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Effects of Room Size and Reverberation, Receiver Location, and Source Rotation on Acoustical Metrics Related to Source Localization

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Summary

This study investigates the effects of room size, reverberation, source rotation, and receiver position on two acoustical metrics related to source localization: distortion of frequency-smoothed magnitude (DFSM)and interaural level differences (ILD), as calculated from measured binaural room impulse responses (BRIR). The spaces tested include a conference room, classroom, theater, and concert hall, with mid-frequency reverberation times ranging from 0.4 to 2.6 sec. For all of the BRIRs, a directional loudspeaker source was placed approximately 0.5 m in front of the receiver, simulating a typical conversation distance. In each space, the receiver was located near the center, one meter away from a side wall, and one meter away from the back wall for the measurements. In each location, measurements were made for three different source rotations: 0 degrees, 45 degrees, and 90 degrees from the receiver. The receiver was facing directly toward the source in each condition. The outcomes of this study indicate that at this source-receiver distance, both DFSM and ILD are more impacted by source orientation relative to the receiver than reverberation time. Also, the values are influenced more consistently by the location of nearby reflective surfaces than varying room reverberation.

PACS no. 43.66.Qp, 43.55.Gx

1. Introduction

How easily a person localizes sound sources in the built environment can impact her communication comfort and/or performance, such as in classrooms where student learning may improve from better source localization. Quantifying the ability of listeners to locate sound sources accurately and separate the target source from competing sources in different architectural environments is therefore an important aspect of room acoustic design and evaluation. This study investigates the effects of room reverberation, source rotation, and receiver position on two acoustical metrics related to source localization: distortion of frequency smoothed magnitude (DFSM) and interaural level differences (ILD).

The localization of sound sources has been rigorously studied from psychological and physiological perspectives, indicating that interaural level differences (ILD) and interaural time differences (ITD) are cues that listeners use for source detection and lateralization [1, 2]. More recent research has covered topics ranging from better understanding of the binaural hearing mechanisms behind localization [3, 4] to the effects of spectral content [5, 6]. Effects of room reverberation on psychoacoustic perception have also been examined, such as with regards to speech intelligibility [7, 8, 9, 10, 11, 12, 13, 14, 15, 16] and distance perception [17, 18]. Investigations on quantifying the effect of room acoustics on source localization have been limited, though [6, 19, 20, 21, 22].

A metric that has been proposed by Shinn-Cunningham *et al.* [21] for source localization ability in rooms is the distortion of frequency-smoothed magnitude (DFSM). Spectral cues are important for localization ability [1], and DFSM quantifies the spectral distortion of the source signal as it reaches the listener. Localization bias, wherein the listener perceives an incorrect source location, may result if more spectral distortion occurs. This condition corresponds to higher DFSM values. Shinn-Cunningham *et al.* [21] calculated acoustics metrics related to source localization, including DFSM and ILD, from measured binaural room impulse responses (BRIR)measured with a KEMAR head for nearby sources in a typical classroom. The broadband reverberation time (RT) of the rectangular room tested was approximately 0.6 s. The receiver was placed in three locations: near the center of the room, near a side wall, and near the corner of the room for the mea-

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surements; and the source was placed at different azimuths around the receiver, varying from directly in front of the receiver (0° source azimuth) to the right side of the receiver (90° source azimuth) at distances of 0.15, 0.40, and 1 m away from the receiver to approximate common conversation distances.

Results showed that the DFSM was most impacted by the presence of energy from early strong reflections relative to the energy from the direct sound, so its magnitude was greater and increased more dramatically with source azimuth in conditions with early reflections. The ILD magnitude tended to be smallest for conditions with more reverberant energy, increasing with higher frequencies. These findings were based on measurements taken in a single space, though. The present study expands upon the study [21] by applying these metrics for source localization ability in reverberant rooms to measured BRIRs from spaces with varying sizes and resulting RTs. It seeks to determine how DFSMs and ILDs are related to RT resulting from room size changes, source location, and receiver rotation for a typical conversation distance. ITDs which play a larger role at low frequencies [2] were not included in the scope of this project, because as confirmed and discussed by other researchers [6, 22], ITDs do not appear to be sensitive to reverberance in rooms.

A limitation of the proposed DFSM metric is that Shinn-Cunningham *et al.* [21] did not conduct psychophysical tests, showing its correlation to human perception of source localization. The scope of the current study does not include psychophysical tests of DFSM either; however, the metric has been shown in other research by the authors to correlate to student achievement on reading comprehension tests in elementary classrooms, even though reverberation times did not [23]. Consequently, the authors believe that DFSM has the potential to provide greater understanding of room acoustic effects on human responses than traditional room acoustic metrics, like RT and C80, and were interested to test how this metric varies across different scenarios.

