THE INTERACTION BETWEEN HEAD-TRACKER LATENCY, SOURCE DURATION, AND RESPONSE TIME IN THE LOCALIZATION OF VIRTUAL SOUND SOURCES

Douglas S. Brungart
Brian D. Simpson
Richard L. McKinley

Air Force Research Laboratory
2610 Seventh Street
WPAFB, OH 45433
douglas.brungart@wpafb.af.mil
brian.simpson@wpafb.af.mil
richard.mckinley@wpafb.af.mil

Alexander J. Kordik[1]
Ronald C. Dallman[2]
David A. Ovenshire[2]

[1]Sytronics, Inc
[2]General Dynamics
Dayton, OH
alex.kordik@wpafb.af.mil
ron.dallman@wpafb.af.mil
david.ovenshire@wpafb.af.mil

ABSTRACT

One of the fundamental limitations on the fidelity of interactive virtual audio display systems is the delay that occurs between the time a listener changes his or her head position and the the time the display changes its audio output to reflect the corresponding change in the relative location of the sound source. In this experiment, we examined the impact that six difference headtracker latency values (12, 20, 38, 73, 145 and 243 ms) had on the localization of broadband sound sources in the horizontal plane. In the first part of the experiment, listeners were allowed to take all the time they needed to point their heads in the direction of a continuous sound source and press a response switch. In the second part of the experiment, the stimuli were gated to one of eight different durations (64, 125, 250, 375, 500, 750, 1000 and 2000 ms) and the listeners were required to make their head-pointing responses within two seconds after the onset of the stimulus. In the open-ended response condition, the results showed that latencies as long as 243 ms had no impact on localization accuracy, but that there was an increase in response time when then latency was longer than 73 ms. In contrast, the data from the time-limited response conditions showed that latencies that exceeded 73 ms had no impact on response time but that they significantly increased the angular localization error and the number of front back confusions. Together with the results of earlier studies, these results suggest that headtracker latency values of less than 70 ms are adequate to obtain acceptable levels of localization accuracy in virtual audio displays.

1. INTRODUCTION

A fundamental requirement of all interactive virtual audio display systems is the ability to quickly update the virtual sound field in response to the movements of a listener's head. These exploratory head movements play a number of critical roles in human sound localization. They help listeners distinguish between sound sources located at equivalent lateral positions in the front and rear hemispheres [1, 2]. They influence the perception of elevation, particularly for low frequency sounds [3]. They allow listeners to increase their spatial acuity by orienting themselves directly towards the sound source [4]. And they also play a crucial role in increasing the realism and immersiveness of virtual audio simulations [5].

However, because of the limitations inherent in virtual audio display systems, it is not always clear that the users of these systems are obtaining as much useful information from exploratory head motions as they would if they were listening in the real world with their own ears. In the real world, there is no time delay between the movement of a listener's head and the corresponding change this movement produces in the sounds reaching the two ears. Unfortunately, this kind of instantaneous responsiveness is not feasible with the current generation (or possibly any future generation) of virtual audio displays. All current display systems introduce some delay between the time the head is moved to the time the sound field is updated. These delays come from a number of sources, including the latency of the actual tracking device, the communications delay between that device and the audio display, the time required to select the appropriate head-related transfer function (HRTF) and switch to that HRTF, the processing time required for the HRTF filtering, and any output buffering that occurs between the digital filtering of the sound and its eventual presentation to the listener over headphones [6].

Additional complications can occur when head-coupled virtual audio display systems are integrated into larger, more complex systems that may include several subsystems that all require headtracking information at the same time. In an aircraft cockpit, for example, headtracking information might be used by an audio display, a head-mounted visual display, and also for other purposes such as target cuing. When this occurs, it is not always clear how to prioritize the routing of the headtracker information to the different competing components within the system. It might be necessary to have the headtracker directly coupled with one system, such as the visual display, and then have this intermediate system pass the information on to other subsystems through a separate communications channel. In these complex systems, there may be important tradeoffs between total system cost and the headtracker latency of the virtual audio display. Thus, the impact that headtracking delays have on the virtual audio display performance is a question of great theoretical and practical interest for the designers of spatial audio systems.

