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Scaling perceived distance of virtual sound sources*

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Abstract

Magnitude estimation and paired-comparison scaling methods were applied to the problem of measuring perceived auditory distance. Stimuli consisted of binaural recordings made in a reverberant hallway at distances of 1, 2, 4, 8, 16, 32, and 64 ft. A loudspeaker-produced broadband noise burst, 100 ms in duration, served as the distal stimulus. Insert-style microphones were placed in the ears of a single individual, with measurements made from two directions, extending in distance either from the individual's front or left side. Construction of virtual sound source stimuli in this fashion insured that the stimulation reaching the listener was naturalistic and therefore possessed the acoustic cues thought to be important in the real-world perception of auditory distance. Five listeners were presented these stimuli in several variants of both the magnitude estimation and paired-comparison paradigms. Though relatively large individual variability exists, the resulting scales are all compressed when compared to the corresponding scale of physical distance. The amount of compression is shown to be approximately constant across scaling method, thereby providing validation for each method's measurement of a similar underlying psychological process. [Work supported by NASA.]

Goal

The goal of this work is to evaluate different methods for scaling perceived distance of sound sources - specifically sources presented in a "natural" environment. Acoustic parameters that vary lawfully with changing physical sound source distance (in most natural environments) include:

- Intensity
- Ratio of direct to reflected energy
- High-frequency energy

It is assumed that optimal scaling of virtual sound source distance will be achieved when all of these cues are made available to the listener and sound sources are perceived as external to the listener's head. The virtual sound source stimuli used in this experiment are intended to satisfy both of these requirements.

Methods

Stimuli

Stimuli consisted of binaural recordings of a noise burst made in a semi-reverberant hallway (see Figure 1). Miniature electret microphones (Sennheiser KE4-211-2) were inserted into the ear canals of a single individual such that an acoustic seal was formed (using Etymotic Research ER-13R-2 ring seals) between the microphone and the entrance of the ear cannel (see Figure 2). Microphone outputs were pre-amplified and fed to a DAT recorder with a sampling frequency of 44.1 kHz (Sony TCD-D3). Recordings were made at distances of 1, 2, 4, 8, 16, 32, and 64 feet from the sound source. Two angular orientations at each distance were recorded - one in which the participant faced the sound source (0° azimuth), another in which the participant was rotated 90° such that the sound source was opposite the left ear (-90° azimuth). The distal sound source was a Gaussian noise burst 100 ms in duration (gated on/off with a 5 ms raised cosine window) played through a loudspeaker (Realistic Minimus 3.5) at ear height.

Recordings were re-sampled via a TDT PD1 A-to-D (44.1 kHz sampling frequency), windowed to a 1.5 second duration (5 ms raised cosine window), and stored on a PC for future playback. All experimental presentation was accomplished via a TDT PD1 D-to-A and Sennheiser HD 520 II headphones. No explicit headphone correction filter was applied to the stimulus.

Listeners

Five paid undergraduates (3 male, 2 female) participated as listeners in all experiments. All had audiometrically verified normal hearing.

Figure 1. View of the recording environment from the listener's perspective at 32 feet.

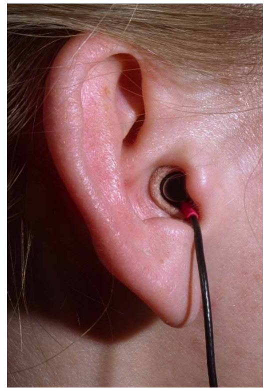


Figure 2. Microphone placement.

Experiment I: Apparent Distance Estimation

Procedure

Listeners were asked to judge the apparent egocentric distance in feet of stimuli presented in random order. A single stimulus angular orientation (either 0° or -90° azimuth) was presented within a block of trials. Twenty repetitions of each stimulus were presented. Responses were made via numeric entry on a computer terminal inside a sound attenuating booth.

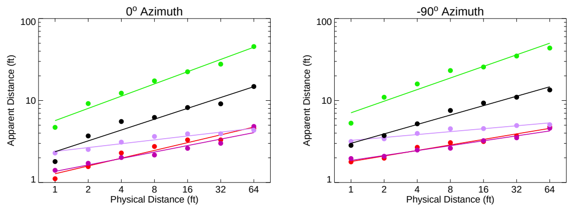


Figure 3. Apparent distance judgments for five listeners (denoted by symbol color) and two angular orientations plotted on a logarithmic ordinate. Each symbol represents the geometric mean of 20 judgments.

