Localization of noise in a reverberant environment

Brad Rakerd[1] and William M. Hartmann[2]

[1] Department of Audiology and Speech Sciences, Michigan State University, East Lansing, MI, 48824, USA
[2] Department of Physics and Astronomy, Michigan State University East Lansing, MI, 48824, USA, hartmann@pa.msu.edu

1 Introduction

The effect of room acoustics on the human ability to localize a broad-band noise was studied in a variable-acoustics concert hall, the Espace de Projection (ESPRO) at the Institut de Recherche et Coordination Acoustique/Musique (Hartmann, 1983). In that study the noise was turned on slowly to eliminate attack transients. Listeners proved able to localize such slow-onset noise accurately, substantially more accurately than they could localize a complex tone with a slow onset. The explanation given for this advantage with noise was that its fine structure is transient and can trigger the precedence effect, a perceptual process that enhances the accuracy of sound localization in rooms (Wallach, Newman, and Rosenzweig, 1949; Litovsky, Colburn, Yost and Guzman, 1999). A question left unanswered at that time was whether the availability of an attack transient might further enhance the localization of noise in a room. That question is addressed here.

The ESPRO study also revealed an interesting decision-making strategy with slow onsets. The listeners tended to make their decisions early, while the noise envelope was still rising. During this interval, the reverberant field of the room had not fully formed and the direct sound stood out by comparison. It was conjectured that listeners chose to exploit this early advantage, even though the direct sound was still relatively faint. As a result, it is possible that the ESPRO experiments did not fairly represent the ability of the listeners to localize noise based on steady-state conditions only. The present study introduces a new onset method whereby only the steady-state sound field is available to the listeners.

Still another finding of the ESPRO study was that listeners localized noise less accurately in a reverberant configuration of the hall than in an absorbing configuration. To account for the increased error with increased reverberation, it was proposed that reverberated sound acts as a masker that obscures the direct sound, an effect that could be quantified by a direct-reverberant sound power ratio. That ratio is a key parameter in the present study. In sum, the present study was undertaken to learn more about the localization of broadband noise in rooms – about the role of onsets and about the strategies that listeners use when onset transients are not available.

2 Experiment 1: Noise onsets

Experiment 1 addressed two questions about noise onsets. The first question was whether an attack transient enhances the localization of noise in a room. To answer this question, we asked listeners to localize two broadband noises, one turned on slowly and the other turned on abruptly. The second question was whether, with slow-onset noise, listeners benefit from making their localization decisions early while the noise onset is increasing and before the reverberant field in a room is fully developed. To answer this question we compared the localization of slow-onset noise with localization of an identical noise that was masked for its first few seconds.

2.1 Methods

The experiment was run in a reverberation room (IAC 107840) with dimensions 7.7 m (wide) $\times$ 6.4 m (long) $\times$ 3.6 m (high) and with a reverberation time of 4 s at speech frequencies. Localization ability was measured using the source identification method (Hartmann, Rakerd and Gaalaas, 1998) with a source array of 24 loudspeakers. The speakers were matched in frequency response, extended to 17 kHz, and flattened in one-third octave bands by an equalizer. The speakers were secured with velcro mounting to the top of two 2.4-m rails, with an inter-speaker separation of 2 degrees. As sources, the speakers were numbered from left to right with speakers 12 and 13 on either side of the listener's forward direction. Thus, the array spanned a total angle of 46 deg, half to the listener's left and half to the right.

An important experimental parameter was the ratio of direct to reverberant sound, controlled by varying the source-listener distance, either 3 m or 6 m. Whenever we changed this distance, we also moved the sources along the rails to maintain the 2-degree separation of adjacent sources. For the 3-m distance the measured C-weighted direct-reverberant ratio was -7 dB. For the 6-m distance it was -13 dB. These differ by 6 dB, as expected if the reverberant level in the room is independent of listener location.

Noise onsets

The stimulus for this experiment was white noise with a steady-state level of 55 dBA at the listener's chair. There were three different noise onset conditions – abrupt, slow, and masked. For the abrupt-onset stimulus, the noise was turned on with a step-function envelope. It remained on until the subject gave a localization response. Following the response, the stimulus was turned off with a 500-ms ramp. The slow-onset stimulus was the same except that the noise was turned on gradually with a linear amplitude envelope, 2 s in duration. For the masked-onset stimulus, a trial began with a masking noise from a loudspeaker directly behind the listener's neck. The masking noise was uncorrelated with the stimulus source noise, and it was sufficiently intense (85 dBA) to render the source undetectable. The masker was turned on with a 100-ms ramp. After 250 ms, one of the source speakers was turned on gradually. After the source onset was completed, the masking noise was removed (500-ms offset ramp), leaving only the source noise sounding.