Although a number of researchers have examined the effects of headtracker latency on sound localization, the results have not been completely consistent. Some researchers have reported that headtracker latencies as large as 150 ms [7] or even 500 ms [8, 9] have relatively little impact on the localization of virtual sounds. Other researchers have reported significant increases in localization error and response time for headtracker latencies as small as 93 ms [10]. Wenzel has suggested that the difference between these studies could be accounted for by the fact that the listeners with the 500 ms headtracker delays were exposed to relatively long-duration stimuli (8 s) while those with the 93 ms headtracker delays heard only short stimuli (roughly 2 s long). However, it is important to note that the listeners in the study with 93 ms latency were not required to respond quickly: they were given as long as they wanted to make their head-pointing localization responses, and they chose to respond after about two seconds. In this paper, we present the results of an experiment that looked at the effects of headtracker latency with a wide variety of short stimulus durations (64 ms to 2000 ms) in a paradigm that required the listeners to make their localization responses very quickly. The results are discussed in terms of their implications for the design of virtual audio display systems.

2. METHODS

2.1. Virtual Audio Display System

The experiments were conducted with the General Dynamics 3D Virtual Audio Localization System (3DVALS) II audio display system, a custom-designed virtual audio display that combines two commercially available DSP processing boards (Texas Instruments TMS320C6211 Evaluation Boards) with a PC104 pentium control computer and a custom-built backplane with twelve 24-bit A/D converters and two stereo 24-bit D/A converters. The basic processing path within the system is that the head-tracker data arrives at one of the two DSP boards where it is used to look up the indices of the appropriate HRTF filters. Then these indices are passed to the second board where they are used to update the HRTFs used to process the input signal. This separation of the I/O and filtering functions of the display allows the HRTF filters to be updated very quickly with almost no buffering delays between the changing of the filter and the updating of the output signal.

For the purposes of this experiment, the 3DVALS system was set into 2D mode, where it uses headtracker information (collected from an Intersense IS-300 headtracker) to switch between 360 possible 126-point head-related transfer function (HRTF) filters, one for each 1° in azimuth in the horizontal plane. The filters used in this experiment were linear-phase FIR filters created at a 48 kHz sampling rate from HRTF measurements that were made every one degree in azimuth at a distance of 0.5 m from the center of the head of a Knowles Acoustic Manikin for Auditory Research (KEMAR) [11]. The processed stereo signals were then presented to the listener via stereo headphones (Beyerdynamic DT-990). For the purposes of this experiment, the software of the 3DVALS was modified to make it possible to artificially increase the latency of the headtracker by buffering the location information sent by the tracker in a first-in first-out (FIFO) queue. The next section describes how the operation of this feature was experimentally verified.

2.2. Latency Measurement Procedure

Figure 1 shows the measurement procedure that was used to determine the headtracker latency of the 3DVALS system. This procedure, which is similar to the one used by Miller et al. [6], was designed to measure the total end-to-end latency of the system from the time the head position changed to a particular location in space to the time the audio output of the system changed to the HRTF associated with that location. First, a set of test HRTFs was downloaded to the 3DVALS system. These test HRTFs consisted of 360 HRTF files, one for each possible relative source angle in azimuth. One HRTF (the one associated with 0° azimuth) was set as a passthrough filter (i.e. a single digital impulse). All of the coefficients of the other 359 HRTFs were set to zero. Thus, the 3DVALS was effectively configured to produce audio output only when the relative source angle was exactly 0° in azimuth.

The headtracker connected to the 3DVALS, an Intersense IS-300, was mounted in the center of a freely rotating disk. This disk was equipped with a small eyelet that could be used in conjunction with an optical switch to determine when it was rotated within 1° of a known orientation. The output of this switch was attached to the trigger of a digital timing analyzer, which could be used to detect the delay between the time the disk moved into alignment with the known position and the time when a positive signal was detected at the audio output of the 3DVALS. This audio output was driven by a 20 kHz sinewave input signal, and it was full-wave rectified to reduce the maximum lag between its onset and the triggering of the timing analyzer to roughly 25 μs.

Prior to each trial, the rotating disk was aligned to produce a positive output from the optical switch and a “Boresight” command was issued to the 3DVALS to define that position as 0° azimuth. Then the disk was moved away from this position, the trigger on the digital timing analyzer was reset, and the disk was manually rotated through the 0° point. The delay between the 0° alignment of the disk and the audio output of the 3DVALS was recorded, and the procedure was repeated for a total of 10 measurements for each of 10 nominal latency settings for the 3D VALS (0, 20, 40, 60, 80, 100, 120, 140, 160, 180 and 200 ms) and each of three output baud rates for the IS-300 tracker (9.6, 19.2 and 38.4 Kbps).

