1. ABSTRACT

To a first-order approximation, the amount of reverberation reaching a listener depends on the properties of the room and is independent of the position of sound source or listener within the room. Nonetheless, there are important changes in the pattern and level of reverberation reaching a listener with changes in listener or source position, especially when sources are near the listener's head. In this study, the transfer functions from a nearby source (within one meter of the head) to the ears of a listener were measured in the same reverberant room in which human localization performance was measured. Transfer functions for sound sources located at different positions in the right front quadrant (varying in both distance and direction) were measured at the ears of a manikin head for different positions of the manikin in the room. Analysis shows that listener and source locations influence the binaural and monaural properties of the reverberation reaching a listener in a room. Localization performance for sources varying in distance and direction in the right front quadrant was also measured. Localization performance was analyzed in terms of the directional and distance accuracy and bias. Comparison of the acoustic transfer functions and behavioral results explores the degree to which localization accuracy and response bias can be explained by properties of the reverberation reaching the listener.
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2. MOTIVATION

PREVIOUS RESULTS

Behavioral results show that reverberation:
- provides auditory distance cues (Santarelli, 2000; Bronkhorst et al., 2000; Zahorik, 2000)
- causes small degradations in directional localization that decrease over time (Santarelli, 2000; Shinn-Cunningham, 2000)

Acoustic analysis (Brown, 2000) shows that reverberation:
- alters monaural spectrum, interaural level and phase differences
- depends on source position relative to the listener
- depends on listener position in the room locations in a reverberant room

CURRENT STUDY

Examines localization cues in reverberant Head-Related Transfer Functions (HRTFs) as a function of source position re: listener (for brevity, acoustic effects of room position are not discussed)

Measures localization in the same room
- in the left/right and distance dimensions
- for different source and listener positions
- as a function of experience in the room

HYPOTHESES

Learning will affect performance
- over time, subject response bias and variability will decrease

Listener location will affect performance
- locations with strong, early reflections will result in worse directional performance
- perceived distance will be influenced by reverberation more strongly than direction

3. METHODS

ACOUSTICAL MEASUREMENTS

Measure reverberant HRTFs using Maximum-Length Sequences (MLS)
Stimuli played through TDT PD1, Crown amplifier, Bose cube speaker
Measured using Knowles mics
Subjects
- KEMAR (at "tympanic membrane")
- 15 students (blocked meatus technique)

Source positions
- 0, 45, 90° azimuth (re: head center)
- 15, 100 cm distance (re: head center) (see Fig 1a)

Analysis examines effect of reverberation on
- monaural spectra at left and right ears
- interaural phase differences (IPDs)
- interaural level differences (ILDs)

BEHAVIORAL STUDY

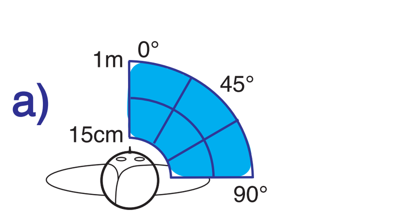
Six normal-hearing subjects
Point at location of stimuli
- five 150-ms-long pink-noise bursts
- level equalized at head +15 dB rove
- presented through TDT system to small speaker positioned by experimenter

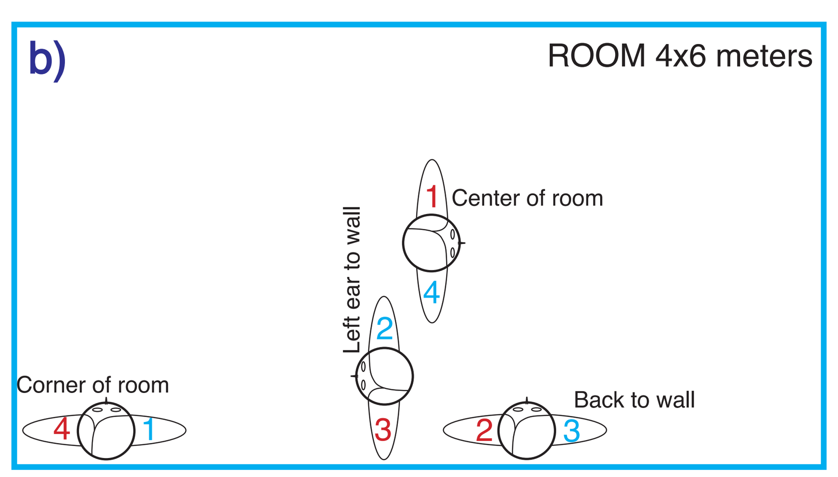
Source positions within horizontal plane in right, front quadrant re: listener (Fig. 1a)
Four listener locations in room ($T_{60} \sim 0.4$ s):
- Center, Back, Ear, Corner (Fig. 1b)
- 300 measurements/subject-position performed in each of four sessions (2 h)

