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PREFERRED SOUND INTENSITY INCREASE FOR SENSATION OF HALF DISTANCE [1, 2]

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Summary.—Two experiments are reported that examine the preferred increase in intensity for creating a percept of half auditory distance from a reference. The results of both experiments indicate that the use of an inverse square law (increments of 6 dB) is not the best signal-processing method for this purpose. The application of the results is potentially useful towards the software design of 3-D auditory display systems that manipulate the perceived distance of auditory inputs in relationship to actual distances of physical objects.

To improve situational awareness in human-machine interfaces, a number of research efforts have investigated the application of auditory displays as an alternative or complementary communication system to visual displays (e.g., Patterson, 1982). Within contexts that include aircraft operating systems, ATC (air traffic control) displays, and auditory feedback from multimedia computer systems, the distance of an object relative to the operator's location is a useful channel of information. Distance can be communicated either numerically or through visual icons, such as seen on a scope display, but the visual system of the operator is already subject to a high workload. An attractive alternative is to exploit the auditory perception "channel" of the operator (Mowbray & Gebhard, 1961; Calhoun, Janson, & Valencia, 1988). A well-known example of this is the auditory display used by sonar operators, who determine distance auditorially by listening to the timing interval between the onset and reflection of a signal from an object.

An alternative to using timing intervals for determining distance is to use a cue used in everyday hearing: loudness. It has been observed that increased loudness of a sound source is associated with a decrease in the distance of the sound source from the listener (Coleman, 1963), especially when manipulation of other distance cues is not involved (von Bekesy, 1960). Manipulation of the perceived distance of auditory warning signals or of auditory "icons" (Gaver, 1986) would be a convenient way, for example, for an air traffic controller to monitor the location of surrounding aircraft,

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relative to his own location. Coupling veridical distance cues with the techniques used in 3-D auditory displays is also desirable for multimedia or "audio windowing" systems in computer interfaces (Ludwig, Pincever, & Cohen, 1990), virtual audio-mixing consoles for recording or reverberation (Kendall & Martens, 1984; Begault, 1987), and visual-auditory virtual environment displays (Fisher, Coler, McGreevy, & Wenzel, 1988; Begault & Wenzel, 1990).

The present investigation focused on distance scaling; specifically, what increase in loudness is necessary to create an illusion of the signal being *twice as close* from an initial position. "Twice as close" is regarded here as a psychological interval that can be quantified by the subject. Fig. 1 illustrates the situation. Assume that we have an auditory display that presents a sound within a "perceived distance space," at distance *A* relative to an egocentric reference point. It would be desirable to be able to manipulate the intensity of the auditory icon at *A* so that it seems to be twice as close (half distant) at position *A*/2.

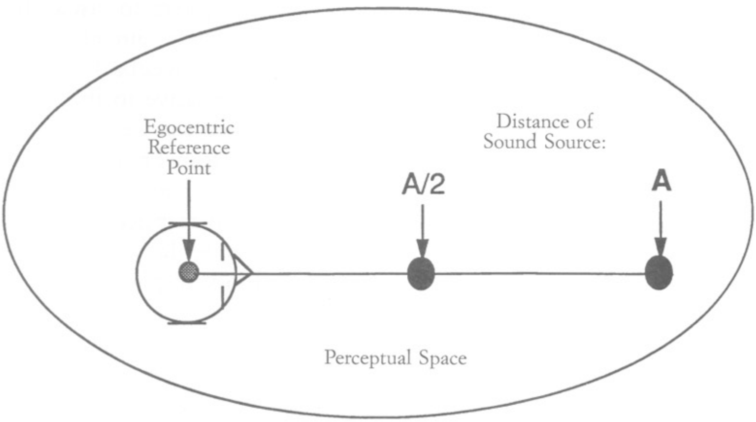

FIG. 1. Illustration of the goal of the experiment: to determine the increase in intensity necessary to produce the illusion of a sound source at distance A/2 in relation to the reference distance A

The software design for adjusting intensity as a function of the distance between a source and a listener is commonly based on a physical model known as the inverse square law (e.g., Chowning, 1971; Moore, 1983). This law states that sound in free space decreases as the square of the distance from the sound source, i.e., 6 dB SPL with each doubling of distance from a given reference point (see Davis & Davis, 1987). For an example of how this law might be applied in an auditory display, consider an airplane at a distance of 1000 meters from an ATC tower, which is represented to the controller as an auditory icon played over headphones at 65 dB SPL. As the airplane gets closer to the tower, let us assume that the icon playback software is designed to become louder, signifying decreased distance. Using a physical scale to adjust intensity, when the airplane is 500 meters distant, the icon would sound at 71 dB SPL.

