure employed for the time order judgment (TOJ) sessions required listeners to complete three sessions of 30 trials within which all of 15 stimuli were presented twice according to a randomly intermixed order. The 15 stimuli comprised the factorial combination of three sound source velocities and five intermodal delay values. If the peak motion of the platform seemed to occur earlier than the peak velocity of the virtual sources (associated with the point in time at which the sources approached the listener's head most closely), then the listener was to give the verbal response of "Platform Earlier." Alternatively, the listener could report "Platform Later." All trials were completed in separate one-hour experimental sessions by each of six listeners (two females and four males, all of whom participated voluntarily).

3. RESULTS

The results of the TOJ experiment can be summarized in terms of the shifting of the PSS values as a function of the peak simulated velocities of the sound sources, which in the three conditions were 2.3, 4.5, and 6.8 m/s. The proportions of 'Platform Later' responses obtained for a single listener are plotted in Figure 3 as a function of the time lag between platform peak motion and time at which the sound sources reached their peak velocities. Logistic regression analysis was employed to fit a smooth curve to the five response proportions observed at each velocity, and the PSS was defined as the intercept of these smooth curves with the line at $y=.5$.
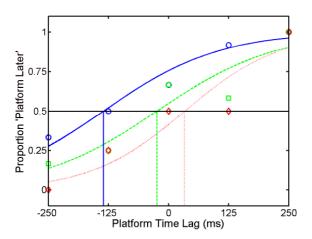

Figure 3. *The proportion of 'Platform Later' responses made by a single listener, plotted as a function of the time lag between platform peak motion and time at which the sound sources reached their peak velocity. Negative "Platform Time Lag" values indicate that peak platform motion preceded peak sound source velocity. Circular symbols plot the resulting proportions for sound sources with a peak velocity of 2.3 m/s, square symbols for a peak velocity of 4.5 m/s, and diamond symbols for a peak velocity of 6.8 m/s. The parameter of the curves fit to the data is the peak velocity attained by the sound sources, with the solid line, dashed line, and dotted line used to indicate the three sound-source velocities.*

At the three tested sound source peak velocities, the PSS values calculated from the responses of this one listener were -135ms, --13ms, and 34ms, observed at the slow, medium, and fast velocities, respectively. The dependence of the proportion of 'Platform Later' responses upon velocity is quite clear for this listener. Indeed, for the slowest peak velocity at which the sound sources were presented, this first examined listener showed strong dominance of the "Platform Later" response only when the peak platform motion occurred later. In contrast, this listener was not so likely to report the platform motion as occurring too early even when it preceded the two slower-velocity peaks by 250 ms. A similar pattern of PSS values was observed for all six listeners, although the average PSS values calculated for the whole group were always negative (in contrast to the one positive value found at the fastest source velocity for the first listener, whose data were shown in Figure 3). These results combining the data from all six listeners are summarized in Figure 4.
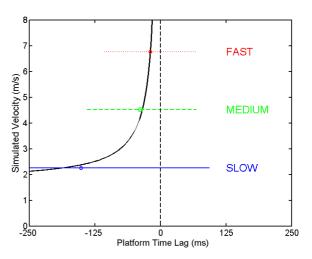

Figure 4. *Plot showing the results of analysis of TOJ data averaged across six listeners. The circular (blue) symbol plots the PSS for sound sources with a peak velocity of 2.3 m/s, the square (green) symbol the PSS at a peak velocity of 4.5 m/s, and the diamond (red) symbol the PSS at a peak velocity of 6.8 m/s. The smooth (black) curve was fit to the stimulus peak velocity data as an inverse function of the PSS values. At each of three sound-source velocities, and drawn in parallel to the x-axis, are lines indicating the distance between the first and third quartiles averaged over all listeners. Each distance (aka interquartile range, or IQR) indicates the time span over which the proportion of 'Platform Later' responses rises from the .25 point to the .75 point. These IQR lines are plotted using the same colors as the symbols used to plot the corresponding PSS values, and are also labeled at y-axis positions corresponding to sound source peak velocity in the three conditions tested (SLOW, MEDIUM, and FAST). Again, as in Figure 3, negative "Platform Time Lag" values indicate that peak platform motion preceded peak sound source velocity.*

The average PSS values shown in Figure 4 for six listeners got closer to the vertical "Time Zero" dashed line as the peak sound source velocity increased. In order to model quantitatively this trend, a smooth curve was fit to the auditory

stimulus peak velocity value as an inverse function of the obtained average PSS values. The assumption that was made here was that, within a reasonable maximum velocity limit, the PSS will retrogress toward a perfect match with the peak in the temporal profile for platform motion. The corresponding horizontal lines drawn through the average PSS values show the average interquartile range (IQR) values at the same sound-source peak velocities. So as the sound-source velocity increased (labeled SLOW, MEDIUM, and FAST in Figure 4), the offset in time of the PSS decreased, and the IQR decreased as well.

4. DISCUSSION

During the course of this study it was observed that when moving sound sources were displayed for a listener in a manner that was consistent with the motion of a listener through an environment populated by stationary sound sources, listeners did indeed perceive self motion when the displayed virtual sound source motion was coordinated with passive whole-body movement. However, the experimental results reported herein do not provide any direct indication of the magnitude nor the character of such perceived self motion. Rather, the obtained results bear primarily on a listener's tolerance for temporal asynchrony between passive whole-body motion and auditory spatial information. As the phenomenon of self vs. sound-source motion was investigated via a multimodal time-order judgment task, the results can be interpreted only indirectly with regard to the vection that resulted from the multimodal display. Nonetheless, the results suggest that sensory integration of auditory motion cues with whole-body movement cues can occur over an increasing range of intermodal delays as virtual sound sources are moved increasingly slowly through the space near a listener's position, and one explanation for such sensory integration is that the stimuli were consistent with self motion. A cognitive analysis might also provide a reasonable explanation for this finding. It may be natural for a listener to expect to move toward a source well before that source grows close to the listener's position, if it were indeed the case that the source was stationary; however, when a source passes by the listener just before that listener begins to move rapidly toward it, such an expectation cannot so easily operate. Therefore, it might be said that a cognitive dissonance would occur in the latter case, since the implied self motion and relative motion of the presented sound sources do not form such a coherent picture.

