EMPIRICAL AND MODELED ACOUSTIC TRANSFER FUNCTIONS IN A SIMPLE ROOM: EFFECTS OF DISTANCE AND DIRECTION

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ABSTRACT

Empirical transfer functions were measured for a manikin head as a function of source position (re: the listener) and listener position (re: the room) for sources within a meter of the listener. Empirical results are compared to room simulations using a standard image-method model combined with anechoic, distance-dependent head-related transfer functions (HRTFs). Results suggest that the biggest discrepancies between measured and modeled impulse responses arise due to interactions of the head with the source, which cannot be ignored for sources this close to the listener. Results give insight into the importance of the acoustic effects of the head and room on the total signal reaching a listener and have implications for understanding spatial perception in rooms and developing realistic 3-D spatial auditory displays.

1. INTRODUCTION

Echoes and reverberation (jointly termed "reverberation" throughout this paper) have many important perceptual effects. Reverberation provides information about the listening environment, causes slight degradations in directional auditory acuity, vastly improves auditory distance perception, and degrades speech intelligibility compared to listening in anechoic space. In virtual displays, inclusion of reverberation improves the subjective realism of a display. While these results are well known, there is little work quantifying how the physical effects of reverberation influence perception. The ultimate goal of this work is to develop a room-acoustics model to enable quantitative investigations of the perceptual influence of reverberation. Recent efforts in our laboratory have focused on characterizing the effects of reverberant energy on perception of source distance and direction [1-3], speech intelligibility [4], and other tasks, when sources are relatively near the listener. For such source positions, robust interaural level differences or ILDs change with source distance and laterality due to the interaction of the source with the listener's head [5-7], and the distance-dependence of the direct sound cannot be accurately modeled by a simple 1/distance scaling.

In order to begin to identify physical bases for these effects in the signals reaching the listener, acoustic transfer functions were measured for different source positions relative to the listener and listener positions relative to the room [8]. Empirical results are compared to results from a room model that incorporates distance-dependent HRTFs with the simple image-method approach (e.g, see [9]). This model is based upon a number of simplifying assumptions (e.g., the source is a uniformly-radiating point source, the only reflecting surfaces are the six sides of the perfectly-rectangular room, the head interacts with each modeled reflection but not with the pattern of reflections, etc.).

2. METHODS

Acoustic transfer functions to the ear canal entrances were measured and modeled for sources at different positions relative to the listener's head. Distances ranged from 15 cm to 1 m and azimuth angles from 0 deg to 90 deg (to the right). All sources were in the horizontal plane containing the ears. The measured / modeled room is roughly rectangular, with dimensions of 5 m x 9 m x 2.9 m; however, one long wall is semi-flexible and retractable, with fairly large absorption (all other walls were hard). Two listener positions were investigated, with the listener positioned in either the center of the room or the corner of the room (i.e., with back and left side within two feet of the back and left walls) of the room.

2.1. Empirical Measurements

Empirical measurements were made at the entrance to the ear canals of a Knowles Electronics manikin (KEMAR) using a Maximum-Length-Sequence (MLS; see [10]) of 32767 points at a sampling rate of 44.1 kHz. For the room in question, this length was sufficient to measure the impulse response beyond the point at which the reverberant tail was 60 dB below the direct sound level.

2.2. Room Model

Simulated impulse responses were generated using a modified version of the image method (e.g., see [9]). In this method, the reverberant room is modeled as an empty box with acoustically reflective walls, each of which has a specific, frequency-dependent absorption characteristic. Reflecting the original source across the walls of the room creates image sources consistent with discrete echoes off the corresponding wall. Each simulated source location is then associated with a measured anechoic HRTF-derived impulse response. The measured impulse response is time shifted and amplitude scaled (preserving interaural cues) to account for small differences between the distance at which the impulse response was measured and distance of the image source. Finally, the impulse is filtered to account for the wall absorption. All such image sources (computed iteratively out to the first 110 ms of the response, which is out to the point at which empirical HRTFs were within 30 dB of their peak value) are summed to produce the total reverberant impulse response (no late reverberant tail was included). The current simulation differs from most previous, similar models in that the measured impulse responses for nearby sources are distance- as well as direction-dependent.