Listeners and procedure

There were seven listeners in the experiment. Five of them (A,B,C,D and E) were students, 17-30 years old, with audiometrically normal hearing in both ears. The other two listeners (F and G) were middle-aged men with audiograms that showed modest bilateral high-frequency hearing loss, approximately 25 dB at 8 kHz.

Listeners were tested one at a time. The chair height was adjusted to put a listener's ears 1.17 m from the floor, which matched the height of the speakers in the source array. To assure that all subjects received the same stimuli, we obliged them to sit still and to make their localization judgments while facing straight ahead. An L-shaped bar, connected to the back of the chair, pressed against the crown of the head as a guide to keep the head stationary. All of the sources of the array could be viewed by moving the eyes without moving the head.

On each trial, a noise stimulus was presented from one of the 24 sources, selected at random. The listener then reported the number of the source (1 through 24) that was heard to have sounded. Test trials were blocked into runs of 48 trials, two presentations from each of the 24 sources. Altogether, a listener did three runs for each onset condition at the 3-m listening distance and three runs at the 6-m distance. The order of these runs varied randomly across listeners.

2.2 Results and discussion

Response plots – Typical listener

A detailed picture of a subject's performance is provided by response plots, as shown in Fig. 1 for listener D, the subject whose response pattern was most similar to the average. The panels of Fig. 1 give listener D's results for the six different conditions of the experiment: tests at 3 and 6 meters with abrupt, slow, and masked onsets. Comparisons among the panels show evidence of three notable effects.

(1) Listener D was sensitive to the direct-reverberant sound power ratio in the room. Function $R(k)$ was closer to the 45-degree line at the 3-m distance than at 6 m for every onset condition. Also, the error bars were smaller at 3 m. We attribute this difference to the fact that the direct-reverberant ratio was more favorable by 6 dB at 3m.

(2) Listener D benefited from an attack transient, particularly when listening at 6 m. The responses in the abrupt-onset condition were visibly closer to the 45-degree line than the responses in the slow-onset condition, and the error bars were generally smaller.

(3) Finally, listener D was able to make successful localization decisions before the reverberant field had reached its steady state. Error bars were much smaller for the

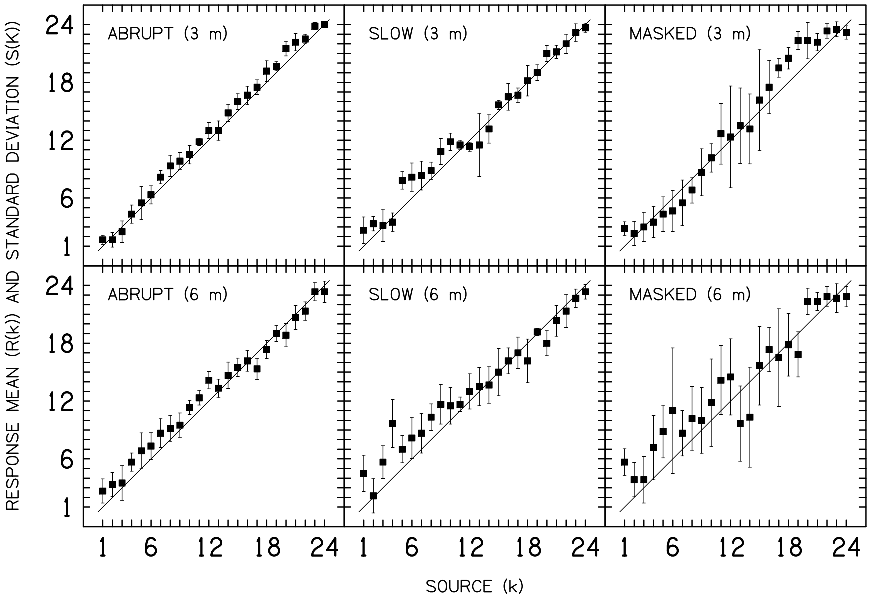

Fig. 1. Response plots for listener D: Statistic $R(k)$ is the mean response number for each source as a function of the source number, k. Perfect performance corresponds to a 45-degree line. The error bars represent one standard deviation about the mean response to a source, statistic $s(k)$. [See Rakerd and Hartmann (1986) for a detailed description of these statistics.] A separate plot is given for each source distance and onset condition of Experiment 1.

slow-onset conditions where the listener was able to hear onsets building in the room, than for the masked-onset conditions where the build-up was inaudible.

