# AUDITORY DISPLAY OF SOUND SOURCE DISTANCE

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## ABSTRACT

Although the majority of research on spatial sound reproduction has concentrated on the directional components of source location, it is clear that full 3-dimensional rendering also requires an understanding of how to reproduce sound source distance. This article reviews and describes recent psychophysical research on distance perception of sound sources, with emphasis on how various acoustical and non-acoustical factors contribute to perceived distance. Results from this research have important implications for distance simulation and reproduction in spatial auditory displays.

## 1. INTRODUCTION

The human auditory system can provide listeners with critical information about the spatial layout of their environment. This information is especially useful under conditions where vision may be ineffective, such as in the dark, or when objects fall outside our field of view, or when the visual scene is especially complex or cluttered. Modern display technology has increasingly capitalized on these proclivities of the auditory system to provide users with spatial information. Spatialized sound reproduction is now the norm in variety of display systems with applications ranging from scientific research to entertainment. The technology behind many spatialized sound displays is grounded in basic psychophyscial research on sound localization (e.g. [1, 2]), which has been concerned primarily with understanding the perception of source direction in the horizontal and vertical dimensions. Relatively little attention has been given to the perception of the third spatial dimension: that of sound source distance. In this article, recent psychophysical research on auditory distance perception will be reviewed and described, with emphasis on how various acoustical and non-acoustical factors contribute to perceived distance. Results from this research have important implications for distance simulation and reproduction in spatial auditory displays, and can facilitate future improvements in display technology.

## 2. ACOUSTICAL FACTORS

A change in physical distance between a listener and a source of sound produces a variety of changes in the acoustical waveform reaching the listener. At least four principal acoustic factors, or cues, may be identified for conditions where the sound source is stationary, although each of these factors is subject to dependencies on source properties and acoustic environments. These factors are:

**Intensity**. Sound intensity at the listener's position decreases as the distance between listener and a fixed-power sound source is increased. Under ideal conditions (a point-source in an acoustic free-field), intensity loss as a function of distance obeys an inverse-square law, which implies a 6 dB intensity loss for each doubling of distance. It is important to note that from the listener's perspective, this distance cue is ambiguous, since intensity at the listener's location can change both as a result of distance changes and as a result of changes in the source's acoustic power.

**Direct-to-Reverberant Energy Ratio**. In environments with sound reflecting surfaces, the ratio of energy reaching a listener directly (without contact with reflecting surfaces) to energy reaching the listener after reflecting surface contact (reverberant energy) decreases systematically with increases in source distance. Although this cue may be especially relevant for indoor, room environments, many outdoor environments also produce reverberation [3], and hence a direct-to-reverberant energy ratio cue that varies with distance.

**Spectrum**. At farther distances, the sound absorbing properties of air significantly modify the sound source spectrum by attenuating the high-frequencies. The effect, however, is relatively small: on the order of a few dB loss per 100 meters [4]. A second type of spectral change occurs in sound reflective environments where the spectrum that reaches the ear may be affected by the acoustic properties of the reflective surfaces. As distance increases, the proportion of reflected energy increases, thereby potentially changing the at-the-ear spectrum systematically. Like the intensity cue, spectral cue changes with distance can potentially be confounded with changes in the sound source spectrum.

**Binaural Differences**. When sound sources are in the acoustic near-field, binaural differences in both intensity and time are no longer independent of radial distance, as they are for far-field planar waves. These differences, often referred to as differences resulting from acoustic parallax, are maximal along the interaural axis and decrease to zero on the median plane. Near-field source distance changes also produce variations in the spectrum reaching the eardrums, due to diffraction around the head and pinnae as characterized by head-related transfer function (HRTF) measurements [5, 6].

What are the effects of each of these acoustical factors on perceived distance? In order to answer this and related questions, we must have a way to reliably estimate distance percepts.

## 3. ESTIMATES OF PERCEIVED DISTANCE

Perhaps the most basic method of estimating perceived distance to a sound source is to simply ask listeners: "How far away does the sound appear?" Listeners respond with judgments of egocentric distance in familiar units, such as feet or meters with decimal precision. Averaging a number of responses to a given physical distance yields a good estimate of perceived distance. Because this simple method produces results that are similar to those using other methods, such as magnitude estimation and paired-comparison [7], as well as walking to the perceived source location [8], it is likely that all methods probe a similar underlying psychological process related to perceived distance.

Figure 1 displays a representative set of average apparent distance judgments for a single listener plotted as a function of source distance. These data are taken from [9] and demonstrate two fundamental aspects of distance perception data: estimate bias and estimate variability.

