Perception of the relative distances of nearby sound sources

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The pressure of a sound varies systematically with a listener's distance from a sound source, providing a useful cue for perceiving changes in the distance between a listener and a sound-producing object. The pressure-discrimination hypothesis predicts that thresholds for discriminating changes in distance are constrained by the underlying ability to discriminate the resulting changes in sound pressure—specifically, that the smallest discriminable change in distance should be about 5% of the reference distance. Previous studies reported thresholds of about 5% for reference distances greater than a few meters but surprisingly worse thresholds for closer reference distances. In the present study, thresholds at two close distances, 1 and 2 m, were within the 5% range predicted from the pressure-discrimination hypothesis. Moreover, thresholds were significantly worse in a control condition in which the pressure cue was removed. Results of previous studies were adjusted to take into account the possibility of conservative response tendencies by the subjects. These adjusted findings agree well with the results of the present study and the pressure-discrimination hypothesis. It is concluded that variations in sound pressure are very useful for perceiving changes in listener-source distances, even at close distances.

Information about the locations of objects that produce or reflect sound is available through the sense of hearing. The distance component of auditory localization has been investigated much less extensively than the directional component, despite the fact that people typically perceive sound sources as being located in three-dimensional space. The research reported here emphasizes an important source of information underlying auditory distance perception—namely, the pressure of a sound. As the distance between a sound source and a listener changes, the pressure measured at the listener's position varies systematically, a relationship known since early work on auditory distance perception (Gamble, 1909). Over the years, a number of potentially useful acoustic correlates of distance have been proposed. Coleman (1963) and Blauert (1983, pp. 116 ff.) reviewed these cues and the related empirical work. The availability of specific cues depends on characteristics of the sound signal, the acoustic environment, and the listener's task. In addition to pressure, some of the cues that have been investigated are the ratio of direct to reverberant sound (this ratio decreases with increasing distance), spectral shifts over long distances associated with frequency-dependent sound transmission through a medium (in air, high frequencies are attenuated more than low frequencies), and spectral shifts over short distances due to filtering properties of the listener's ears, head, and torso.

Clearly, there are multiple sources of information for auditory distance perception, with presumed redundancy across them. The present study does not attempt to assess the relative importance of different cues or how information is integrated across cues. Rather, it focuses on the usefulness of the pressure cue, especially for perceiving changes in self-environment distances, whether the changes arise from one's own movements or from movements of sound-producing objects.

The physical description of how sound pressure, which is often called intensity,¹ varies with distance from a sound source is straightforward. The power from a spherically radiating sound source is distributed over the surface of a sphere with area $4\pi r^2$, where r is the radius of the sphere, corresponding to the distance between a listener and a sound source. For small values of r , the total power is concentrated in a small area, so the power measured over an absolute subsection of that area is relatively large. For large values of r , the same total power is spread over a large area, so the power measured over the same-sized absolute subsection is relatively small. Specifically, the power measured over a constant-sized area varies with distance (r) from the source by a proportion of $1/(4\pi r^2)$. Removing the constants from this relationship, power varies with distance by $1/r^2$. The auditory system actually responds to sound pressure, not power, so the variation of pressure with distance from the source needs to be considered. In wave motion, power is proportional to the square of pressure, or conversely, pressure is proportional to the square root of power. Therefore, pressure varies as the inverse of distance from the source—that is, as $1/r$. Here is an example, with pressure expressed in both absolute units (dynes/cm²) and relative units

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(dB SPL). A fairly loud sound would be 6.32 dynes/cm², or 90 dB. If this was the pressure measured at a given distance from the source, then the pressure measured at twice that distance would be lower by a factor of one half—that is, 3.16 dynes/cm², or 84 dB. Performance consistent with the $1/r$ relation was reported by Warren (1968), who found that subjects could adjust their own vocal output to keep a constant sound level at a microphone that varied in distance from them.

According to the pressure-discrimination hypothesis, the limiting factor for relative distance discrimination of sound sources is the availability of discriminable differences in pressure. Pressure discrimination has been extensively studied as a topic in its own right. Although there are subtle variations in pressure discrimination with overall sound level and with frequency, an accurate generalization is that pressure changes of about 5% (0.4 dB) are discriminable in listening situations approximating everyday activities. Summaries of this research are available in Green (1976, p. 254 ff.) and Scharf (1978, p. 188 ff.). Such a change in pressure is brought about by a 5% change in distance. Therefore, the pressure-discrimination hypothesis predicts that the smallest discriminable change in distance of a sound source will be about 5%.