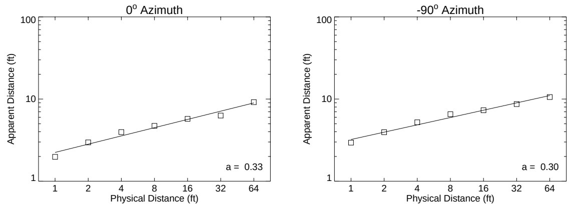


Figure 4. Average apparent distance judgments ($n = 5$) for two orientations plotted on a logarithmic ordinate. Symbols represent geometric means across all judgments and listeners (100 trials/symbol). Values of Stevens' exponent, **a**, are shown in the lower right corner.

Results

Figures 3 & 4 show results of the apparent distance judgments, both in terms of averages (Figure 4) and individual listeners (Figure 3). Two general conclusions may be drawn. First, listener's judgments of apparent distance tend to underestimate physical distance. This effect has been frequently reported in the literature, dating to at least von Békésy (1949). Second, the amount of underestimation varies considerably between listeners. Such variability has also been reported by Nielsen (1993), among others.

Experiment II: Ratio Scaling

Procedure

Listeners performed two variants of a magnitude estimation task, one in which no standard stimulus was presented, and a second in which 3 different standards were presented. In both cases, angular orientation remained constant within a block of trails. The 1, 8, and 64 foot stimuli were utilized as standards. They were played before every trial and did not vary within a block of trials. Listeners were told that the standard stimuli corresponded to magnitudes of 1, 10, and 100. Twenty repetitions of each stimulus were presented in random order for all cases. Listeners entered responses on a computer terminal located inside a sound attenuating booth.

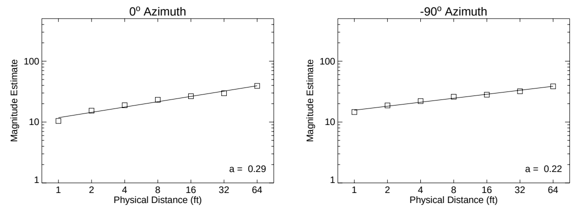


Figure 5. Average magnitude estimates ($n = 5$) for two orientations. Symbols represent geometric means across all judgments and listeners (100 trials/symbol). Values of Stevens' exponent, **a**, are shown in the lower right corner.

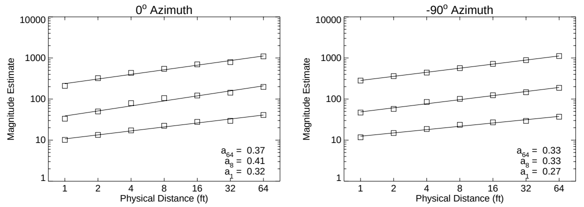


Figure 6. Average magnitude estimates ($n = 5$) for two orientations and three standard conditions (standard stimuli at 1, 8, or 64 feet). Symbols represent geometric means across all judgments and listeners within a given standard condition (100 trials/symbol). Values of Stevens' exponent, **a**, are shown in the lower right corner for each of the standard conditions.

Results

Figures 5 & 6 show results of the magnitude estimation experiments. Stevens' exponent values were computed via linear regression in log-log space. Since standard errors for all values of **a** (including those from Experiment I) were greater than 0.20, it may be concluded that no significant differences exist between exponent values for the various conditions. Additionally, these exponent values agree with those of Petersen (1990) who reports **a** = 0.28 for magnitude estimates of distance varying tonal stimuli in a free-field environment.

Experiment III: Thurstonian Scaling

Procedure

Listeners were presented with all possible pairs (not including like pairs) of the 7 stimuli (42 pairs) in random order for each angular orientation. Angular orientation was held constant within a block of trials. The listener's task was to indicate which stimulus from the pair appeared egocentrically farther away from them. Fifty repetitions of each stimulus pair were presented. Listeners entered responses on a computer terminal (inside a sound attenuating booth) and were provided no feedback as to the correctness of their response.

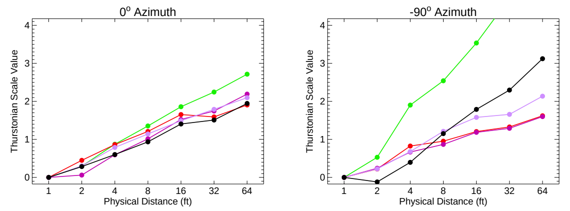


Figure 7. Thurstonian scale values for five listeners (same coloring scheme as Figure 3) and two orientations. Scales were derived from 2100 paired-comparison judgments.

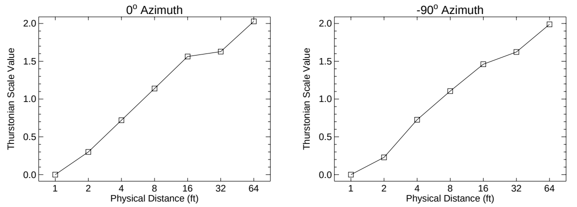


Figure 8. Average Thurstonian scale values ($n = 5$) for two orientations. Scales were derived from 10500 paired-comparison judgments.