This 6-dB increase follows the inverse square law, but it does not correspond to the increase predicted by a perceptual scale for loudness. The sone scale of equal loudness intervals corresponds to a 10-dB reduction for a sound to be judged half as loud as a reference (Stevens, 1955). In the study by Stevens and Guirao (1962), judgements of softness were interchangeable with judgements of distance, with both magnitude estimation and production tasks. Returning to the previous example, if physical distance is mapped to a psychological scale for loudness in the software model, in other words, twice as loud means twice as close, then when the airplane moves to 500 meters from 1000 meters from the tower, the icon should be designed to play at 75 dB SPL, a 10-dB increase, rather than at 71 dB SPL.

Contrary to Stevens and Guirao, Warren (1963) argued that long-term experience of seeing and hearing sounding objects at different distances would result in loudness and distance judgements equivalent to the inverse square law. He gathered experimental evidence to support the hypothesis that a 6-dB reduction corresponded to half distance and half loudness. His experimental conditions differed from Stevens and Guirao in that his subjects were blindfolded, and heard the sounds in a reverberant environment rather than over headphones. Sheeline (1982) obtained results that do not fully support Stevens and Guirao's nor Warren's results. He found that intensity decrements between 6 and 10 dB were related to doubled source distance under conditions of medium and heavy reverberation, but that 3 or 4 dB was appropriate for conditions of low reverberation.

The current study was motivated by the need for applying a distance scale to a human interface software design, in light of the disagreement in the conclusions of the research cited above. Two experiments are described below that investigate the relationship between intensity of sound source and perception of a distance interval twice as close as a given reference. First, results are given on a 2AFC study where subjects evaluated the inverse square law (6-dB intervals) and an inverse cube scheme (9-dB intervals) for halving distance. The inverse cube scheme was chosen to correspond to the sone scale. Last, results are given on a paired-comparison preference study where subjects evaluated 3-, 6-, 9-, and 12-dB intervals for creating a sensation of half distance. Both familiar and unfamiliar stimuli were used in the second study; both studies were conducted under headphone conditions, without reverberation.

Experiment One

Method

Subjects.—Six students were used in the study, 4 men and 2 women, ranging from 20 to 34 years of age. All reported no significant hearing loss.

Stimuli.—A piano tone (C5, 523.2 Hz, played on an upright piano, duration 0.7 sec.) at 65 dB rms intensity level was used as the reference stimulus. Two probe stimuli were used: the same sound, but digitally multiplied to an rms intensity level of 71 and 74 dBc SPL (6- and 9-dB increases). The 6-dB increase corresponded to the inverse square law, and the 9-dB increase corresponded to the sone scale via an inverse cube scheme. The piano tone was recorded in a moderately quiet recording studio (apx. 35 dB background noise level) with an omnidirectional microphone (Electrovoice RE-55) positioned 6 in. behind the center soundboard, directly into a Dec VAX 11-780 computer with a 16-bit digital to analog converter and sound recording software. Software was used to play the sounds back from the Vax to subjects in a small recording studio control room, using intra-aural earphones (Sony MDR-E265).

Each trial consisted of either the reference tone followed by the probe, or the probe followed by the reference; a .25-sec. silence was interspersed in between these sounds. Each subject participated in six blocks of 18 trials, with an equal number of 6- and 9-dB increases randomized within each block. Three of the blocks heard by each subject contained trials ordered as probe-reference, and the other three blocks were ordered as reference-probe; the ordering of block types was random for each subject. The subjects were informed in advance of each block whether the first or second sound in each trial was the reference.

Subjects were instructed for each trial to imagine where the sounds would be in terms of their distance from the center of their head and to indicate in the experiment whether or not the probe sound seemed twice as close as the reference sound. Responses were written by the subject listening to the stimuli in a studio control room; subjects wrote a '1' for yes, and a '0' for no. A test block of 18 trials was played before beginning the actual experiment; if the subject was unable to externalize the probe and reference to a position outside the head, they were disqualified for the experiment (one person was rejected on this basis).