3. RESULTS

3.1. Magnitude Spectra

Figures 1 and 2 show the measured and modeled (respectively) long-term magnitude spectra of the impulse response at the right (black) and left (gray) ears for different source positions when the listener is in the room center.

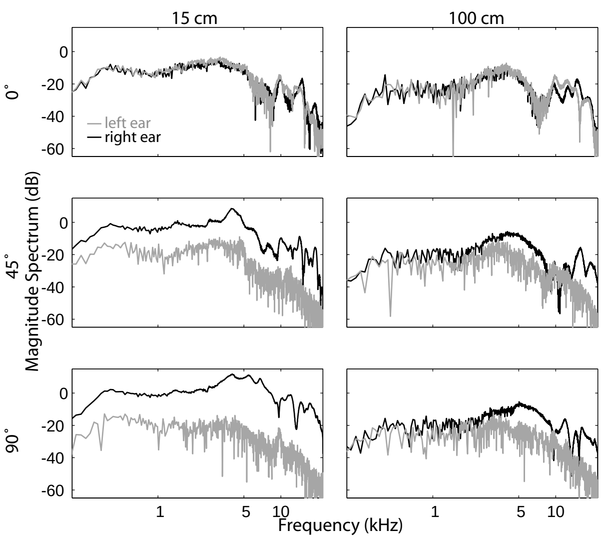

Figure 1. *Magnitude spectra of measured transfer functions for various source positions (room center).*

Qualitatively, measured and modeled results show the same patterns. When the listener is in the center of the room, the main effect of reverberation is to cause frequency-to-frequency variations in the received spectral energy such that the magnitude spectra vary randomly about the direct-sound-alone spectral levels. The variations are largest in the left ear, which is, for the tested positions, always the ear farther from the source and the ear facing the "hard" wall in the asymmetrical room. These results are consistent with the fact that the dominant energy in the impulse response comes from the direct sound; the amount of spectral "distortion" depends on the direct-to-reverberant energy ratio (D/R), which decreases with distance, increases at the right ear and decreases at the left ear as the source moves laterally to the right, and is larger in the right ear than the left.

While not shown here for sake of brevity, measured and modeled results also agree well when the listener is in the corner of the room. In this case, frequency-to-frequency variations in the magnitude spectrum are also observed. However, strong, early reflections from the walls additionally lead to pronounced comb-filtering of the received spectra. This effect is strongest at the far ear; in some cases, the far-ear direct-sound impulse is lower in level than the first wall reflection. The resulting long-term magnitude spectra show strong peaks and notches that arise directly from the in-phase and out-of-phase interference of early, discrete echoes.

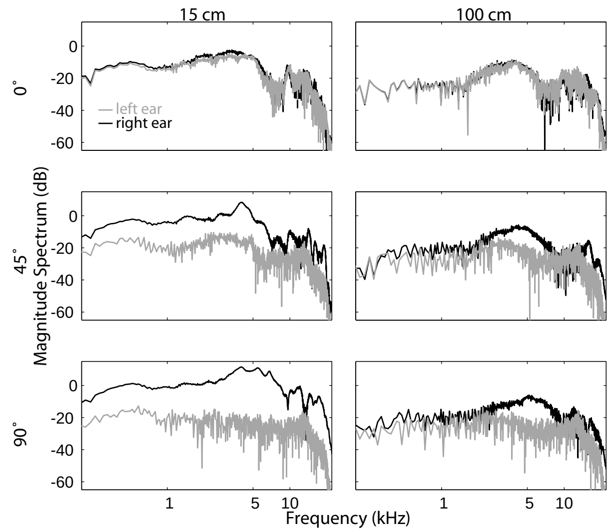

Figure 2. *Magnitude spectra of modeled transfer functions for various source positions (room center).*

3.2. Interaural Time Differences

Interaural time differences (ITDs) were calculated from the long-term spectra of the reverberant impulse responses. While such a simple analysis does not directly predict the degree to which reverberation may degrade directional hearing (since it ignores temporal structure and perceptual phenomena such as the precedence effect), it helps to quantify the degree of interaural distortion produced by reverberation. Figures 3 and 4 show ITD as a function of frequency for direct-sound-alone (gray) and reverberant (black) impulse responses for the center-room position. Figures 5 and 6 show corresponding plots for the corner-room position. ITD was calculated by dividing the interaural phase angle at each frequency by 2 f; inherent phase ambiguity is shown by plotting the 2 multiples of interaural phase. The "true" ITD is roughly the ITD value of the resulting contour that is constant as a function of frequency.