The available findings on discrimination of changes in the distance of sound sources provide mixed support for the pressure-discrimination hypothesis. A number of older studies (e.g., Edwards, 1955; Gamble, 1909) reported distance changes much larger than the predicted 5%. For example, Edwards reported thresholds ranging from 22% at an 8-m reference distance to 55% at 1 m. Because of inadequate stimulus control and informal methods for threshold measurement, however, these findings may be considered underestimates of distance discrimination and are therefore equivocal with regard to the pressure-discrimination hypothesis.

More recently, Strybel and Perrott (1984) reported distance-discrimination thresholds of about 6% for reference distances from 6 to 49 m, but larger thresholds for shorter reference distances (19% at 0.49 m, 11% at 1.52 m, and 9% at 3.04 m). Simpson and Stanton (1973, Experiment 2) reported similarly high thresholds at short reference distances (33% at 0.61 m, 19% at 1.24 m, and 13% at 2.13 m). The pattern of findings from these studies suggests that pressure changes provide a basis for distance discrimination beyond a few meters but not at closer distances. This is paradoxical in that a perceptual ability that appears to be utilized over one range of distances is not utilized over another range in which it should still be available and for which there is clear functional value.

A possible resolution of this paradox is that certain methodological features may have produced an underestimate of abilities at short distance. Both of these recent studies used the method of limits, in which the subjects' task was to identify when a sound source that was being moved steadily toward or away from them had changed

from its original distance. This method may have encouraged subjects to be more conservative and to delay responding until a bit after they first perceived a change in order to be more accurate. If this were the case, then underestimates of true ability should have been greater at shorter than at longer distances. This is because the change in distance during the response delay, expressed as a proportion of the overall distance, would have been larger for shorter than for longer overall distances. Rather than the method of limits, the present study involved randomly interspersed trials on which a sound shifted toward or away from the subjects. A forced-choice procedure required subjects to respond by voting "toward" or "away" after each trial, thus preventing a cautious approach to the task.

Thresholds for discrimination of differences in distances of sound sources were measured in separate testing sessions at reference distances of 1 and 2 m. Both reference distances are within the short range at which relatively poor discrimination has been reported. On each trial, sounds were presented sequentially at two distances, and the subjects voted whether the closer sound was presented first or second. To ensure that performance was mediated by the pressure cue rather than by other distance cues, the experiment included a control condition in which sounds were presented from different distances but the pressure cue was eliminated by appropriate adjustments of signal strength.

METHOD

Subjects

The subjects were 8 young adults, 24 to 35 years of age, with normal hearing. All were graduate students or faculty members at Vanderbilt University. The first and second authors were subjects and knew the study's purposes, but the other subjects were naive. Except for the authors, the subjects were paid for participating.

Apparatus

The experiment was conducted in a 6×6×6 m anechoic chamber. The environment provided a low background sound level (38 dBC) and minimal reverberant sound. The apparatus for moving the loudspeaker was positioned near one corner, with the subject seated along the diagonal of the chamber at a listening distance of 1 or 2 m. The loudspeaker apparatus resembled a bicycle turned upside down so that a board with the loudspeaker attached could be rolled along the tops of the tires. The tires were 27 in. in diameter and were mounted to an upright support. The 5-in. JBL 8110 loudspeaker was attached to one end of a 74-in.-long board of 1.5×1.5 in. cross section. An experimenter moved the board manually to position the loudspeaker at various distances from the subject, using a ruler taped to the board as a guide and following instructions displayed on a computer monitor. Pilot work established that subjects rarely heard the movement of the board along the tires, and that when they did hear it they could not discriminate the direction of the movement.

The auditory stimulus was noise from a digitally simulated shift register, produced by a Zenith 158 computer using an eight-bit digital-to-analog converter on a Scientific Solutions Lab Tender board, with a sampling rate of 20 kHz. The signal was filtered to

pass frequencies between 100 and 8000 Hz using a KrohnHite 3202 filter. The stimulus duration was 500 msec with linear rise/fall times of 10 msec. The average sound level was 70 dBC at each of the reference listening distances, 1 and 2 m, but the level was varied randomly across trials within a range of ± 3 dB in order to prevent the subjects from basing their performance on a familiar sound level.