Two groups differing in position order
- Group 1: Center, Back, Ear, Corner
- Group 2: Corner, Ear, Back, Center

Analysis examines bias and variability in subject responses in dimensions of
- left/right
- distance

FIGURE 1 a) Source locations relative to listener b) Listener positions in room (group order shown by numerals)





4. GROSS BEHAVIORAL EFFECTS

Left/right bias (Fig 2a)
- experience causes slight decrease in magnitude of bias (statistically significant at p = 0.05 level)
- Corner room position causes slight overall bias of 2.5° to the left (re: Center; however, result is statistically significant only for group 2)

Left/right and distance variance (Fig 2b & 2d)
- group 1: response variability decreases or is essentially constant with time
- group 2: response variability always decreases
- results imply an interaction between experience and room position
  - variability tends to decrease with experience
  - variability tends to be larger for Corner than Center room position

Distance bias (Fig 2c)
- most subjects overestimate distance
  - two group 2 subjects consistently show very large bias in this direction, causing a consistent difference in the group means
  - distance bias is roughly independent of experience and room position

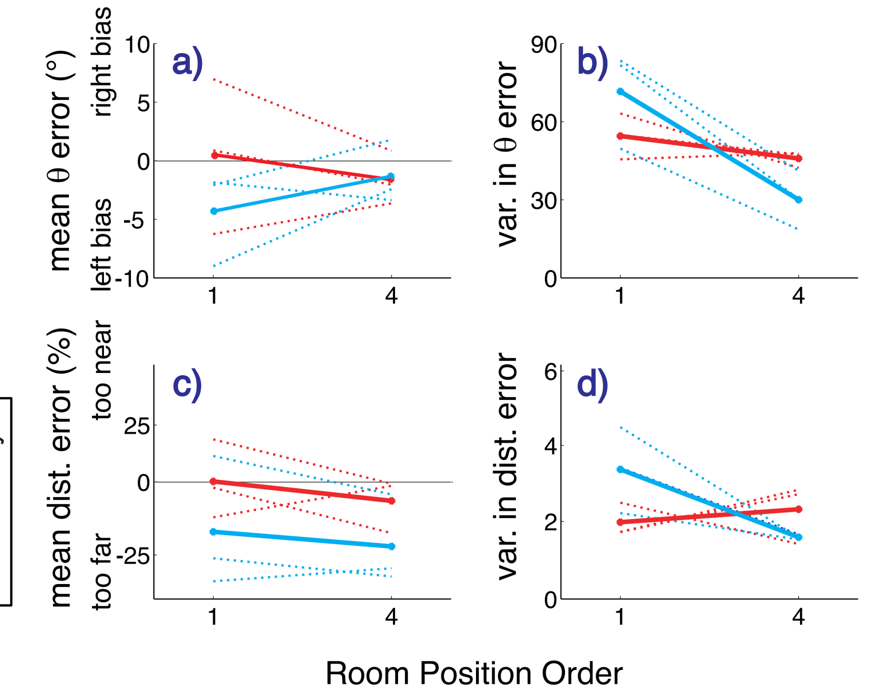


FIGURE 2 Average bias and variability in subject response errors (averaged over source position) for initial and final room positions (1 is center for Group 1, corner for Group 2; 4 is corner for Group 1, center for Group 2). a) left/right response bias b) left/right variance c) distance response bias d) distance variance.

EXPERIENCE AND ROOM POSITION

The way in which the above statistics change with time is explored in more detail as a function of source distance and group.