2. Methods

DFSM and ILD from BRIR measurements were examined in four different spaces to determine if the results from the Shinn-Cunningham *et al.* [21] study are applicable to spaces with varying sizes and resulting RTs.

2.1. Space descriptions

The spaces tested include a conference room, classroom, theater, and concert hall. These four spaces were chosen to investigate a wide range of rooms with different geometric and acoustic conditions, rather than for their specific use types. Both the conference room and classroom have primarily rectangular shapes, with thin carpet on the floor, gypsum board walls, and acoustical ceiling tile. The conference room was furnished with a large table surrounded by upholstered chairs. The classroom contained several student desks attached to upholstered chairs and a large desk at the front of the space. Both the conference room and the classroom are located in the Peter Kiewit Institute at the University of Nebraska at Omaha.

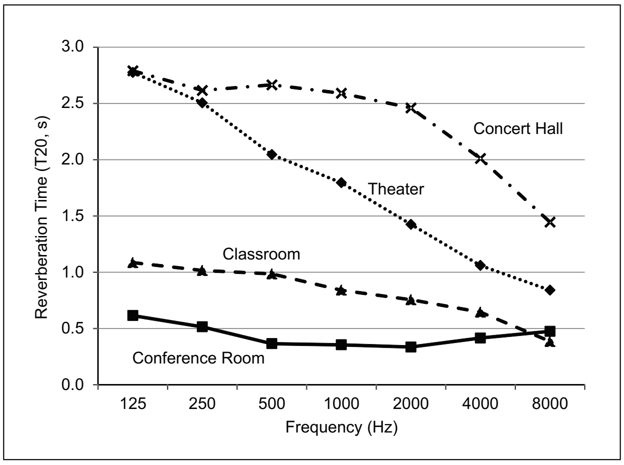

Figure 1. Octave band reverberation time (T_{20}) values for the four spaces tested.

The theater is the main stage theater in the Lied Education Center for the Arts at Creighton University in Omaha, NE. The theater has a fan-shaped seating area, shallow balcony along the rear and side walls, and a stage house. The surface materials include concrete walls, wood ceiling, thin carpet on the floor aisles, and upholstered seating.

The concert hall is the Peter Kiewit Concert Hall in the Holland Performing Arts Center in Omaha, NE. This is the largest space examined, with two stacked balconies along the back wall and two stacked shallow balconies along the side walls. The stage is open to the seating area, with a floating reflector panel above. The room finishes include upholstered seating with hard wood and concrete floor surfaces. The walls are comprised of hard surfaces with shallow indentations to provide diffusion, partially covered by absorptive panels. The ceiling is a hard, convex surface.

The RTs of the conference room, classroom, theater, and concert hall are shown in Figure 1, with mid-frequency averages across 500 and 1000 Hz ranging from 0.4 to 2.6 s. The RTs shown in this figure are the T_{20} values in each octave band from 125 to 8000 Hz, measured as detailed in section 2.2. The RTs increase from the conference room to the classroom to the theater to the concert hall.

2.2. Measurement procedures

The BRIRs were generated and recorded using the Electronic and Acoustic System Evaluation and Response Analysis (EASERA) room acoustics analysis software, operating on a notebook computer. The notebook computer was connected to an EASERA Gateway, which served as the soundcard for the measurements. A pink-weighted logarithmic sine wave sweep with two presends and four averages was used to excite each space. The signals were generated by a directional Peavey PR 12 loudspeaker and recorded via a Brüel and Kjær Type 4104 binaural microphone headset, placed on an adult female human head. The level of the signal was standardized among spaces by setting the level of pink noise generated to 70 dBA (re: 20 μPa), recorded one meter away from the source.

For all of the measurements, the source was placed approximately 0.5 m in front of the receiver, simulating a typical conversation distance. The distance between the floor and the receiver microphones was approximately 1.57 m, which was the distance from the ear level of the standing adult female to the floor. The middle of the source loudspeaker was approximately 1.52 m above the floor, so that the height of the loudspeaker was similar to the height of the receiver. In each space, the receiver was positioned near the room center, one meter away from a side wall, and one meter away from the back wall for the measurements. In the theater and concert hall, the center measurement location was the approximate center of the main floor audience seating area. In each location, measurements were made for three different source rotations: 0 degrees, 45 degrees, and 90 degrees from the receiver. The source was rotated to mimic conversational situations where the talker is not facing the receiver. The receiver was facing directly toward the source in each condition. See Figure 2 for a schematic plan view of the different source rotations and receiver positions tested. In the theater space, the measurements were repeated three times in each location for each source rotation to quantify the measurement repeatability.