Procedure

A trial consisted of presenting the sound at two distances, the "far" or reference distance (1 or 2 m) and a "near" distance that was less than the reference distance by a percentage that varied across trials. There was a 1.5-sec silent interval between sounds, during which the experimenter moved the loudspeaker. The order of sound presentations (near-far vs. far-near) varied randomly across trials. The subject verbally reported whether the near sound occurred during the first or the second interval. After the subject voted, the experimenter gave feedback by saying "correct" or "incorrect." On the first trial, the distance between the two loudspeaker positions was 10% of the reference distance. On subsequent trials, the distance between loudspeaker positions varied in 1% steps according to a 2-down, 1-up algorithm (Levitt, 1971). For example, in the 2-m tests, the reference distance was always 2 m while the near distance began at 180 cm and changed in 2-cm steps. The minimum and maximum differences in distance were 0% and 20%, respectively. Testing continued through 20 reversals. Individual subject thresholds were calculated by averaging the differences (unsigned) between loudspeaker distances surrounding Reversals 6-20.

Each subject was tested at two reference distances, 1 and 2 m, on different days. During each session, three separate tests were conducted over a 1-h period. The first was always a practice test using the same stimuli as in the later experimental test. The second and third tests were experimental and control tests, given in counter-balanced orders across reference distances and subjects. On experimental and practice tests, the sound level was identical at the loudspeaker for the near and far sounds. In other words, a constant source pressure was presented at two different distances. On control tests, the digital signal amplitude for one of the loudspeaker distances was adjusted to produce different source pressures but equal pressures at the subject's position. Measurements with a sound-level meter confirmed that this adjustment resulted in equivalent pressures to within 0.25 dB. This should have rendered pressure ineffective as a basis for relative distance judgments without strongly affecting other cues such as spectral information. The subjects were told that the first test during each session was for practice, but they were not informed about the pressure cue or the distinction between experimental and control tests until after they completed all testing. The subjects wore a blindfold during testing but had ample opportunity to view the room layout beforehand.

RESULTS

Preliminary analyses of variance showed that thresholds were equivalent across the orders of reference distance (1, 2 vs. 2, 1 m) and experimental and control tests (experimental, control vs. control, experimental). Therefore, data were combined across these variables.

Effectiveness of Pressure Cue

Table 1 shows individual thresholds within each test condition, along with averaged performance. Thresholds are expressed as percentages of the reference distance. For example, Subject 1's experimental thresholds were 6.63% at 1 m (6.63 cm divided by the reference distance of 1 m) and 6.77% at 2 m (13.54 cm divided by the reference distance of 2 m). If sound pressure mediated discrimination, then thresholds on experimental and practice sessions should have been about 5% according to the reasoning outlined in the introduction of this paper, and thresholds on control sessions should have been substantially higher.

Individual thresholds were entered into a repeated measures analysis of variance with test type (practice, experimental, and control) and reference distance (1 and 2 m) as within-subjects factors. The main effect of test type was significant [$F(2,7) = 74.08, p < .001$], but neither the main effect of reference distance nor the interaction approached significance. The mean thresholds associated with the three test types collapsed across reference distance were 5.82% for experimental, 7.18% for practice, and 16.09% for control. Scheffé tests indicated that the mean experimental and practice thresholds did not differ from each other but were both significantly lower than the control threshold.

The effectiveness of the pressure cue was also reflected in the subjects' qualitative impressions of the control trials, when this cue was absent. Of the 6 subjects who were unfamiliar with the study's hypotheses, 3 spontaneously inquired within the first few control trials whether they could switch from a two- to a three-alternative choice by adding a "no difference" response option. None of the subjects made such a request on the experimental or prac-

Table 1
Individual Subjects' Thresholds
for Each Experimental Condition and Reference Distance