Results

The favorable responses for 6- and 9-dB choices were pooled across subjects; a total of 216 judgements for each dB level increase were gathered. The order of the stimuli (probe-reference or reference-probe) was not significant. The mean value for the 9-dB choice was 54% of all possible choices (standard deviation 14%), while the mean value for the 6-dB choice was 27%

(standard deviation 13%). This 2:1 preference ratio was significant ($F_{1,5} = 10.18$, $p < .05$). This supports the generalization that, in the absence of other alternatives and with the particular sound pressure level and sound type used, an inverse cube scheme using 9-dB intervals is preferred over an inverse square law for halving of distance. However, the low mean values also indicate that neither value is a strong choice; almost as many responses favored the 9-dB increment as ones that did not. The second experiment involved comparison of four rather than two different dB increases to determine if there was an "ideal" increase that was not predicted by the inverse square law or the sone scale. The second experiment used a more extensive range of reference levels, sound types, and dB increases from the reference.

Experiment Two

Method

Subjects.—Nine students between the ages of 19 and 35 years participated in the study. All reported having no noticeable hearing loss. Six of the subjects were graduate students in various fields associated with audio; none had previously participated in a distance hearing experiment.

Stimuli.—In this study, four different methods of increasing the SPL level of a stimulus from a particular reference level were compared: (1) 3-dB increase, (2) 6-dB increase, (3) 9-dB increase, and (4) 12-dB increase. A paired-comparison, 2AFC test was used to establish the preferred amplitude increase from a given reference level for halving of distance, for all possible combinations of these increases.

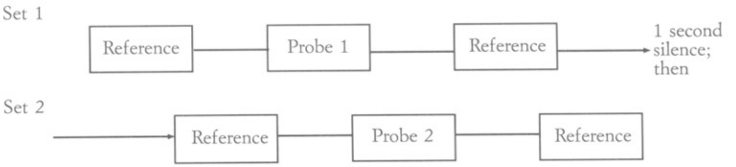

FIG. 2. Temporal arrangement of reference and probe stimuli in the second experiment. There was a .25-sec. silent interval between the probe and reference stimuli.

Each trial consisted of two sets of three stimuli ordered as follows: reference-probe-reference. A 1-sec. silence was interspersed between sets, and a .25-sec. silence was interspersed between the probe and the reference; see Fig. 2. The probe in the first set was set at a different intensity level increase than the probe in the second set; for example, 6 dB in the first set, and 9 dB in the second set. Subjects were asked in a two-alternative forced-choice paradigm to choose the set that sounded most convincingly as if it came twice as close as the reference in terms of auditory distance. Trials were not repeated. The matrix of intensity combinations is displayed in Table 1.

TABLE 1
MATRIX OF INTENSITY COMPARISONS FOR STIMULI IN EXPERIMENT 2: dB INCREASES FOR PROBE 1 AND PROBE 2; SEE FIGURE 2

	Probe 1	Probe 2		Probe 1	Probe 2
1.	3	6	2.	6	3
3.	3	9	4.	9	3
5.	3	12	6.	12	3
7.	6	9	8.	9	6
9.	6	12	10.	12	6
11.	9	12	12.	12	9

For an applications context, it was important to determine whether over-all sound pressure level and familiarity of the stimuli were significant factors for a preferred SPL increase for half distance. Therefore, separate trial blocks were run with the reference level set at 65 and 75 dBc SPL. Speech (male speaker, the word *shoe*, spoken in monotone) and the same piano stimuli used in the first experiment were used as the familiar stimuli sound sources; and a click produced by an electronic impulse device was used as an unfamiliar sound source. Each trial block used one type of sound source and one SPL level for the reference; hence, there were six unique block types. Subjects listened to each unique block type twice, resulting in a total of 12 blocks per subject. The ordering of the blocks was randomized for each subject.

The speech sound and the click were digitally recorded with a digital taperecorder (Sony PCM-F1, sampling rate 44.1 kHz) in an anechoic chamber using a binaural head microphone system (Sennheiser MKE-2002). The sound source was situated at a distance of 1 meter on the front of the median plane of the binaural head. The three sounds were transferred to a DEC computer (Vax-11/780) running the audio-signal-processing software programs (U.C. San Diego/Computer Audio Research Laboratory Software). The duration of the speech sound was 0.6 sec., and the duration of the click was 0.002 sec. Each sound was measured for its rms intensity level and then increased or decreased in amplitude via digital multiplication. Intra-aural earphones (Sony MDR-E265) were worn by the subject.

Trials were collected from a given subject in two separate sessions, with the total duration of both sessions equal to c. 50 minutes. The playback of the recording was in a moderately quiet recording studio (c. 35 dBc SPL background noise).