In all cases, the interaural distortion is greatest for the far sources (right column) compared to the near sources (left column) and grows with source laterality. Empirical and modeled results show similar patterns. For the center room listener positions (Figures 3 and 4), the ITD distortion is essentially random around the direct-sound-alone ITD. For the corner room listener positions (Figures 5 and 6), the distortion is much more systematic, with large fluctuations and discontinuities in the ITD as a function of frequency. This pattern arises from the comb-filtering effects of the early wall reflections and the frequency-dependent cancellation and reinforcement caused by the reflections.

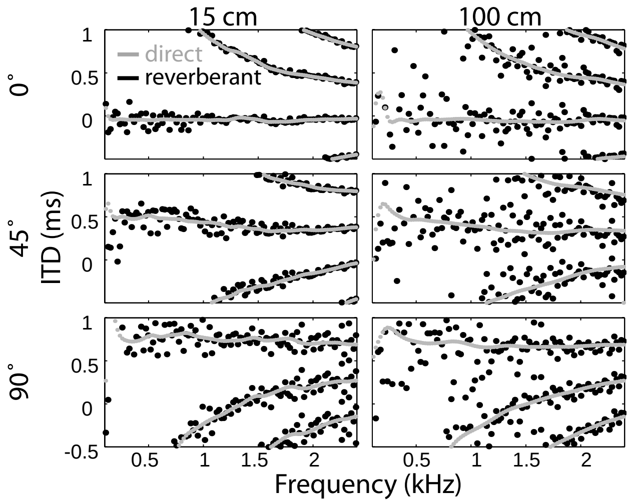

Figure 3. *Interaural time delay (ITD) versus frequency for measured transfer functions for various source positions (room center).*

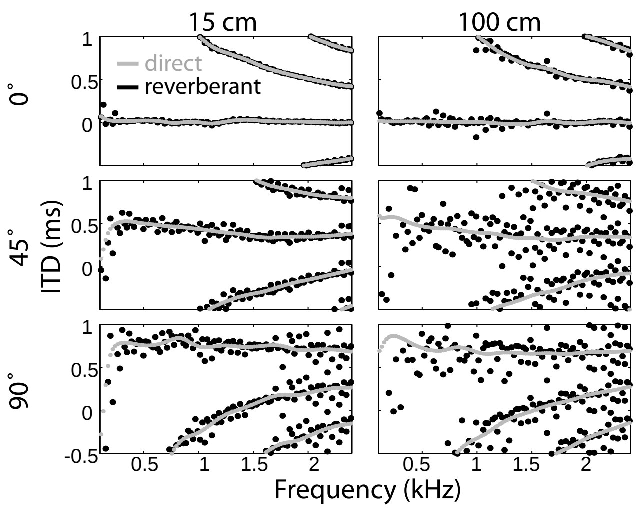

Figure 4. *ITD versus frequency for modeled transfer functions for various source positions (room center).*

3.3. Direct- and Reverberant-Sound Energy

The qualitative agreement between the measured and modeled impulse responses demonstrated in Figures 1-6 is encouraging; however, more quantitative comparisons are critical for understanding how well the simple room-acoustics model describes the effects of reverberation. In all cases (for all physical cues considered), the amount of "distortion" produced by the reverberant energy varies directly with D/R. For source and listener positions yielding large D/R, the reverberation causes small changes in the physical signals at the ears; when D/R is small, the reverberation has a larger effect. Due to the fact that the direct-sound HRTFs used in the simulation were taken from empirically-measured, distance-dependent HRTFs, the direct sound energy at the left and right ears changes identically in the measured and modeled results. The distance-dependence of these empirical HRTFs, which is usually modeled as varying with 1/distance, differs from most other simulations due to the fact that sources are relatively close to the head and the interaction of the head and source wave cannot be ignored.