3. Results and discussion

3.1. Distortion of frequency-smoothed magnitude

The DFSM metric quantifies how reverberant energy distorts the spectral content of the incoming signal, and it is calculated from the frequency response of a room. The frequency-smoothed reverberant frequency response is compared to a corresponding frequency-smoothed ‘pseudo-anechoic’ frequency response. The pseudo-anechoic frequency response is calculated from the time-windowed impulse response to eliminate all reflections occurring after the direct sound. The spectral level of the pseudo-anechoic frequency response is subtracted from the level of the reverberant frequency response. The absolute value of this difference is computed in each one-third octave band and averaged across frequency. This mean absolute difference between the frequency-smoothed reverberant and pseudo-anechoic impulse responses is the DFSM. More details on the DFSM calculation procedure may be found in [21].

Comparisons of the DFSM among the four spaces included in this study are shown in Figure 3. This figure shows the values measured at both the left (gray bars) and right ears (white bars). The error bars depict the range about the average value from the three sets of repeated measurements conducted in the theater space only, to provide a sense of the uncertainty of these measurements. Figure 3a shows the DFSM for the center receiver position with the source directly facing the receiver (0° source rotation). For this configuration, the DFSM values are approximately equivalent between the two ears and among the four spaces.

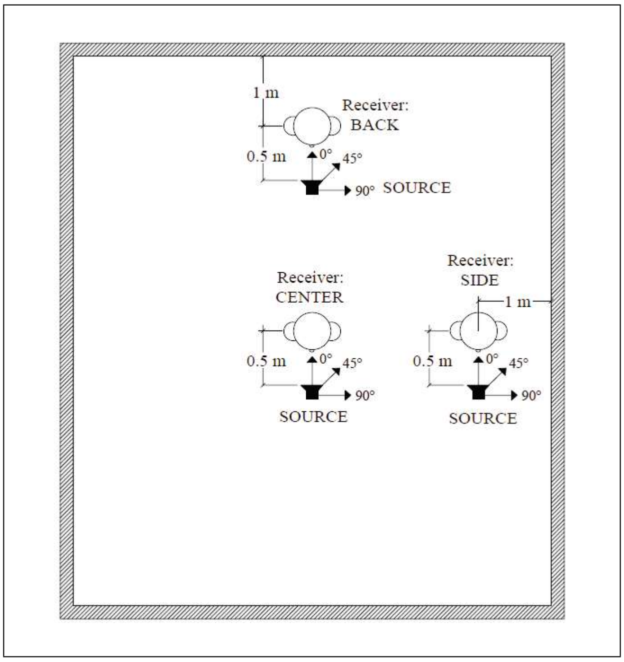

Figure 2. Plan view of source rotations and receiver positions used in each space (not to scale).

Figure 3b displays the DFSM values for the side receiver position, 0° source rotation. For this condition, a strong reflection from the side wall is present, which is closest to the left ear. In this configuration, the DFSM values tend to increase with increasing room reverberation time, though the DFSM values in the three spaces with the longest reverberation times are all within the range of uncertainty quantified by the repeated measurements in the theater space. The DFSM value is greater in the left ear than the right ear for the space with the longest reverberation time (concert hall).

The DFSM values for the back receiver position, 0° source rotation are shown in Figure 3c. In this position, the conference room has the lowest DFSM values, and the classroom and theater have similar DFSMs within the range of uncertainty. The concert hall has the highest DFSM values, and they are above the uncertainty range. The DFSM values between the left and right ears are similar in all spaces.

Figure 3d shows the DFSM values for the back receiver position, 90° source rotation. The back wall provides a strong reflection to both the left and right ears in this condition; however, the left ear is receiving more direct sound energy than the right ear due to the rotation of the source. In this configuration, the left ear DFSM is greater than the right ear DFSM in each space, and the DFSM values are highest in the classroom and concert hall, above the measured uncertainty range. The DFSMs in the conference room and theater are similar within the range of uncertainty.