The results of these measurements are shown in the right two panels of Figure 1. The bars in the middle panel show the mean latency values for each of the three measured headtracker baud rates in the baseline condition with 0 ms of nominal latency. The error bars shown the standard deviations across the ten measurements made in each condition. As expected, both the mean latency value and variability in the latency were lowest in the 38.4 Kbps condition and highest in the 9.6 Kbps condition. This reflects the fact that the head position records were transmitted less frequently from the headtracker to the 3DVALS in the lower baud-rate conditions. Also, it should be noted that the custom architecture used in the 3DVALS system produced substantially lower mean latency values (12.6 ms @ 38.4 Kbps) than the 29ms-33.8ms minimum values reported for other systems that have been used to examine the effects of headtracker latency on auditory localization (29-33.8 ms with headtrackers operating up to 115 Kbps [10, 8, 9, 6]).

The right panel of Figure 1 shows the end-to-end latency of the 3DVALS as a function of the nominal desired amount of additional latency D that was introduced by buffering the appropriate number headtracker records in a FIFO queue. A linear fit of these data indicates that the actual mean end-to-end latency was approximately 11.7 + 0.95*D ms, with a mean standard deviation of less than 1.5 ms.

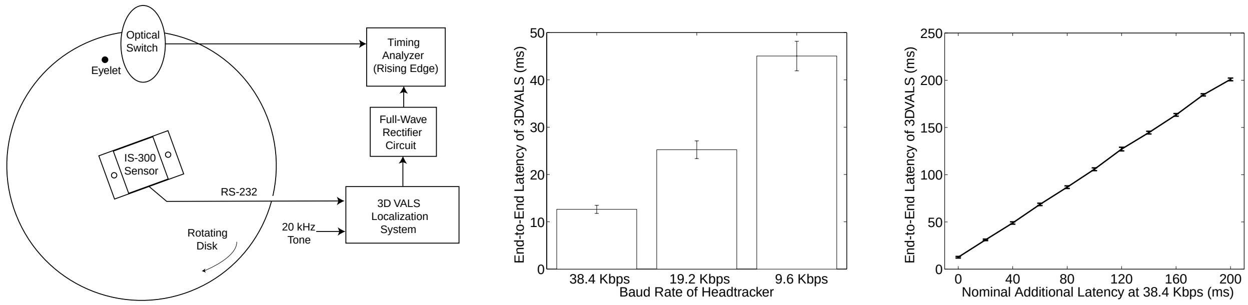

Figure 1: *Measurement of end-to-end latency in the 3D VALS system. The left panel shows the apparatus was designed to measure the delay between the time the orientation of a rotating headtracking sensor changed to 0° azimuth and the time a measurable output was produced from an audio display system that was programed to have a null HRTF at all locations except 0° azimuth. The middle panel shows baseline end-to-end latency of the system ± 1 standard deviation for each of the three headtracker baud rates tested. The right panel shows latency ± 1 standard deviation for nominal additional latency setting of 0 to 200 ms with the headtracker baud rate set at 38.4 Kbps. See text for details.*

2.3. Experimental Design

2.3.1. Participants

Seven paid volunteer listeners, four male and three female, participated in the experiment. All had normal hearing ($<$ 15 dB HL from 500 Hz to 8 kHz), and their ages ranged from 21-24 years. Five of the seven listeners had participated in previous experiments involving both real and virtual localization. All subjects completed at least two training blocks in order to acquaint them with the procedure, and the two naive subjects completed two additional blocks of training to gain additional experience with auditory localization prior to the start of the experiment.

2.3.2. Stimuli

The stimuli in the experiment consisted either of continuous broadband noise or broadband noise bursts that were rectangularly gated to of one of eight different durations (64, 125, 250, 375, 500, 750, 1000, or 2000 ms). These noise stimuli were generated in real time with a control computer running MATLAB, and then output through the sound card at a 44.1 kHz sampling rate to the audio input of the 3DVALS system.