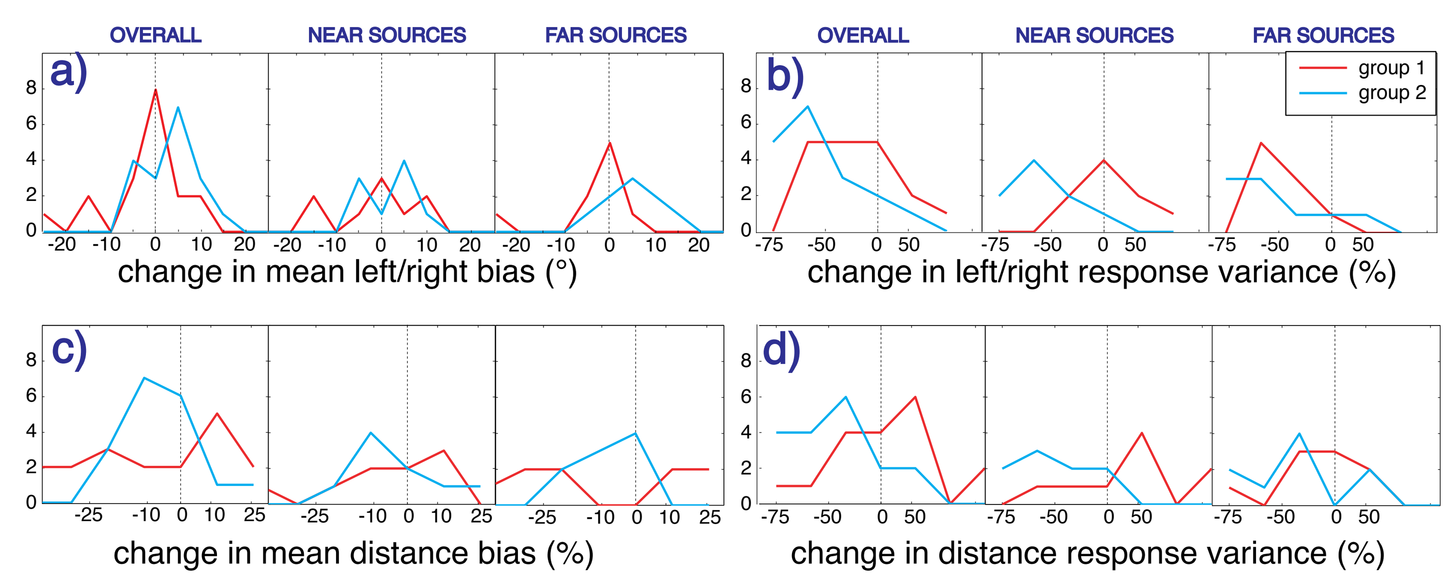
Left/right bias (Fig 3a)
- no clear trends are evident

Left/right and distance variance (Fig 3b & 3d)
- as noted above, overall variance decreases for both groups
- group 2: variance decreases for near and far sources
- group 1
  - for far sources, variance decreases with time
  - for near sources, variance shows little change

Distance bias (Fig 3c)
- no clear trends are evident

The interaction between room position and experience plays out differently depending on room position order and source location
- group 1 started in an "easy" room position; response accuracy only improves for far sources (where reverberation is strong)
- group 2 started in the "most challenging" room position where reverberation is always strong; response accuracy improves for all source positions when they move to the center of the room

FIGURE 3 Histograms of change in performance over time for Group 1 (initially in center) and Group 2 (initially in corner). Left column: all source positions (18 points). Middle and right columns: break down for near and far positions, respectively (9 points). a) Difference of absolute initial and final left/right bias b) % change in left/right variance c) Difference of initial and final distance bias d) % change in left/right variance.



EFFECT OF ROOM POSITION

The same statistics are plotted as a function of room position, broken down by source location and group. Room effects are evident in panels with a consistent pattern across groups as a function of room position. Differences between groups suggest either subject effects or an influence of experience.

Left/right bias
- is larger when a wall is behind the subject (B and Co) overall
  - shows similar trends in 3/6 spatial regions, independently
- the bias is largest for condition B (leftward bias is 3.4° re: Ce), and is statistically significant at p = 0.005
- effect is reduced for group 1 (experience reduces bias?)

Left/right variance
- is smallest for Center and largest for Corner
- increases with source laterality, especially for near sources
- decreases with experience for many source positions

Distance bias
- shows little systematic change with room position
- is more positive for group 1 than group 2
- is larger in magnitude for near compared to far sources

Distance variance
- is largest in Corner, especially for near sources

Room position causes different effects on different aspects of localization. These effects vary with source location. Experience decreases response variability and bias in left/right judgments, but has no systematic effect on distance judgments.