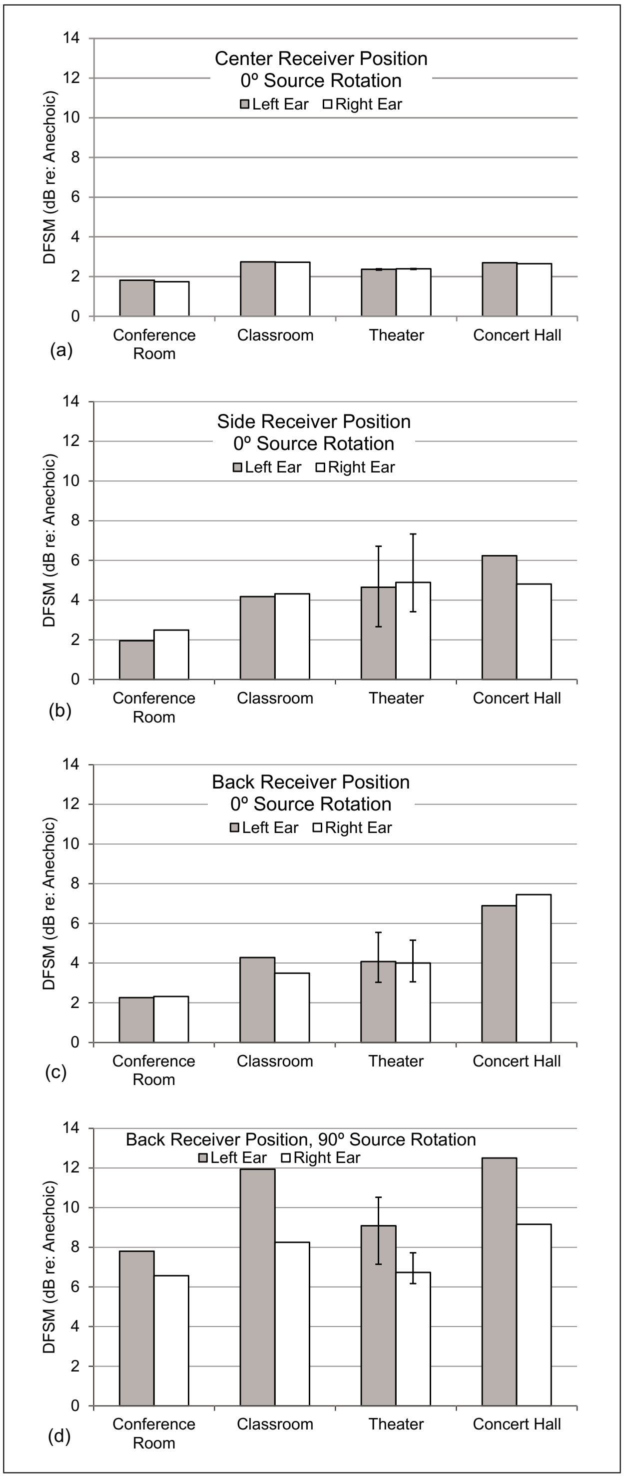

Figure 3. Distortion of frequency-smoothed magnitude for the (a) center receiver position, 0° source rotation; (b) side receiver position, 0° source rotation; (c) back receiver position, 0° source rotation; and (d) back receiver position, 90° source rotation. Error bars for theater space show the range about the average value from the three sets of repeated measurements.

These results show that the DFSMs in theater space are not consistently greater than the DFSMs in the classroom and conference room, though the reverberation time in the theater is longer than the reverberation times in the conference room and classroom. The comparisons of DFSM among spaces with varying reverberation times suggest that DFSM does not have a direct relationship to room reverberation time at the source-receiver distance tested. This indicates that other factors may have a greater impact on DFSM than room reverberation time.

To explore the effect of other factors on DFSM, an assessment of how DFSMs are impacted by source rotation and receiver location is provided next. The DFSM values measured at the left ear for the different receiver positions and source rotations for the conference room, theater, and the concert hall are shown in Figures 4a, 4b, and 4d, respectively. In the conference room, the DFSM values increase for the 45° and 90° source rotations as the receiver moves from the side to the center to the back of the room. The DFSM values also increase as the source rotates from 0° to 45° to 90°. Similar trends occur for the right ear DFSM values in the conference room, but the magnitude of the values is generally smaller.

The theater DFSM values, shown in Figure 4b, increase as the source rotates from 0° to 45° to 90° for the center and back positions. For the back position, this increase is greater than the range of uncertainty, but the change is within the uncertainty range for the center position. For the side position, the DFSM left ear values decrease beyond the range of uncertainty as the source rotates from 45° to 90°. The right ear DFSM values for the theater are shown in Figure 4c. For the right ear in the side position, the DFSM values increase as the source rotates from 45° to 90°. This increase is greater than the measured uncertainty range. Trends similar to those measured in the theater for the left and right ear DFSM values occur in the classroom.

The concert hall DFSM values, shown in Figure 4d, have a wider range among the different conditions. The DFSM values in the center position increase as the source rotation changes from 0° to 45° to 90°, as they do in the conference room. However, the DFSM value in the back location is lower for the 45° source rotation than for the 0° and 90° source rotations. The DFSM values in the side location are similar among the varying source rotations. The right ear DFSM trends are similar to those measured in the left ear, with a reduced magnitude.