2.3.3. Procedure

The experiment was conducted with listeners located in a sound-treated listening room. A CRT was set up outside of a window in the sound room to allow the listeners to receive information during the experiment. Prior to the start of each trial of the experiment, the listener was asked to turn to face directly at this CRT and press the response switch. This response was used to "boresight" the headtracker by assigning that location to 0° azimuth. Then the stimulus was randomly presented at one of 24 azimuth locations in the horizontal plane (spaced roughly 15° apart), and the listener was asked to respond by turning to face directly at the apparent location of the stimulus and press the response switch. Then the listener turned back to face directly at the CRT to boresight the headtracker for the next trial, and the CRT was used to provide visual feedback about the location of the target stimulus, the location of the response, and the angular error between these two locations.

Each experimental session was conducted with one of six possible headtracker latency values (12, 20, 38, 73, 145 and 243 ms of mean end-to-end latency as measured by the procedure described in Section 2.2), with the order of the latency values randomized across listeners. The first 12 trials of each session were conducted with the continuous stimulus, and the listeners were instructed that they could take as long as they needed to make their responses in these trials. At the end of these 12 trials, the listeners were instructed that they would have to make their subsequent responses within a two-second time window, and that trials that produced responses that were not made within two seconds would be discarded and added in random order to the end of the block. Then they participated in a total of 96 additional trials, 12 repetitions with each of the eight possible stimulus lengths tested in the experiment. At the end of the block, they were told the mean azimuth error across all the trials in that session.

Each of the seven subjects participated in a total of 24 of these experimental sessions, four for each of the six possible latency values tested in the experiment. Thus, each subject participated in a total of 2596 trials in the experiment (4 repetitions X 24 speaker locations X 6 latency values X 9 stimulus durations).

3. RESULTS

Figures 2 and 3 provide three different measures of the effects that headtracker latency and stimulus duration had on overall angular localization accuracy in the experiment. The top panels of the figures show the mean absolute angular errors that occurred in each condition. The middle panels show the percentages of front-back reversals that occurred in each condition. These reversals were defined as trials where the target stimulus was located in the front hemisphere and the listener's response was in the rear hemisphere or the target was in the rear hemisphere and the target was in the front hemisphere. The bottom panels show the mean left-right angular errors in each condition. These errors represent the mean absolute angular errors that occurred after the front-back confusions in the listeners' responses were corrected by reflecting them across the frontal plane into the same hemisphere as the stimulus location. The individual subject scores for each of these error metrics were also analyzed with two-factor within-subjects repeated-measures

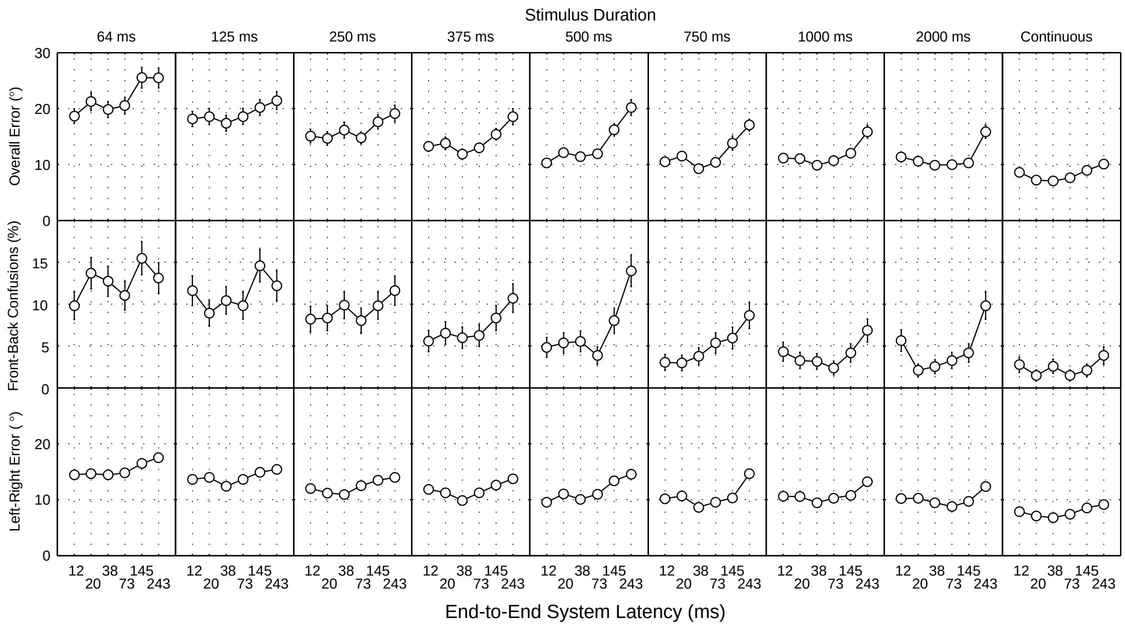

Figure 3: Effects of stimulus duration and headtracker latency on overall localization accuracy in the experiment. The top panels show the mean absolute angular error in each condition. The middle panels show the percentages of front-back reversals in each condition, where reversals were assumed to occur whenever the stimulus was in the front hemisphere and the response was in the rear hemisphere or vice-versa. The bottom panels show the mean left-right errors in each condition, which is the mean absolute error in azimuth after correcting the responses for front-back confusions. The error bars indicate ± 1 standard error around each data point.