Results

Interval scales were constructed from the paired comparison data based on Thurstone's case V model (for details see Torgerson, 1958). This type of model contends that the proportion of times a given stimulus is judged "farther away" than another stimulus is directly related to the perceived distance between the two stimuli. Figures 7 & 8 display the resulting scales for both individuals (Figure 7) and the group (Figure 8). An initial scale value of zero was arbitrarily chosen for all scales. Approximately equal scale intervals are obtained between doubling distance increments. A slight difference in inter-listener variability is observed between angular orientations.

Experiment IV: MDS

Procedure

Listeners were presented with all possible pairs of the 14 stimuli, 7 distances at each of the two angular orientations (196 total possible pairs). The listener's task was to judge the apparent distance (in feet) between pairs of stimuli. Ten repetitions of each pair were presented. Responses were made via numeric entry on a computer terminal inside a sound attenuating booth.

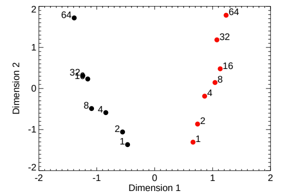


Figure 9. Stimulus configuration for a 2-dimensional INDSCAL solution. Black symbols represent Stimuli at 0° azimuth, red symbols -90° azimuth. Distance in feet is displayed adjacent to each symbol.

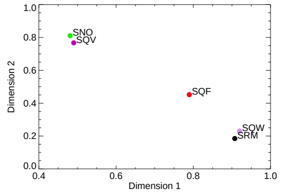


Figure 10. Derived listener weights for a 2-dimensional INDSCAL solution. Symbol color represents individual listeners (listener ID codes are adjacent to the symbols).

Results

A multidimensional scaling algorithm, INDSCAL, was applied to the data. INDSCAL allows for scaling analysis of both stimuli and listeners. A 2-dimensional solution was determined to adequately fit the data (R^2 = .86). Solutions of higher dimensionality did not account for significantly more variance (3-D R^2 = .89, 4-D R^2 = .90). Figure 9 displays the derived stimulus configuration for a 2-D INDSCAL. The stimulus space dimensions may be interpreted as corresponding to perceived angular orientation (Dimension 1) and perceived distance (Dimension 2). The resulting interval scale of perceived distance (Dimension 2) shows approximately equal intervals between doubling physical distance increments. Figure 10 shows individual listener weights for each dimension. These weights reflect the relative importance each listener placed on a given dimension when making his/her distance judgments. Individual variability is observed in weighting strategies.

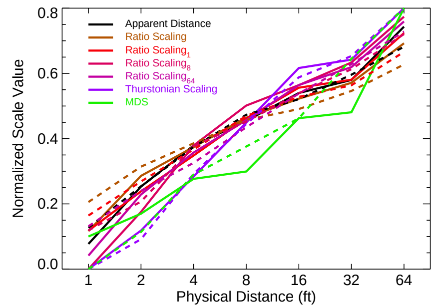
Conclusion

A summary of all scales of perceived distance is displayed in Figure 11. Little difference is observed between scaling methods. It may be concluded that all methods probe a similar psychological process, one in which exponentially varying physical distance maps to linearly changing perceived distance. It is plausible to suppose that this process may be related to a loudness process, since both have similar exponents (**a** ≈ 0.3 for the *sone* loudness scale) and similar physical variables. Individual differences in this process are also observed. It may be additionally concluded that angular orientation does not affect perceived distance. Parting considerations for scaling method selection are summarized in Table 1.

Figure 11. Summary plot of all scales. Solid lines represent scales for 0° azimuth, dashed lines -90° azimuth. Scale values have been normalized for comparison purposes according to the following permissible scale transformations (Stevens, 1975).

Apparent Distance Scales & Ratio Scales	:	$\log(y') = \log(k) + \log(x)$ which is equivalent to $y' = kx$.
Thurstonian Scales & MDS	:	$y' = kx + c$

k and *c* are constants



	Apparent Distance	Ratio Scaling	Thurstonian Scaling	MDS
Listener Response Method	Apparent Distance Judgment	Magnitude Estimation	Paired Comparison	Apparent Distance Between Pairs
Resulting Scale Measurement Level	Ratio 👍	Ratio 👍	Interval 👎	Interval 👎
Scale Dimensionality	Uni- 👎	Uni- 👎	Uni- 👎	Multi- 👍
Total Number of Trials (0° & -90°)	1400 👍	1400 👍	21000 👎	9800 👎
Ease of Task Explanation to Listener	👍	👍👎	👍	👍
Computational Complexity	👍	👍	👎	👎

Table 1. Summary information and ratings of scaling procedures.

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