To summarize these results, the DFSM values did not change systematically with varying room reverberation times at the source-receiver distance tested. Instead, this metric is more sensitive to the room geometry and measurement configuration, which impacts the amount and level of early sound energy received. Similar DFSM values between the left and right ears occur for the 0° source rotation as expected, since the two ears are receiving similar amounts of direct and early energy. The left ear DFSM values are typically slightly higher than or equal to the right ear DFSM values for the 45° source rotation. The DFSM values tend to be greater in the left ear than in the right ear for the 90° source rotation in the center position in the classroom and in the back position in all spaces. For the 90° source rotation, the left ear receives more early sound energy than the right ear, so the DFSM results are

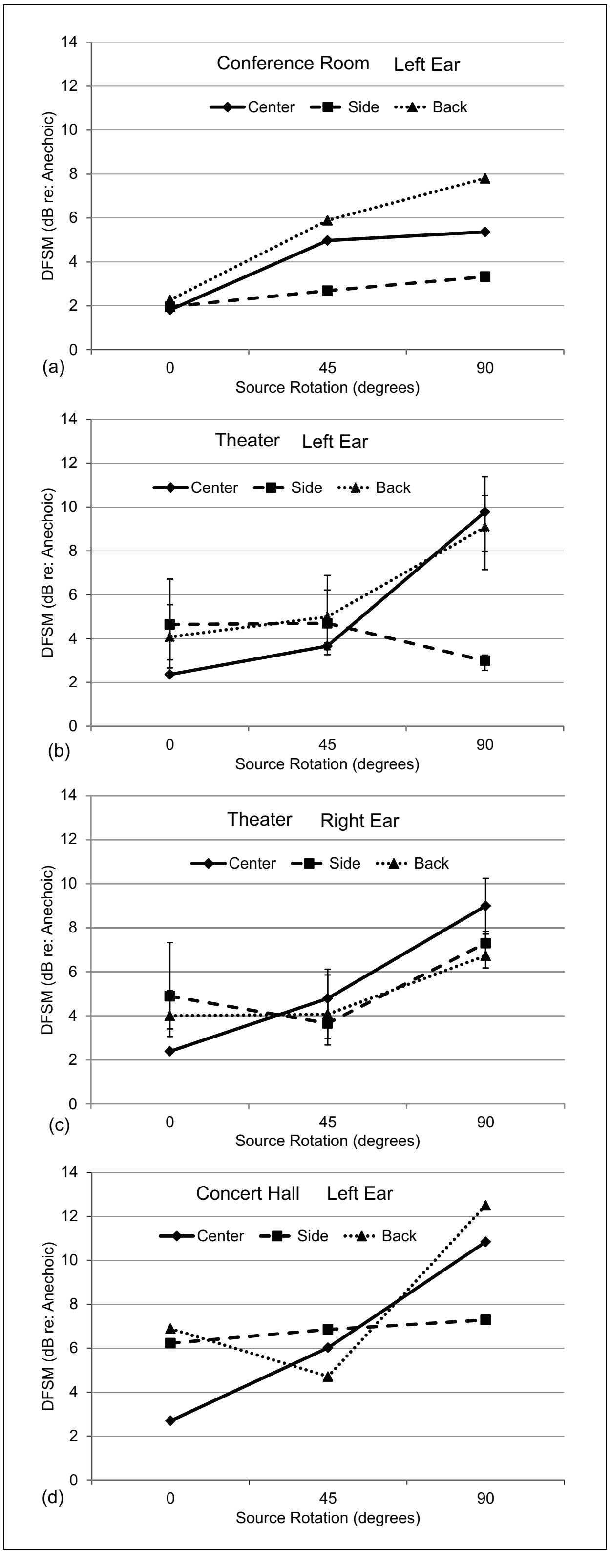

Figure 4. Distortion of frequency-smoothed magnitude measured at the (a) left ear in the conference room; (b) left ear in the theater; (c) right ear in the theater; and (d) left ear in the concert hall. Error bars for theater space show the range about the average value from the three sets of repeated measurements.