ANOVAs conducted on the experimental factors of latency and duration[1].

Figure 2 shows the overall results for the main effects of duration and latency, which were statistically significant at the $p < 0.0001$ level for all three measures of localization accuracy. The duration results (left column) show that the angular errors and front-back reversals both decreased systematically as the stimulus duration increased from 64 ms to 2000 ms, and that performance in the continuous-stimulus condition was better than in any of the time-limited response conditions of the experiment. The latency results (right column) show that the mean localization error was roughly flat for latencies from 12 ms to 73 ms, and that it increased systematically as the latency increased to 145 ms and 243 ms. Averaged across all the duration values, the percentage of front-back reversals increased from 6% to 10% and the mean absolute angular error increased from 13° to 18° as the headtracker latency increased from 12 ms to 243 ms. Post-hoc tests (Fisher LSD) indicate that the performance in the 243-ms latency condition was significantly worse than in any of the other conditions in all three performance metrics ($p < 0.02$), and the the number of front-back reversals was significantly worse in the 145-ms latency condition than in any of conditions with latencies of 73 ms or less.

Figure 3 shows the interaction between duration and latency, which was also statistically significant at the $p < 0.05$ level for both the front-back reversal percentages and the mean absolute angular errors. These results show that the listeners' responses were least sensitive to latency in the conditions with very short ($<=$ 125 ms) and very long (continuous) stimulus durations, and most sensitive to latency in the conditions with intermediate (375-750 ms) stimulus durations. In the short duration conditions, the listeners may have been relatively insensitive to headtracker latency because the stimuli were not on long enough to allow them to make exploratory head movements. In the continuous stimulus condition, the listeners had time to move their heads slowly enough to minimize the effects of latency on their localization responses. However, the 2000 ms stimulus was clearly not long enough to allow the listeners to compensate for the 243 ms latency condition: the 243-ms latency value produced nearly twice as many front-back reversals and more than 50% larger angular errors than any of the other latency values in the 2000 ms duration condition.

It is also interesting to note that front-back confusions could account for most, but not all, of the degradation in localization performance that occurred when the latency of the system increased. The data from the left-right error dimension show a slight increase in error in the high-latency conditions for all the stimulus lengths tested in the time-limited response portion of the experiment.

3.1. Response Times

Figure 4 shows the impact that increased headtracker latency had on the listeners' response times. The left panel of the figure shows the reaction time data for each of the six latency conditions tested in the continuous condition of the experiment, where the listeners were given as much time as they desired to make their localization responses. These data show that the response times varied in a narrow range (2280-2380 ms) as the latency increased from 12 to 73 ms, but then increased to 2580 when the latency increased to 135 ms and to more than 2800 ms when the latency was increased to 243 ms. At the same time, the data in Figures 3 show

[1]The percentages of front-back reversals were arcsine-transformed prior to conducting this analysis