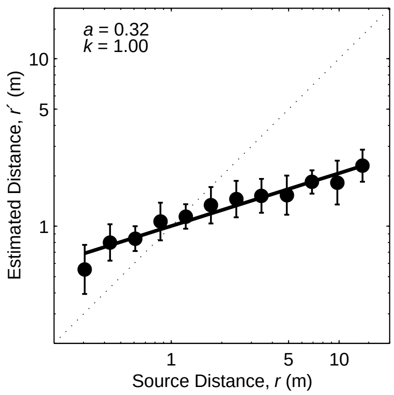


Figure 1. *Average estimated distance as a function of physical source distance for one representative listener (SQW). Bars denote one standard deviation. The data are fit with a power function of the form $r' = kr^a$ using a method of least-squares. Parameters of the fitted function (a, k) are displayed in the upper-left.*

### 3.1. Estimate Bias

The data shown in Figure 1 demonstrate that estimates of perceived distance can be substantially biased when compared to their corresponding physical source distances. This may be seen by noting the location of the data points relative to the dotted line that displays perfect accuracy of the estimates, or zero bias. The data show that for sources farther than roughly 1 m, estimated distance is substantially less than physical source distance. This suggests that listeners hear these sounds as being closer than they actually are. The opposite is true for very close sound sources, however. For sources less than approximately 1 m, listeners tend to overestimate source distance.

In order to more formally describe these biases, it is helpful to fit a function to the data. Here an exponentially compressive power function of the form $r' = kr^a$ represents a very good fit to the data ($R^2$ = .94), which is equivalent to the linear function shown on the logarithmic coordinates in Figure 1. In [9], similar power functions were fit to individual listener data under a number of different stimulus conditions. The fitted exponents ranged from approximately 0.15 to 0.70, with exponent variability being much larger between listeners than between the stimulus conditions examined (varying source direction and source signal).

Accumulating evidence suggests that a compressive power function is a reasonably good approximation of the psychophysical function that relates perceived distance to physical source distance. In a comparison of the results from 33 auditory distance experiments reported in 10 studies, nearly every data set was found to be well approximated by a compressive power function [9]. Although the exponents of the fitted functions varied considerably from experiment to experiment, the average exponent was found to be in general agreement with results reported in [9], in which the average exponent was roughly 0.4. The fitted constant values were also roughly consistent and had an average value of slightly greater than one. As a result, one may conclude that for almost every source distance, estimated distance is significantly biased: close source distances are overestimated and far sources are often substantially underestimated.

Although listeners appear to be unable to accurately estimate the distance to a source of sound, they can accurately determine whether the acoustic power of the source has remained constant or not during changes in source distance [10]. This result is surprising, given both the known confounds between source distance and source power in the intensity of the sound reaching the listener, and the demonstrated inability of listeners to accurately judge distance. One explanation of these results suggests that certain other auditory processes (such as the process of source loudness determination) may be able to compensate for distance estimate biases.

### 3.2. Estimate Variability

Although often overlooked, another critical feature of auditory distance judgment data is the variability in judgments for a given source distance. This feature of the data may be clearly seen by noting the size of the estimate standard deviations shown in Figure 1, which are on the order of 25% of the average source distance estimate. Figure 2 displays an analysis of estimate variability from the data of [9]. It reveals that estimates from all listeners were quite variable, although certain listeners were more variable than others. Variability within a given listener was reasonably constant as a function of source distance, however. Averaging over source distance reveals that estimate standard deviations ranged from roughly 20% – 60% among the nine listeners in the study, although certain distances yielded standard deviation as high as 106% for one listener (SRQ). The distance estimates were also found to be approximately normally distributed in logarithmic coordinates about the mean estimate, as verified by Kolmogorov-Smirnov normality tests.

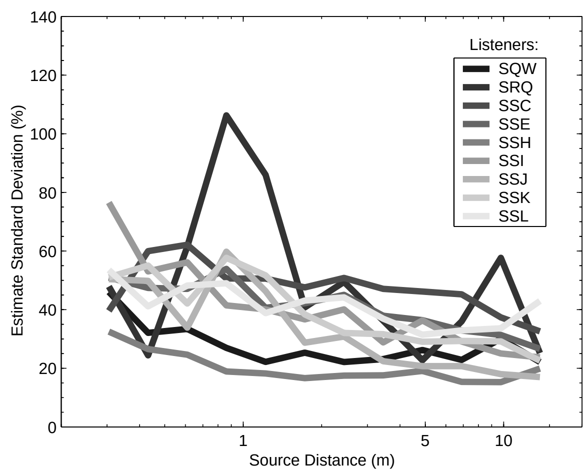


Figure 2. *Distance estimate standard deviation as a function of source distance for 9 listeners. Each standard deviation is based on 40 distance estimates.*

Although the precise cause of this variability is currently unknown, it likely results from a combination of two sources: variability or blur in the distance percepts and variability in the estimated distance responses. Preliminary results suggest that the majority of variability is due to perceptual blur, because apparent distance estimates to visual targets presented under full-cue viewing conditions are found to be much less variable, and also highly accurate. The shape of the distribution of estimates may also lend additional support to the idea that the majority of estimate variability is a result of percept-blur rather than response variability, since one would not necessarily expect the latter source of variability to produce normally distributed data in logarithmic space.