Results: Evaluation of Data

Each of the six comparisons shown in Table 1 were first averaged on a per-subject basis to obtain the mean percentage of responses favoring the larger intensity increase in the trial. Fig. 3 shows the mean percentages for each type of comparison. The 3-dB increase was favored the least often when compared to 6, 9, or 12 dB; the mean percentage of preference for 3 dB is around 8%. This contrasts with the results of Sheeline (1982), who found half distance to correspond to 3- or 4-dB intervals under low reverberation conditions. The subjective preference for 12 or 9 dB over the 6-dB increases (around 69%) supports the conclusion of the first experiment that an inverse square law is inadequate for producing a sensation of half distance. There is almost no preference when comparing between 9 and 12 dB (45%), indicating that the loudness scale is not necessarily the best means of scaling for half distance. This is contrary to the results of Stevens and Guirao (1962), who found that judgements of loudness and distance were interchangeable and that these judgements followed 10-dB increments.

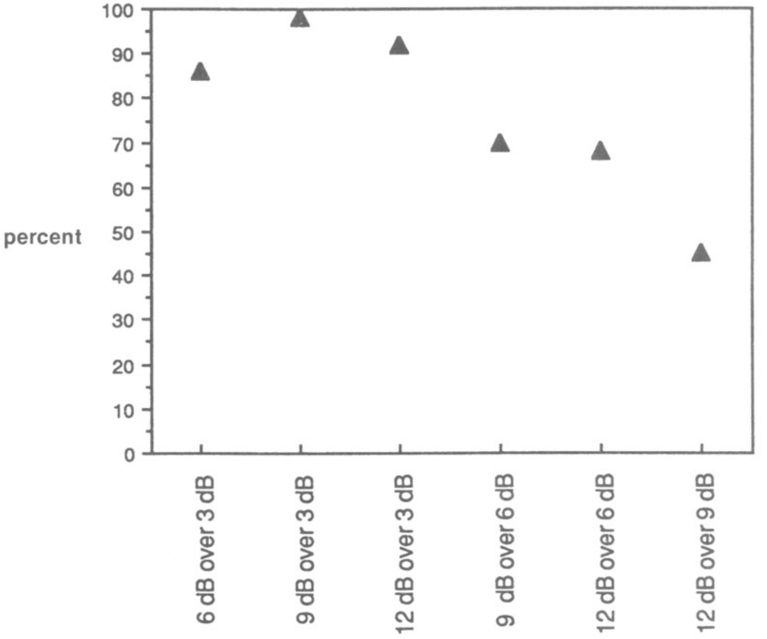

FIG. 3. Paired comparisons of dB increases for producing a sensation of half distance; mean preference percentages across subjects and conditions for the larger dB increase in the paired comparison

To compare these results with those of the first study, it is possible to disregard the 3- and 12-dB comparisons and pool the results of the other comparisons in terms of preference for either 6- or 9-dB intervals. In other words, the mean percentage of judgements favoring a 6-dB interval when 3-, 9-, and 12-dB intervals were available choices can be compared to the mean percentage of judgements favoring a 9-dB interval when 3-, 6-, and 12-dB intervals were available choices. The mean percentages calculated in this way are 49% for 6-dB intervals and 74% for 9-dB intervals.

Analyses of variance were done on the conditions used (increase vs sound type vs SPL level) to assess whether the type of sound or the playback intensity was significant. There were no interactions in the results as a function of whether playback level was at 65 or 75 dBc SPL. The preferences for larger increases in amplitude were significant across subjects ($F_{5,40} = 9.97$, $p < .001$), as was the interaction between the type of sound vs the comparison ($F_{10,80} = 3.95$, $p < .001$). By a ratio of about 3:1, the larger increase was chosen over the smaller increase between any two of the dB increments in these paired comparisons.