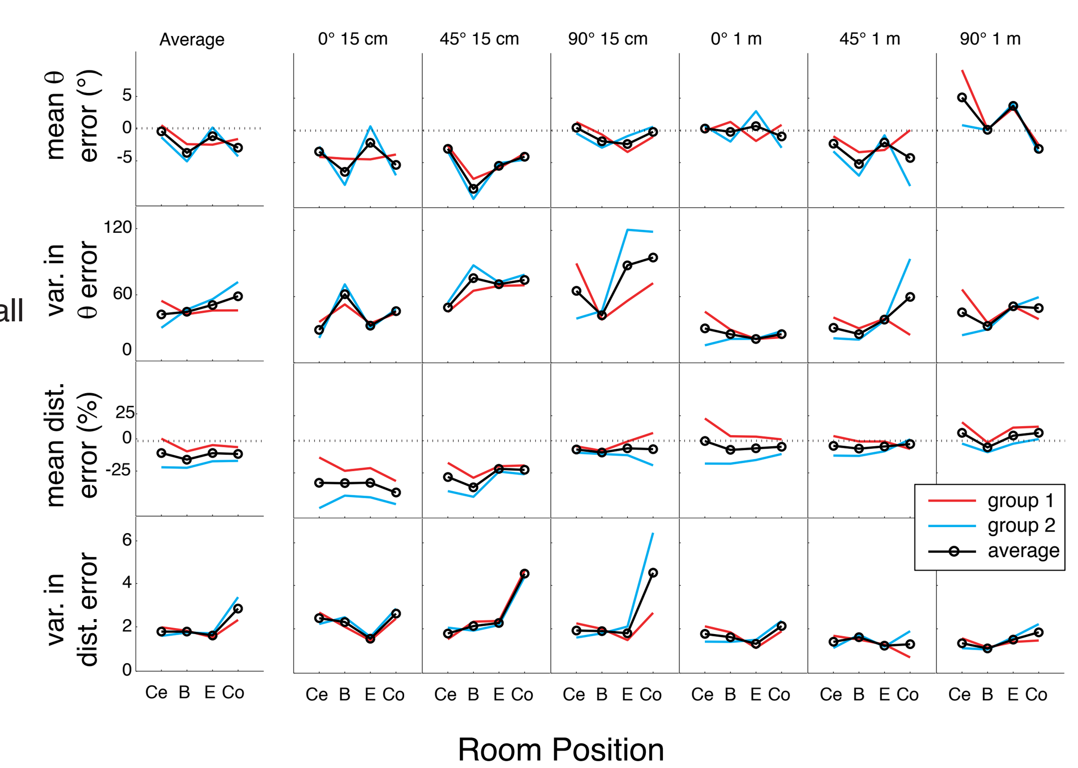


FIGURE 4 Localization performance as a function of listener position in room (Center of room, Back to wall, Left Ear to wall, and Corner). Columns show different regions of source; last column is the average across all source locations. Rows show the four statistics of azimuthal bias, azimuthal variance, distance bias, and distance variance (top to bottom, respectively). Overall average in black; group means in color.

5. LISTENER IN CENTER OF ROOM

ACOUSTIC MEASURES

Reverberation causes frequency-to-frequency variability in localization cues (Fig 5a & 5b), which may add to localization uncertainty. This variability is measured by computing the mean of the magnitude of the first-order difference in 1/12-octave smoothed versions of the cues (Fig 5c and 5d).

Reverberation fills in high-frequency notches in the monaural transfer functions (Fig 5a), primarily for the far (left, in these cases) ear
- ILD tends to be reduced in magnitude at high frequencies

Reverberation increases the variability in ITD as a function of frequency (Fig 5b), primarily at low frequencies
- ITD is less reliable at low frequencies

Frequency-to-frequency variability changes consistently with source position
- for far ear spectrum (top panel, Fig 5c) and binaural cues (Fig 5d), variability increases with source laterality and source distance
- for near ear spectrum (bottom panel, Fig 5c), variation decreases with source laterality and increases with source distance

Hypotheses
- left/right response variability may increase with source laterality and distance (due to low-frequency ITD and high-frequency ILD variability)
- distance responses may be less reliable for near and medial sources
- distance judgments may be based on frequency variation in other cues