RMS error – All listeners

An overall measure of localization ability is statistic $\overline{D}$, the root-mean-square error averaged over all 24 sources. Figure 2 shows how $\overline{D}$ varied with distance to the sources and with the various onset types. Functions are plotted separately for each listener. Analysis of variance on the results showed significant effects of both distance to the sources [$F(1,6) = 51.26, p < 0.001$], with the listeners overall more accurate at 3 m than at 6 m, and onset type [$F(2,12) = 34.62$, $p < 0.001$], with listeners most accurate for noise with an abrupt onset, intermediate for noise with a slow onset, and least accurate for noise with a masked onset. (Post-hoc tests showed all of the pairwise difference among the onset means to be significant; $p < 0.01$). The results of Experiment 1 support two conclusions about the role of noise onsets. The first conclusion is that the presence of an attack transient does increase the accuracy of localization of noise in a room. The second conclusion is that when listening to noise with a slow onset listeners benefit by listening in advance of the buildup of the reverberant field of a room. Figure 2 shows that this benefit is reduced when the source-listener distance is increased from 3 meters to 6 meters. We conjecture that this effect occurs because increasing the distance reduces the delay between the direct sound and early reflections.

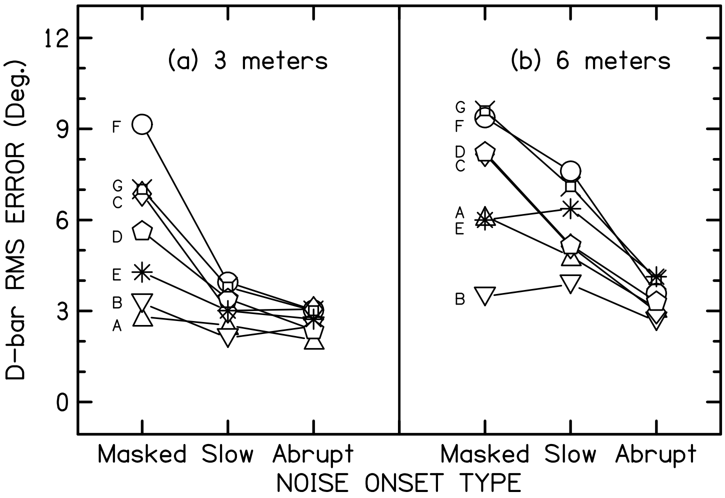

Fig. 2. RMS error $\overline{D}$ for seven listeners depending on listening distance (direct-reverberant power ratio) and onset type.

3 Experiment 2: Head/body turn

In Experiment 1 subjects were required to hold their heads and bodies motionless so that stimuli from individual sources were reproducible. In everyday life, listeners are free to move, and it seemed possible that movement could improve localization ability here by allowing integration of information obtained from different perspectives. Experiment 2 was run to see whether rotating the head and body would enhance the ability to localize noise in a fully formed reverberant sound field.

3.1 Method

The stimulus for this experiment was the masked-onset noise. It was presented at the 6-m distance where the direct-reverberant ratio was most disadvantageous. Two good localizers (A and C) and two poor localizers listeners (F and G) did three interleaved runs under each of two conditions: (1) while sitting still and facing straight ahead, (2) while free to rotate the head and body. In condition (2), a seated listener was minimally required to rotate the trunk around once and to move the head back and forth once before making a localization response. The listener was then free to make any additional movements as desired, so long as he remained seated. All of the listener elected to move extensively, devoting 5 to 10 minutes per (48-trial) run to the exercise.

3.2 Results and discussion

Figure 3 shows the results of the experiment. In the absence of a head/body turn, both of the older listeners (F and G) made large localization errors, as in the prior experiments with masked-onset noise. When they were allowed to move, F and G both improved their localization accuracy substantially (mean decrease in $\overline{D}$ = 3.3 deg, or 35 percent). The two younger listeners (A and C) were much more accurate than the older subjects when sitting still. One of them (A) was helped substantially by moving, even relative to this good baseline, improving accuracy by 1.6 deg, which exceeded the error bars. The other young listener (C) was unaffected. A comparison of 12 stationary-moving run pairs (4 listeners $\times$ 3 run pairs per condition) showed an advantage for moving (accuracy improved by 1 deg or more) on ten of the twelve (sign test, $p < 0.005$). We conclude that head/body motion can aid a listener in localizing noise in a room, particularly when the listener is substantially challenged by reverberation or by some limitations on hearing.