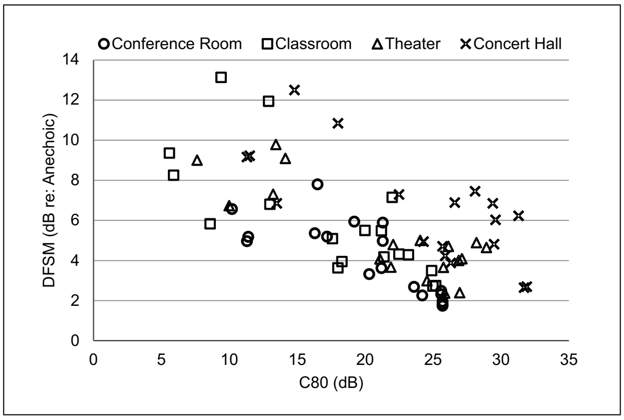

Figure 5. Distortion of frequency-smoothed magnitude versus clarity for all of the source-receiver configurations measured at both the left and right ears.

as expected. These results are similar to those reported within the one room tested by Shinn-Cunningham *et al.* [21], wherein source-receiver configurations with strong early reflections have higher DFSM values.

3.1.1. Comparison of DFSM to Clarity

To compare DFSM to a more commonly accepted room acoustics metric, the clarity (C80) values of each measurement configuration were also computed. C80 is the ratio of the energy occurring in the first 80 ms of the impulse response to all of the energy occurring after 80 ms. A scatter plot between DFSM and C80, including results from both ears at all measurement configurations, is shown in Figure 5. In general, the DFSM values tend to decrease as the clarity values increase, with a correlation value of -0.63 between the two variables. However, as expected, some deviations from this trend occur, since C80 directly relates to the impact of reverberant energy on the time domain of the received signal, whereas the DFSM assesses the impact of reverberant smearing in the frequency domain. Because spectral distortion is an indication that localization bias may occur [21], DFSM may provide localization information that is not captured by the C80 quantification of signal distortion in the time domain.

The impacts of source rotation and receiver position on C80 are compared to their effects on DFSM for the specific source and receiver configurations presented in section 3.1. The C80 values measured at the left ear for the conference room, theater, and concert hall are shown in Figures 6a, 6b, and 6d. The right ear C80 values for the theater are shown in Figure 6c. The measurement configurations shown in Figure 6 for clarity are the same as those shown in Figure 4 for DFSM. In general, C80 decreases, whereas DFSM increases, as the source rotation changes from 0° to 45° to 90°. However, receiver position tends to impact C80 less than DFSM. For example, very small separation exists among the clarity values of the three receiver positions measured at the left ear in the conference room (Figure 6a), but a wider range of DFSM values occur among the three receiver positions for this configuration (Figure 4a). The comparison between DFSM and C80 shows that, although an inverse relationship exists between the two variables, DFSM may define the impact of the location of reflective surfaces relative to the listener on localization ability better than clarity.

3.2. Interaural Level Difference

ILDs are calculated by taking the difference in signal level between the left and right ears. The ILDs presented in this paper are the level differences occurring in one-third octave bands from 200 to 16,000 Hz. The ILDs are reported as a dB value, with the level in the left ear calculated with reference to the level in the right ear (dB Left re: Right).

The ILD values for the four different spaces are shown for various source rotations and receiver positions in Figure 7. Figure 7a shows the ILDs for the center receiver position, 0° source rotation. For this condition, the ILDs are similar among the conference room, classroom, and theater spaces. The ILDs for the concert hall are slightly greater in magnitude than the ILDs for the other spaces at higher frequencies. This difference in ILD magnitude between the concert hall and other spaces is greater than the range of uncertainty of the measurements, as determined from the repeated measurements in the theater space. These trends are similar to those occurring for the ILD values measured in the side and back receiver positions, 0° source rotation.

Figure 7b contains the ILDs for the side receiver position, 45° source rotation. In this condition, the ILD magnitude is similar among the four spaces, and is typically greater at higher frequencies. These trends are similar to those occurring in the side and back receiver positions for the 45° source rotation. The only deviation from these trends occurs in the classroom for the back receiver position, shown in Figure 7c. In the classroom in the back receiver position, 45° source rotation, the ILD magnitude is significantly greater from 3,150 to 16,000 Hz than at the other frequencies.

The ILDs for the 90° source rotation for the side receiver position are shown in Figure 7d. For the 90° source rotation, the ILD magnitude tends to increase for all spaces as the frequency increases. This increase in ILD magnitude is generally greater than the uncertainty range. This trend also occurs for the 90° source rotation at the center and back receiver positions. The magnitude of the increase in ILD values is greater for the side receiver position than the center and back receiver positions, though. With the receiver in the side condition, the magnitude of the ILD values ranges from 0 to 22 dB (Left re: Right) for the 90° source rotation.