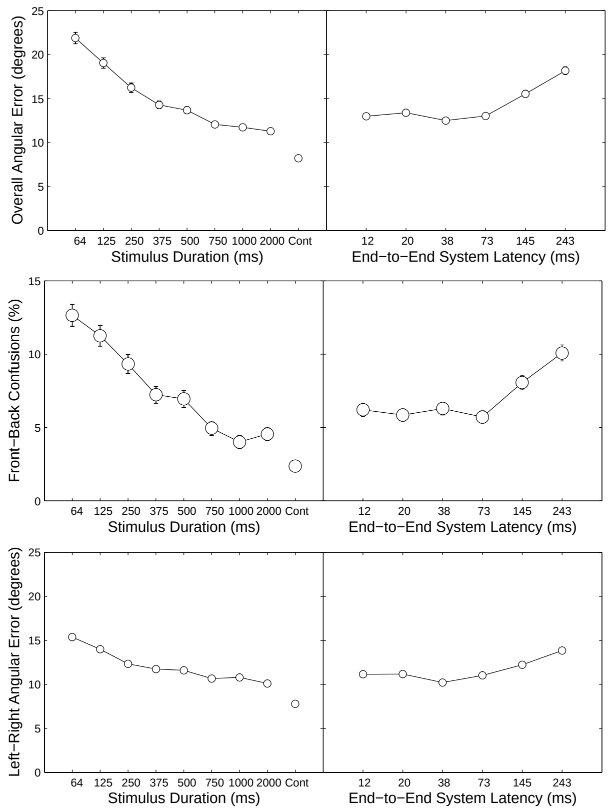

Figure 2: *Effects of stimulus duration and headtracker latency on overall localization accuracy in the experiment. The top panel shows the mean absolute angular error in each condition. The middle panel shows the percentage of front-back reversals in each condition, where reversals were assumed to occur whenever the stimulus was in the front hemisphere and the response was in the rear hemisphere or vice-versa. The bottom panel shows the mean left-right error in each condition, which is the mean absolute error in azimuth after correcting the responses for front-back confusions. The left column shows overall performance averaged across all the latency values tested at each stimulus duration value. The right column shows performance averaged across all the stimulus durations tested at each latency value. The error bars indicate ± 1 standard error around each data point.*

that latencies above 73 ms had very little impact on localization accuracy in the continuous-stimulus condition of the experiment. Thus, it seems that listeners are able to make accurate localizations responses with high-latency virtual audio displays, but that these responses take substantially longer than they do with lower-latency display systems.

The right panel of Figure 4 shows the reaction time data for the main portion of the experiment where the listeners were given only two seconds to make their localization responses. The mean response times of each individual subject in each condition were also analyzed with a 2-factor, within-subject, repeated-measures ANOVA with latency and stimulus duration as the two factors. This analysis showed that there was a significant main effect of stimulus duration ($F_{(7,42)} = 36.1$, $p<0.0001$), as indicated by the overall increase in reaction time with increasing stimulus length

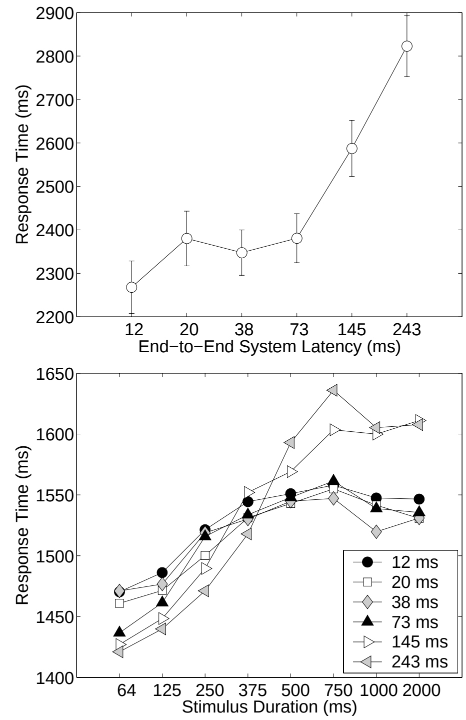

Figure 4: *Response time data. These two panels show the mean time delay between the onset of the audio stimulus and the pressing of the response button in each condition of the experiment. The left panel shows response time as a function of headtracker latency in the continuous-stimulus trials where the listeners were given as long as they needed to make their responses. The error bars in that panel show ± 1 standard error around each data point. The right panel shows response time as a function of stimulus duration for each latency condition (indicated in the legend) tested in the the main portion of the experiment, where the listeners were required to make their responses in less than 2 seconds.*

exhibited by all of the curves in the figure. Overall, the response time increased approximately 110 ms as the stimulus duration increased from 64-2000 ms. A subsequent post-hoc analysis (Fisher LSD) revealed that the eight duration conditions of the experiment could be divided into four homogeneous groups with statistically-different reaction times: 64-125 ms, 250 ms, 375 ms, and 500-2000 ms.