It is also worth discussing how the current results relate to previous results using similar multimodal display systems. In one such study [11], participants made magnitude estimates for the speed of moving sound images, and judgment of goodness of movement matching between auditory motion and whole-body motion that was controlled via a front/rear pivot of the same motion platform as that used in the current study. The resulting magnitude estimates showed that pivot magnitude significantly affected the estimated velocity of sound sources whenever there was a convincing match between auditory information and whole-body acceleration information. Since the quality of the multimodal match was judged by the same participants, their velocity estimates could be related to these reports, which indicated that poor matching was the result when the velocity of moving sound sources was extremely high or low. Just as was suggested in the results of the current study, these other results suggested that multimodal interaction occurs most strongly when participants perceive a single, well-integrated event. The implications of this observation should be clear for potential applications.

One natural application for which multimodal stimulation has clear benefit would be scientific visualization accompanied by sonification, since allowing an observer to travel through the abstract space in which data has been rendered enables superior exploratory analysis. Knowing where one is in that abstract data space, and how one is traveling through it, can potentially reduce cognitive load, allowing observers to pay more attention to the data itself, rather than requiring them to cognize their path through the space. Thus, users of such a multimodal display system could not only direct their attentions with more clarity, but should be able to naturally steer their own point of view to provide perspectives of interest on the data.

Although there may be many applications that could benefit from coordinating passive movement of a listener's whole body with auditory cues to self motion, it is most likely that the most appreciable differences will be made under conditions when listeners are "taken for a ride" through a virtual acoustic environment, rather than conditions in which listeners actively control their movement through that environment. This view is based upon observations that active localization is quite good even when a listener is given only fairly simple cues from a basic virtual auditory display that approximates most of the primary cues to range and azimuth changes (e.g., see [12]). It is easy to understand that when changes in the sound signals reaching the ears are dependent upon voluntary navigational motion of the listener, there is an advantage in interpreting these signals as resulting from listener motion (though observers may be well aware that they are maintaining a relatively fixed position within the reproduction space). However, when listener motion is passive, there is a need for additional information to reveal that motion, and so coordinated multisensory stimulation is to be recommended as a means to disambiguate the auditory cues that are delivered via virtual acoustic rendering. Two additional likely "passive motion" applications will be suggested hereafter.

First, moving observers though virtual architectural spaces seems to be a very practical application for such coordinated multisensory stimulation, especially since the acoustical behavior of a space prior to its construction can afford insights that have the potential to save on costly retrofits when acoustical treatment is needed. More realistic impressions of motion provided by passive whole-body motion could easily make a non-interactive "walkthrough" or "flythrough" a greater source of such insights. Secondly, there are natural applications of such coordinated multisensory stimulation in the arts. For example, a popular form of electroacoustic music has come to be called "Spatial Music," in which the spatial component of a composition plays an important role in its creation. Of course, the audience may not be able to appreciate fully the spatial component if they do not hear the musical sound sources moving as the composer intended. For some spatial music composition, creating cues to audience movement may be quite interesting, and indeed there has been some interest in producing such a multimodal realization of a piece at the Multimodal Shared Reality Lab within McGill's CIRMMT.

One composition in particular is worth presenting in this context, as work already has begun to create a multimodal realization of it using the motion platform that was used in this study. The piece is Gary Kendall's "Five Leaf Rose," which was first presented over 25 years ago [13]. In this four-channel piece, the composed musical notes moved past the audience from the two front loudspeakers towards the two rear

loudspeakers, according to the observer moving forward though the composed space. Of course, it was difficult for audience members to imagine that they were moving on the implied path. However, in the multimodal realization of the piece, the audience can be informed of their movement via the motion platform as they are taken passively on the designed path though that space. Progress on this project was described in a presentation [14] at a recent CIRMMT workshop on "Multimodal Influences on Perceived Self Motion."

5. CONCLUSIONS

In this study a listener's tolerance for temporal asynchrony between passive whole-body motion and auditory spatial information was investigated via a multimodal time-order judgment task. The obtained results suggest that sensory integration of auditory motion cues with whole-body movement cues can occur over an increasing range of intermodal delays as virtual sound sources are moved increasingly slowly through the space near a listener's position. Most interesting was the finding that asynchrony could be relatively easily tolerated when the listeners' whole-bodies were moved before the virtual sound sources passed by the listening position. In contrast, and especially for more slowly moving virtual sound sources, whole-body motion that occurred after the virtual sound sources passed by the listening position were much more difficult to tolerate, and this difficulty could be related to the TOJ data obtained from six listeners as follows: Whole-body motion that occurred later was associated with more extreme TOJ proportions in comparison to whole-body motion that occurred earlier, yet at comparable absolute values of intermodal delay. It was suggested that listeners are more inclined to experience convincing sensory integration when they begin to move toward a source well before that source approaches their position, since a cognitive dissonance can occur when a source passes by just before a listener begins to move toward it.

6. ACKNOWLEDGEMENTS

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