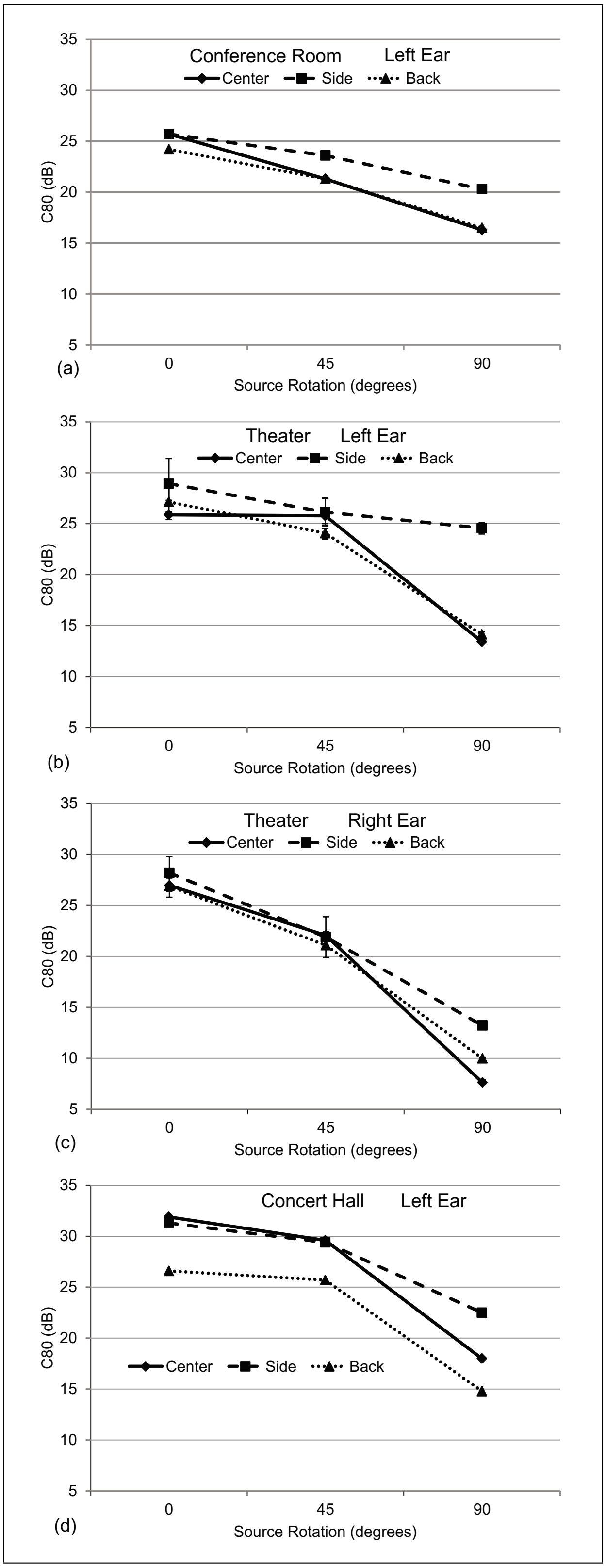

Figure 6. Clarity measured at the (a) left ear in the conference room; (b) left ear in the theater; (c) right ear in the theater; and (d) left ear in the concert hall. Error bars for theater space show the range about the average value from the three sets of repeated measurements.

Since positive ILD values typically occur for the 45° and 90° source rotations and in the side receiver positions, this indicates that the level in the left ear is greater than the level in the right ear as expected for these conditions. The ILDs are typically greater at higher frequencies as observed in previous research [21]. However, the ILDs are not consistently reduced in spaces with longer reverberation times as expected from results reported by Shinn-Cunningham *et al.* [21]. There are some differences between the spaces shown in Figure 7, even at some octave bands but not others, but a primary reason for this