The results of the ANOVA also indicated a significant interaction between system latency and stimulus duration ($F_{(35,210)}$=6.2, $p<0.0001$). This interaction can be seen in the curves for the two highest-latency conditions tested (white and gray triangles in Figure 4), which show longer response times than the lower-latency conditions for the longer-duration stimuli (as was the case for the baseline case with the continuous stimulus), but slightly $shorter$ response times than the lower-latency conditions for the shorter-duration stimuli. The reason for this small (≈ 50 ms) decrease in reaction time for the high-latency conditions is not clear, but it is possible that the listeners in those conditions simply made less of an effort to incorporate dynamic head-motion cues into their responses and that this allowed them to make their localizations responses more quickly.

4. DISCUSSION AND CONCLUSIONS

The results of this experiment have shown that headtracker latencies of 73 ms or less had little or no effect on either the speed or accuracy of auditory localization in the horizontal plane. Even when the headtracker latency was reduced to 12 ms, a value that was only roughly one-third as large as the lowest latency values tested in previous examinations of head-tracker latency [10, 9], there was no significant improvement in overall localization performance. However, when the headtracker latency was increased from 73 ms to 143 ms, there was a measurable decrease in localization ability that could take one of two forms depending on the exact task the listener was asked to perform. Listeners who were asked to maximize localization accuracy independent of response time were able to compensate for latency and respond nearly as accurately as they could at lower latency values. However, this compensation increased their response times by as much as 200 ms when the latency was 145 ms and by nearly 500 ms when the latency was 243 ms. Listeners who were asked to localize as accurately as possible within a fixed time interval were not able to compensate for latencies higher than 73 ms and exhibited significantly larger numbers of front-back reversals when the latency was 143 ms and significantly larger left-right angular errors when the latency was 243 ms.

These results are roughly consistent with those of earlier experiments that have examined the effect of latency on localization performance, but there are important differences. Sandvad [10] examined localization performance in a condition similar to our continuous condition, where listeners were given as long as they needed to turn and point their heads in the direction of a virtual sound source. His results, like ours, showed that latencies of 29 ms and 69 ms were not large enough to produce any measurable effects on localization speed or accuracy. However, Sandvad's results also indicated that 96 ms of headtracker latency was enough to significantly increase the azimuth error that occurred in the localization of a continuous noise source. In contrast, our results showed that latency values as long as 243 ms had no impact on the ability to localize a continuous stimulus. The most likely explanation for this difference is that our design, which used the same latency value for every trial within a session and provided listeners with performance feedback after each response, allowed the listeners to learn an effective strategy for compensating for the headtracker delay, while Sandvad's design, which randomly changed the parameters four times within a session and provided no feedback, did not. While it is possible to argue the merits of either design, we feel that ours was probably more consistent with the performance results that would occur in real-world audio display applications both because the latency values of real-world systems are likely to remain relatively steady over time and because most real-world operators will have at least some opportunity to learn how to use a virtual audio display system before they would require it for the completion of any time-critical tasks.

Our results are somewhat less similar to those of Wenzel [9], which examined the effects of latency on the localization of stimuli that were limited in duration (3000 ms and 8000 ms) without placing any restrictions on the amount of time the listeners were allowed to use to make their responses. Her results showed only modest differences in front-back confusions and localization error between the baseline condition with 33.8 ms of latency and the test conditions with 100.4 and 250.4 ms of latency, even when the stimulus was limited in duration to 3000 ms. A likely explanation for the larger effects of latency that occurred in our study is that the 2-s response window we used forced the listeners to move their heads almost immediately in order to make their responses, while the listeners in Wenzel's study could choose to move their heads slowly enough to compensate for the headtracker delays that were present in her stimuli.

Together with the results of these earlier studies, the results of this experiment allow us to state with some confidence that headtracker latencies of 70 ms or less are unlikely to adversely impact localization ability in virtual audio display systems, even when the stimuli are short in duration and the listeners are required to move their heads and make their responses as rapidly as possible. At the same time, there is evidence that latencies exceeding 90 ms do impair localization ability, either by increasing the time required to localize a continuous sound or by decreasing the accuracy of localization judgments for short-duration sounds. Thus, in terms of pure localization accuracy in azimuth, it appears that less than 70 ms of headtracker latency is sufficient to obtain satisfactory localization performance in a virtual audio display system. However, it is important to note that other aspects of the virtual display performance, including the naturalness and realism of the simulation and possibly the ability of listeners to tolerate the use of the system over long periods of time, *may* be affected by headtracker latencies less than 70 ms. Consequently, we believe it is prudent for the designers of virtual audio displays to view 70 ms only as the absolute upper limit on headtracker latency, and to try to achieve latency levels of no more than half that amount in operational audio display systems.

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