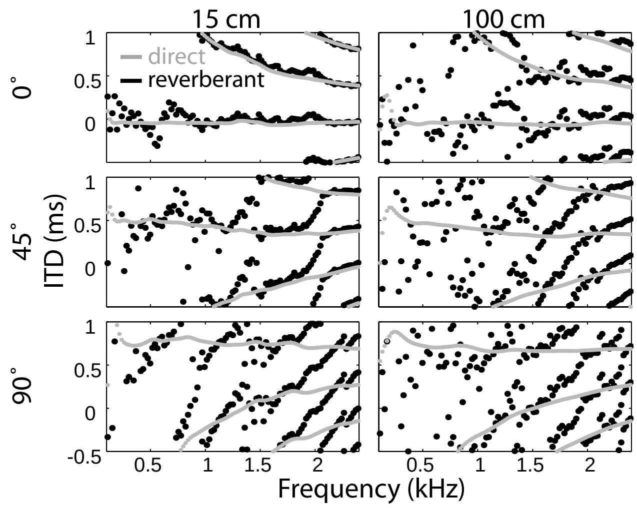

Figure 5. *ITD versus frequency for measured transfer functions for various source positions (room corner).*

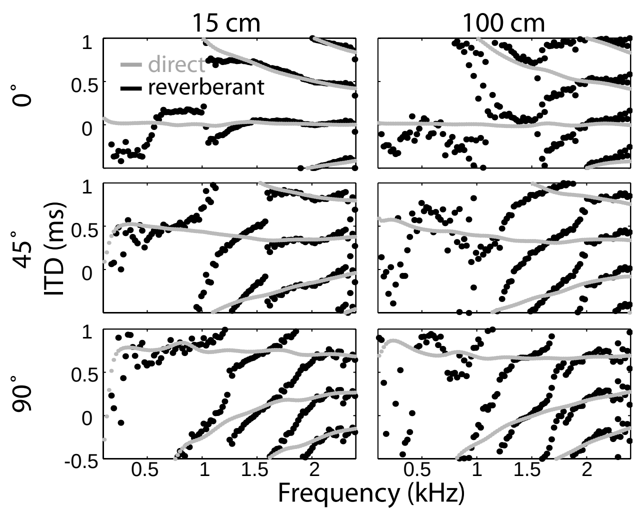

Figure 6. *ITD versus frequency for modeled transfer functions for various source positions (room corner).*

One effect that is not perfectly captured by the model is a systematic increase in the reverberant energy in the measured HRTFs (calculated by time-windowing out the direct impulse in the HRTFs and summing the remaining energy) with decreasing source distance. Figure 7 shows the reverberant energy reaching the left and right ears as a function of source azimuth (source distance varies parametrically in the figure). The amount of reverberant energy is almost always greater in the left (dashed lines) compared to the right (solid lines) ear as a result of the absorption characteristics of the right-side wall. In addition to this, however, the reverberant energy tends to decrease with source distance, particularly in the right (near) ear. We believe this pattern to be a result of the interaction of the head and source. Specifically, for sources close to the head, the head diameter is large compared to the radiating wavefront of the source. As a result, large amounts of energy are reflected back away from the head, adding new reflections not accounted for in the current room model. While our simulation includes the interactions of the head with the source wavefront for the direct sound (including, for example, the large interaural level differences that arise for nearby, lateral sources), it does not take into account this interaction in the reflectance model.

The model's failure to accurately account for the dependence of the reverberant energy level on source distance directly affects the modeled D/R. Since the D/R directly predicts the magnitude of any acoustic effect of the reverberation on the total signals reaching the ears, this error yields quantitative errors in the effects of reverberation on all perceptually-relevant spatial auditory cues.