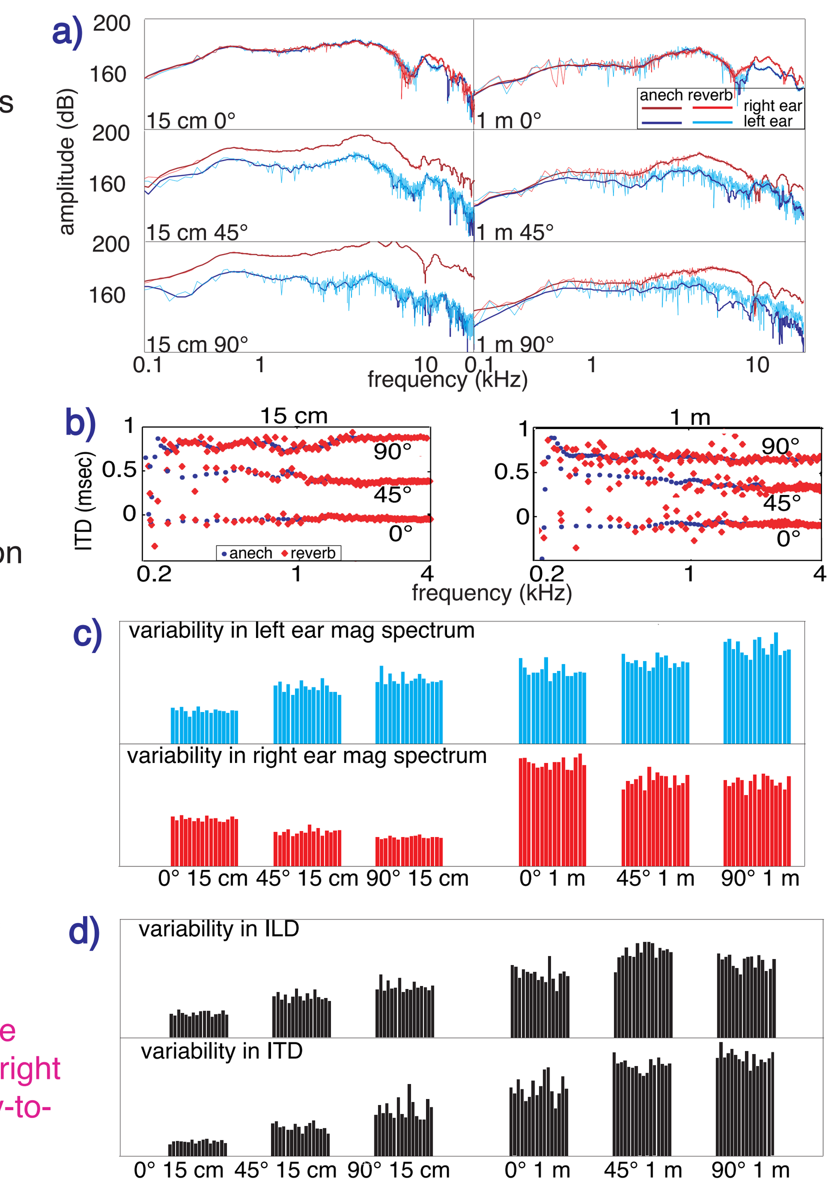


FIGURE 5 a) Anechoic and reverberant magnitude spectra (KEMAR) at 6 source positions. b) Anechoic and reverberant ITD (KEMAR) for the same source positions. c) Frequency-to-frequency variability in the left (top) and right (bottom) magnitude spectra (16 subjects, 6 source positions) d) Frequency-to-frequency variability in ITD and ILD (16 subjects, 6 source positions).

BEHAVIORAL MEASURES

Individual listeners' localization performance when seated in the center of the room is shown in Figure 6.

Left/right bias (Fig 6a)
- no clear trends in bias as a function of source position

Left/right variance (Fig 6b)
- variance grows with source laterality; however this may be due to psychoacoustic as well as acoustic factors
- variance decreases with distance; however, this may be due to a fixed absolute error in inches (which corresponds to a relatively large angular error for near sources)

Distance bias (Fig 6c)
- bias decreases with distance (subjects overestimate distance of near sources, but are accurate for source near 1 m)
- bias depends on source laterality for near sources

Distance variance (Fig 6d)
- variance decreases with source laterality
- variance decreases with source distance; however, this may be due to a fixed absolute error in inches

Results suggest that the strength of reverberation is inversely proportional to left/right accuracy and that distance judgments depend on the monaural near-ear signal.