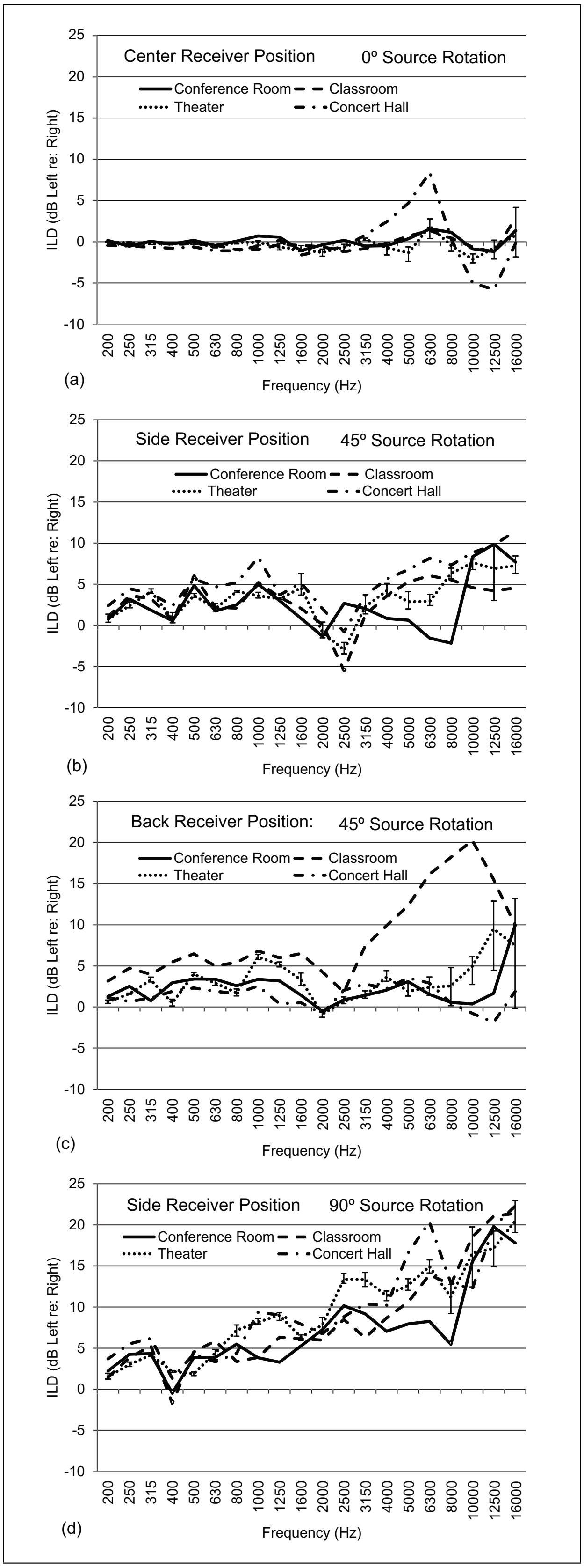

Figure 7. Interaural level differences for the (a) center receiver position, 0° source rotation; (b) side receiver position, 45° source rotation; (c) back receiver position, 45° source rotation; and (d) side receiver position, 90° source rotation. Error bars for theater space show the range about the average value from the three sets of repeated measurements.

may again be the variation in the geometrical parameters among the spaces tested. The location of each room's surfaces and their material properties across frequency, relative to the source and receiver positions, may have a larger impact on ILDs than overall room RT.

4. Conclusions

This investigation has documented two acoustical metrics related to source localization (DFSM and ILD) in spaces with varying shapes and reverberation times. This study indicates that DFSM values are not systematically altered by rooms with varying reverberation times at a source-receiver distance of 0.5 m. The location of nearby reflective surfaces and measurement configurations in which the source faces away from the receiver tend to increase the DFSM, as this will increase the amount of early sound energy received relative to the direct sound energy. This was also documented by Shinn-Cunningham *et al.* [21], who suggested that that localization bias may occur in these conditions. This study has also shown an inverse relationship exists between DFSM and clarity, although DFSM quantifies different information than clarity about the room effects on localization ability. Future research in this area should include psychoacoustical studies of DFSM to determine exact relationships between the spectral smearing quantified by this metric and source localization ability.

The ILDs measured in this investigation typically increase with frequency as expected. This effect is most drastic for the side receiver position, 90° source rotation. This may be due to the pronounced asymmetry between the two ears that occurs in this condition. This trend agrees with results from Shinn-Cunningham *et al.* [21]. However, the ILDs are not systematically reduced in spaces with longer reverberation times, which may again be due to specific room geometries and material properties relative to source and receiver positions. To isolate the effect of reverberation on ILD, measurements in more spaces with similar geometries and finishes should be conducted.

This investigation has provided insight on how certain acoustical metrics related to source localization may be impacted by room characteristics. An additional area of interest is to determine if DFSM and ILD can be used to provide a more detailed characterization of spaces than traditional room acoustics metrics. The outcomes of this study indicate that at the source-receiver distance tested of 0.5 m, both DFSM and ILD are more impacted by source orientation relative to the receiver than room RT. Also, they appear to be influenced more consistently by the local geometry and material finishes than varying room reverberation. These metrics may therefore be able to quantify acoustical differences in rooms with similar RTs. Indeed, the authors have shown that higher DFSM values correlated significantly with reduced reading comprehension scores in elementary school classrooms, even when RT did not [23].

Other extensions suggested for future work are to test a wider range of spaces with varying reverberation times at farther source-receiver distances (e.g. at typical distances between a lecturer and student in a classroom), to include other metrics such as direct-to-reverberant ratios [19], as well as to use computer room acoustic modeling rather than measuring in situ as in this project.

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