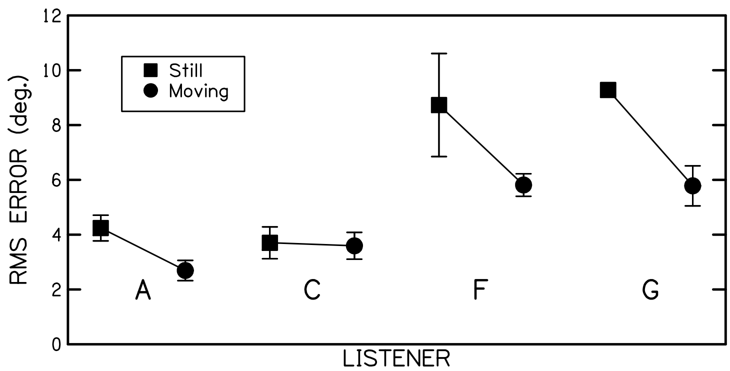

Fig. 3. RMS error $\overline{D}$ for four listeners when seated in a fixed position (squares) and when allowed to move (circles). Error bars show $\pm$ one standard deviation over runs.

4 Summary and conclusions

This study examined the localization of broadband noise in a reverberant environment. Experiments were primarily devoted to the role of noise onsets. In Experiment 1, we varied the onset characteristics of a broadband (white) noise in two ways: (a) An abrupt onset and a slow onset contrasted in that the former invited precedence effect with an attack transient and the latter did not. (b) The slow onset and a masked onset contrasted in that the former was audible during the development of the reverberant sound field and the latter was not. We also varied the ratio of direct to reverberant sound by positioning a listener at different distances from the sources. In Experiment 2 we studied the possibility that localization performance might improve if listeners were allowed some motion. The results of the experiments, as described in Figs. 2 and 3, lead to the following conclusions:

(1) Localization of noise is enhanced by an attack transient. An attack transient appears to be particularly helpful when the direct-reverberant ratio is low. Attack transients give an advantage over slow onsets when the reflections are not much delayed *re* the direct sound. By contrast, attack transients are of only marginal value when noise is presented by headphones or tones are presented in an anechoic room (Tobias and Schubert, 1959; Rakerd and Hartmann, 1986).

(2) Onsets are a great leveler among individuals. Whereas the ability to localize steady steady-state sounds varies greatly among listeners, the ability to localize sounds with an onset transient shows best to worst differences less than 1.5 degrees among our seven listeners.

(3) Given a slowly increasing direct sound, listeners make localization decisions early, before the reverberant response of a room has fully formed. During this interval the power of the direct sound is low, but the ratio of direct sound power to reverberant sound power is favorable. Thus, the ESPRO experiments (Hartmann, 1983) do not fairly represent the ability of listeners to localize in a steady-state reverberant field.

(4) Listeners can use head and trunk motions to improve localization of sounds in the steady state. It is interesting to try to imagine what kind of computations the auditory system actually performs on the binaural sound field to obtain improved performance.

5 Acknowledgements

This project was supported by the National Institutes of Health through NIDCD grant DC00181.

References

Hartmann, W.M. (1983) "Localization of sound in rooms," J.Acoust. Soc. Am. 74, 1380-1391.

Hartmann, W.M., Rakerd, B. and Gaalaas, J.B. (1998) "On the source identification method," J. Acoust. Soc. Am. 104, 3546-3557.

Litovsky, R.Y., Colburn, H.S., Yost, W.A. and Guzman, S.J. (1999) "The precedence effect," JASA **106**, 1633-1654.

Rakerd, B. and Hartmann, W.M. (1986) "Localization of sound in rooms, III: Onset and duration effects," J. Acoust. Soc. Am. 80, 1695-1706.

Tobias, J.V. and Schubert, E.R. (1959) "Effective onset duration of auditory stimuli," J. Acoust. Soc. Am. 31, 1591-1594.

Wallach, H., Newman, E.B., and Rosenzweig, M.R. (1949) "The precedence effect in sound localization," Am. J. Psychol. 52, 315-336.