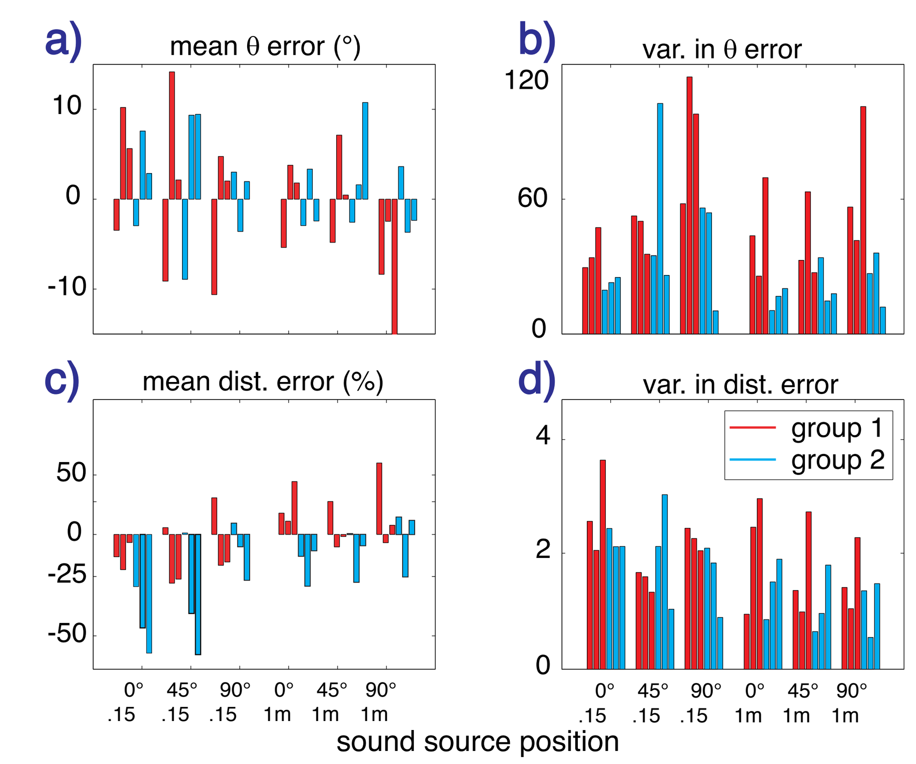


FIGURE 6 Mean and variance in localization judgments as a function of source position. Each bar represents one listener. a) left/right bias b) left/right variance c) distance bias d) distance variance.

6. CONCLUSIONS

Behavioral Experiments
- Room position has a strong impact on localization behavior
- Experience has a strong impact on localization behavior
- Response variance tends to be large when a listener is near a (any) wall, but decreases with experience
- Distance bias is not affected by room position or experience, despite the importance of reverberation for distance perception
- Room position matters more for near sources than far sources.

Acoustic Measurements
- Reverberation causes systematic degradations in acoustic localization cues that vary with the level of the direct sound
  - variations are largest for far sources
  - effects vary with source laterality

Relating Acoustics to Behavior
- Acoustic predictions are confounded with other factors in this study, making strong conclusions problematic
- Results are consistent with the hypothesis that
  - laterality is determined by binaural cues
  - in reverberant rooms, distance is determined by monaural near-ear cues

7. REFERENCES

Bronkhorst, AW & Houtgast, T (2000) "Auditory distance perception in rooms" Nature 397: 517-520

Brown, T (2000) "Characterization of Acoustic Head-Related Transfer Functions for Nearby Sources", Unpublished M.Eng. Thesis, MIT

Brungardt, DS (1998) "Near-Field Auditory Localization". Unpublished Ph.D. Thesis, MIT

Santarelli, S. (2001) "Auditory Localization of Nearby Sources in Anechoic and Reverberant Environments" Unpublished Ph.D. Thesis, Boston University

Shinn-Cunningham B. (2000) "Learning Reverberation: Considerations for Spatial Auditory Displays" in Proceedings of ICAD, Atlanta, GA, 126-134