Subject	Reference Distance					
	1 meter			2 meters		
	Practice	Experimental	Control	Practice	Experimental	Control
1	5.17	6.63	18.23	7.84	6.77	16.64
2	4.30	4.77	18.68	5.04	3.17	17.84
3	10.23	8.30	18.30	6.30	5.04	19.41
4	8.57	4.37	14.25	9.17	3.77	14.96
5	15.10	8.37	18.17	6.70	13.50	16.10
6	2.23	1.77	14.50	3.90	2.67	11.10
7	7.77	7.03	12.83	11.04	9.77	15.57
8	4.90	4.63	15.77	6.64	2.57	15.04
<i>M</i>	7.28	5.73	16.34	7.08	5.91	15.83
<i>SD</i>	4.08	2.26	2.29	2.26	3.93	2.43

DISCUSSION

tice tests. All 6 naive subjects reported that the strategies they had used on previous tests were ineffective in the control condition and that they found the control test more frustrating. The two authors were nominally blind to their own orders of testing, but could tell within several trials whether the pressure cue was present or absent.

Performance without Pressure Cue

Although relative distance discrimination was significantly better when pressure information was available, performance did not fall entirely to chance levels in the absence of this information. As Table 1 shows, thresholds in the control condition averaged about 16%. Although the 20% maximum could have imposed a ceiling effect, this was not the case for at least half of the subjects, on the basis of visual inspection of the records. Four subjects showed no ceiling effects, 1 showed a ceiling effect at 1 m but not at 2 m, and 3 showed ceiling effects at both distances. At least 4 subjects, then, had a basis for discriminating distance changes in the absence of the pressure cue. If the maximum stimulus level had been set higher than 20%, the other subjects might also have had a basis for discrimination.

Another test of whether the subjects had some basis for correct responding in the control condition is the comparison of percentage correct across all control trials to the chance level of 50% expected from the two-alternative forced-choice procedure. Each subject's percentage correct was calculated across the 1- and 2-m reference distances for all trials from Reversals 6–20, which was the portion of the session used for the threshold estimates. The percentages were entered into a matched-sample *t* test for comparison with the 50% chance level. There was a mean of 57.2% correct, which was significantly above the 50% chance level [$t(7) = 3.21$, $p < .02$].

These analyses show that relative distance discrimination was possible in the control condition. However, this discrimination required considerably greater differences in distance than when the pressure cue was available, by a factor of 2.8 (the ratio of average thresholds on the control vs. the experimental conditions). This implies that changes in the distance between a sound source and a listener would be perceived sooner on the basis of the pressure cue than from other cues.

Individual Performance across Conditions

Individual thresholds were averaged across the 1- and 2-m reference distances within each test condition (practice, experimental, and control). Using these averaged data, the pair-wise correlations between test conditions were as follows: practice and experimental [$r(6) = 0.84$, $p < .01$], practice and control [$r(6) = 0.21$, n.s.], and experimental and control [$r(6) = 0.36$, n.s.]. This pattern indicates that consistency in individual performance appears to be related to the use of the pressure cue and not to the use of other cues or to individual variations in general psychophysical testing.

Discrimination of the relative distances of nearby sound sources was possible for differences in distance of about 6% when the pressure cue was available, whereas differences of 16% were required when this cue was removed. These results agree well with the pressure-discrimination hypothesis, which predicts thresholds of about 5%. Furthermore, this level of performance requires little, if any, training, as indicated by the findings that thresholds were almost as good, about 7%, on practice tests, and that experimental and practice thresholds were highly correlated. In contrast to these findings, previous studies have reported that the pressure cue is useful in the distance range of several meters or more but that thresholds were elevated at shorter distances. Consideration of methodological differences between the studies may help to resolve this discrepancy.

Figure 1A shows data from Simpson and Stanton (1973) and Strybel and Perrott (1984), along with Edwards's (1955) data. The data from these studies are discrepant from the present findings in two specific ways. First, thresholds in the present study were within the 5% range predicted by the pressure-discrimination hypothesis, whereas the other studies reported considerably higher thresholds at short reference distances. Second, in the present study, there was no difference between thresholds for the 1- and 2-m reference distances, whereas in other studies thresholds varied strongly and inversely with distance across this range of reference distances.