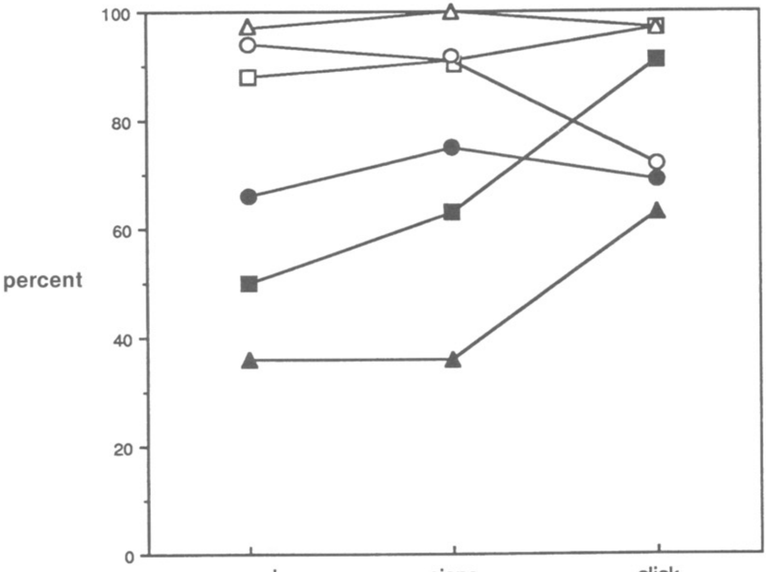

FIG. 4. Paired comparisons of dB increases for producing a sensation of half distance; mean preference percentages across subjects by stimulus type for the larger dB increase in the paired comparison (□ 3—12, △ 3—9, ○ 3—6, ● 6—9, ■ 6—12, ▲ 9—12)

Fig. 4 shows the mean preference percentages for the larger dB increase by the type of sound used. The type of sound used as the stimulus affected preference the least in the comparison of 6-, 9-, and 12-dB to 3-dB intervals, and the comparison of 9-dB to 6-dB intervals. For these four comparisons, the greatest difference in preference is between the click (72%) and speech (94%) sound sources in the 6- to 3-dB comparison. But in the comparisons of 12-dB to 9- and 6-dB intervals, the differences between the click and the other sound types is quite marked. For these two comparisons, the click sound source required a greater intensity interval than the piano or speech. The most extreme comparison is between the click and speech sound sources; 63% vs 36% preference, respectively, for 12-dB over 9-dB intervals; and 91% vs 50% preference, respectively, for 12-dB over 6-dB intervals. This could be a result of familiarity; the speech and piano sounds are encountered in the environment at different distances, thereby making a 12-dB difference too extreme for these sounds due to experience with the inverse square law (Warren, 1963) or with loudness (Stevens & Guirao, 1962).

Conclusions

In a virtual auditory display environment, it is highly desirable to have control over perceived distance. However, it is not clear what the best model is for scaling intensity with distance; particularly, what the ideal intensity increment would be for creating a sensation of halved or doubled distance from a particular reference. Sheeline (1982) found increments of 3 or 4 dB to be appropriate under low reverberation conditions and 6 to 10 dB under medium and high reverberation conditions. Warren (1963) reported 6-dB increments in a reverberant environment, while Stevens and Guirao (1962) reported 10-dB increments under headphone conditions.

To address these discrepancies, two experiments were run to evaluate how effective different increments were for producing a sensation of half distance. Both experiments were more similar to the study by Stevens and Guirao (1962) than to those by Sheeline (1982) and Warren (1963), in that the former used headphone presentation and nonreverberant sound field stimuli. In the first experiment, subjects responded in a 2AFC paradigm as to whether or not 6-dB and 9-dB increases caused a sensation of half distance from a reference. A piano sound at 65 dBc SPL was used as the stimulus. Only 27% responded positively to the 6-dB difference, while 54% responded positively to the 9-dB difference. This implies that a scheme based on the inverse square law works less well than a scheme based on a loudness scale. However, there were almost an equal number of responses that were positive and negative towards the 9-dB increment. A second study involved paired comparisons between all possible orderings of 3-, 6-, 9-, and 12-dB increments. Speech, piano, and click stimuli were run with references at 65 and 75 dBc SPL. The results showed that 3-dB increments were preferred the least often, while increments of 6-, 9-, and 12-dB seemed to depend on whether the stimulus was familiar (speech or piano) or unfamiliar (click). The influence of familiarity with the stimulus has been important in formulating absolute and relative distance judgements (Gardner, 1969) and is possibly a reason for the difference in results obtained here for the click vs the speech and the piano stimuli. The difference in playback level was not significant in the results.

Undoubtedly, further work will need to be pursued in the area of distance manipulation in 3-D audio displays. While it may be concluded from these studies that an intensity-reduction scheme based on the inverse square law is inadequate, it cannot be said with any certainty that a scheme based on a loudness scale will have any generalizable applicability. Indeed, as shown in the second experiment, it may be possible that different schemes will need to be applied depending on the type of stimulus used. The relative difficulty found here in determining a stable scheme for producing an illusion of half distance is probably an artifact of using intensity as the only cue. Research conducted by von Bekesy (1960), Mershon and King (1975), and Sheeline (1982) has shown that reverberation can act both as an absolute cue to distance and as an additive cue, in conjunction with intensity. Future studies should explore the distance segmentation schemes shown here under both reverberant and nonreverberant conditions. It is clear at this point that the use of a physical model of intensity adjustment is inadequate for the psychoacoustic demands of a 3-dimensional auditory display and that an acceptable distance scheme will require further refinement.

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