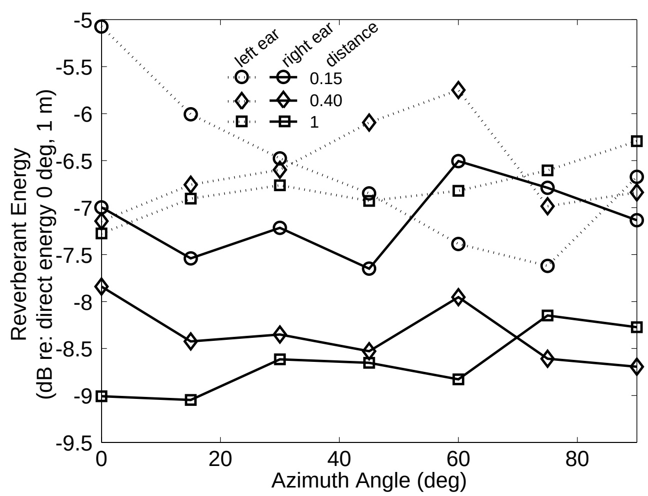

Figure 7. *Reverberant energy in measured impulse responses to the left and right ears as a function of source direction and various distances (room center).*

4. CONCLUSIONS

Direct and reverberant energy levels vary systematically with source distance as well as direction when sources are near a listener. As a result, D/R also varies systematically for nearby sources in a room. Since this energy ratio determines how large the acoustic influence of reverberation will be (i.e., how reverberation influences the magnitude spectra and interaural differences of the signals reaching the ears), it is important to model this dependence appropriately. A simple room-image model that incorporates the distance-dependence of the direct sound impulse response yields qualitatively similar results to empirically-measured impulse responses in a simple room; however, by ignoring the effect of the head on the reverberation pattern, the approach fails to quantitatively reproduce the dependence of reverberation (and the direct-to-reverberant energy ratio) on source distance. Other simplifications in the model may also be critical; however, for nearby sources, failing to account for the effects of the head on the reflected energy causes the most obvious discrepancy between measured and modeled results.

Future efforts directed towards including these effects may yield a room model that can be used to simulate realistic reverberation patterns for spatial auditory displays. Such a model will be useful for exploring the importance of reverberation for spatial auditory perception, particularly in distance, as well as for the effects of reverberation on perceived realism in spatial auditory displays.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1] S. Santarelli, "Auditory Localization of Nearby Sources in Anechoic and Reverberant Environments," unpublished Ph.D. dissertation, Dept. of Cognitive and Neural Systems, Boston University, Boston, MA, 2000.

[2] B. G. Shinn-Cunningham, "Learning reverberation: Implications for spatial auditory displays," Proceedings of the International Conference on Auditory Displays, pp. 126-134, Atlanta, GA, 2000.

[3] B. G. Shinn-Cunningham, "Distance cues for virtual auditory space," Proceedings of the IEEE-PCM 2000, pp. 227-230, Sydney, Australia, 2000.

[4] B. G. Shinn-Cunningham, J. Schickler, N. Kopčo, and R. Y. Litovsky, "Spatial unmasking of nearby speech sources in a simulated anechoic environment," *Journal of the Acoustical Society of America*, vol. in press, 2001.

[5] B. G. Shinn-Cunningham, S. Santarelli, and N. Kopčo, "Tori of confusion: Binaural localization cues for sources within reach of a listener," *Journal of the Acoustical Society of America*, vol. 107, pp. 1627-1636, 2000.

[6] D. S. Brungart and W. M. Rabinowitz, "Auditory localization of nearby sources I: Head-related transfer functions," *Journal of the Acoustical Society of America*, vol. 106, pp. 1465-1479, 1999.

[7] R. O. Duda and W. L. Martens, "Range-dependence of the HRTF for a spherical head," IEEE ASSP Workshop on Applications of Digital Signal Processing to Audio and Acoustics, 1997.

[8] T. J. Brown, "Characterization of Acoustic Head-Related Transfer Functions for Nearby Sources," unpublished M.Eng. thesis, Dept. of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA, 2000.

[9] P. M. Peterson, "Simulating the response of multiple microphones to a single acoustic source in a reverberant room," *Journal of the Acoustical Society of America*, vol. 80, pp. 1527-1529, 1986.

[10] D. D. Rife and J. Vanderkooy, "Transfer-function measurement with maximum-length sequences," *Journal of the Audio Engineering Society*, vol. 6, pp. 419-444, 1989.