All three of the other studies shown in Figure 1 used the method of limits, in which a sound source was moved in the same direction until the subject reported that it was closer or further away than a reference distance. In both the Edwards (1955) and the Simpson and Stanton (1973) studies, subjects heard a slow, continuously moving sound source and were told to report when they perceived it as moving toward or away from them. They were instructed to minimize incorrect responses by waiting until they were sure before responding. This instruction may have led the subjects to delay responding some time after they had barely perceived the distance change in order to be sure that there had been a change. In the study by Strybel and Perrott (1984), the sound source was moved in small increments, and subjects reported after each incremental movement whether the sound was closer than, equal to, or further than the sound from a reference speaker. Thresholds were based on the transitions from the equal-response option to the closer or further options. The availability of the equal-distance response category may have resulted in a delay in reporting that the sound had changed position perceptibly. In all three studies, then, the subjects could have adopted a relatively conservative response criterion by which they reported distance changes somewhat later than when they could first barely perceive them. In contrast, the present study's two-alternative forced-choice response, coupled with random presentation of

Figure 1. Threshold values from several studies for relative distance discrimination at various reference distances. (A) Thresholds as a percentage of the reference distance, as originally reported. (B) Thresholds expressed as absolute distance changes, also as originally reported. (C) Adjusted thresholds as a percentage of the reference distance.

toward and away trials, eliminated the potential for such a response criterion.

If the subjects in the earlier studies delayed making a "change" response and if the absolute magnitude of their delays was constant across reference distances, then there would be a greater elevation of threshold estimates at shorter than at longer reference distances. That is, with thresholds expressed on a percentage basis, the effect of a constant absolute delay in responding would vary inversely with reference distance. Figure 1B shows the data in Figure 1A plotted in absolute distance units. Applying linear regression to the points plotted for each study, the y intercepts are 0.05 m for Strybel and Perrott (1984), 0.17 m for Simpson and Stanton (1975), and 0.41 m for Edwards (1955). (Linear regression is appropriate for these data sets, since all of the accompanying correlation coefficients are .98 or greater.) These y intercepts can be regarded as estimates of subjects' conservative response tendency, since the logical y intercept without such a tendency would be zero. For example, in the Strybel and Perrott study, the implication is that time equivalent to about 5 cm (0.05 m) of additional change in distance was required beyond the just-perceptible level. If this 5 cm is subtracted from their reported percentage threshold of 19% (9.31 cm) at the 49-cm reference distance, then the adjusted threshold estimate is 8.8% (4.31 cm), which is much closer to levels predicted from the pressure cue.

Figure 1C shows the data from Figure 1A replotted with this adjustment applied to all of the data points. For the Edwards (1955) and the Simpson and Stanton (1973) studies, there is no threshold elevation at short distances using the adjusted data. In fact, for the Edwards data, the lowest threshold—and the only one within the range predicted from the pressure cue—is at the shortest reference distance, 1 m. For the Strybel and Perrott (1984) data, there is still some threshold elevation at shorter distances, but much less than with the unadjusted data, and even the highest threshold—8.8% for the 49-cm reference distance—is close to the level of about 5% predicted from the pressure cue. These analyses suggest that previously reported threshold elevations at short distances may be attributed to subjects' use of conservative response criteria encouraged by the method of limits and the task instructions. We conclude that findings on relative distance discrimination at short distances, from the present study as well as from previously reported studies, are described well by the prediction of the pressure-discrimination hypothesis.

Although the findings of the present study and the adjusted findings from several previous studies indicate that pressure is useful for relative distance discrimination even at short distances, it does not follow that pressure is the only important information for auditory distance perception. In fact, there appeared to be some basis for correct responding in the control condition, when the pressure cue was rendered ineffective. Also, the present data were collected in an anechoic chamber in order to eliminate the influence of another important source of auditory information about distance, the reverberation cue. The ba-

sis for this cue is that with increasing distance from a sound source, the ratio of direct sound to reverberant sound decreases. Mershon has shown that the reverberation cue is very useful, especially when the task requires absolute rather than relative distance perception (Mershon & Bowers, 1979; Mershon & King, 1975). Therefore, the present study leaves open questions such as how useful other kinds of information are and how multiple sources of information are integrated. It does, however, show that sound pressure is an extremely useful basis for distance perception at near as well as far distances.

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NOTE

1. The physical term, intensity, differs from pressure in that intensity is a measure of energy over time, whereas pressure is a measure of instantaneous amplitude. Although the generic term intensity is widely used in describing sound levels, pressure is the correct term with regard to the physical units in which auditory sensitivity is measured.

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