## 4. CONTRIBUTIONS OF ACOUSTICAL FACTORS TO PERCEIVED DISTANCE

The general pattern of subjective distance estimates described here can be observed under a variety of stimulus conditions in which one or more acoustic factors available to the listener are correlated with source distance changes. Perhaps the most universally observed pattern is the bias to underestimate source distance. This effect has been observed for the intensity cue [11], the direct-to-reverberant energy ratio cue [12-15], the spectrum cue [16], and for binaural cues [17, 18]. Further, the amount of bias does not appear to be strongly related to any one cue, which suggests that all distance cues are capable of supporting similar levels of distance localization performance, at least under the stimulus condition examined in these experiments. It is important to keep in mind, however, that all distance cues will not yield equally accurate distance estimates in all conditions. For example, distance estimates using the intensity cue can be extremely inaccurate when variation in the acoustic power of the source is present [19]. Similarly, estimates using the direct-to-reverberant energy ratio can be significantly affected by factors such as background noise [14] and the degree of signal coherence between the two ears [20]. Spectrum and binaural cues may also only be effective over relatively limited ranges of source distances. For most cues, estimate accuracy also improves as the listener is presented with sounds from multiple distances, because this allows for relative comparisons to be made. The direct-to-reverberant energy ratio cue, however, has been shown to elicit relatively accurate distance estimates from only one stimulus presentation [13, 21]. This result has led researchers to suggest that listeners may be able to extract absolute distance information from this cue.

### 4.1. Multiple Acoustical Factors

Because multiple distance cues are available to listeners in most natural environments, it is of particular interest to determine the relative contributions of these cues to perceived distance. Recent results [9] suggest that in room environments, intensity and direct-to-reverberant energy ratio are the primary cues to distance. These results also suggest, however, that information from each cue is combined and processed in different ways depending on factors such as source direction, source distance, and the type of source signal. This is perhaps a result of situations in which the intensity cue is more or less reliable than the direct-to-reverberant cue. While other environments and situations may elicit contributions from additional cues, it is clear that information from multiple distance cues plays a role in perceived distance.

Although the processes subserving distance cue combination are currently unknown, a conceptual framework originally developed to explain the perceptual combination of visual depth cues [22] has significant appeal. This framework suggests that each of the individual distance cues available to the listener produces its own estimate of source distance. The individual estimates are then compared to one another and evaluated in terms of the particular auditory scene. Consistent cues are "trusted" and given high perceptual weight. Cues that are either unavailable or unreliable in the particular scene, or that yield distance estimates that are inconsistent with other cues, are given less perceptual weight in the combination process. The final distance percept is the weighted sum of the estimates from the individual cues. Such a framework can perhaps explain how auditory distance perception processes are able to produce relatively stable estimates – albeit biased estimates – of source distance under a wide range of acoustic conditions in which different distance cues are available to listeners.

### 4.2. Unimportant Acoustical Factors

One factor that appears to be unimportant for distance localization is the use of individualized head-related transfer functions (HRTFs). It has been shown that the systematic distortions in spectrum and binaural cues to distance caused by the use of non-individualized HRTFs do not significantly degrade distance localization performance compared to an individualized-HRTF condition, provided that in both conditions, additional sources of distance information, such as intensity or direct-to-reverberant energy ratio cues, are available to listeners [23]. Because of the potential impact of this result on display technology, the experiment will be described in some detail.

Distance estimate data for 6 listeners (identification codes: SQW, SRQ, SSC, SSH, SSJ, SSI) in the individualized-HRTF condition of this experiment were provided by [9], a study where the HRTFs were somewhat specialized. These HRTFs contained not only the acoustical transfer characteristics of the listener's head and ears [1], but also the transfer characteristics of a semi-reverberant room environment, and were measured from 12 distances ranging from 0.3 m to 13.8 m, and two directions on the horizontal plane (0º and 90º relative to the midline). As such, these HRTFs provided listeners with all of the acoustic cues thought to be important for distance localization including: intensity, direct-to-reverberant energy ratio, spectrum, and binaural differences. Within a block of trials, listeners were presented with virtual sound sources over equalized headphones that were constructed using their own individualized HRTFs and asked to judge the apparent distance to the sound source using verbal responses of either feet or meters with decimal precision. No feedback as to the accuracy of the judgment was given, and listeners were instructed to report a distance of zero for any sources that did not appear to be external from the head. Each of the 12 distances was presented 10 times in a randomized order within a block of trials and source direction was varied between blocks. The source signal was a 50 ms broadband noise.

The non-individualized HRTF condition of the experiment proceeded in exactly the same way as individualized-HRTF condition, except for differences in the stimulus. Here, the same six listeners were presented with stimuli constructed from the same general type of HRTFs (containing room transfer characteristics) but measured from a different listener's ears. All listeners except SRQ were presented with virtual sound sources synthesized using SRQ's HRTF set. Listener SRQ was presented with sources synthesized using HRTFs from listener SSE.

Power functions were fit to the individual listener data similar to that displayed in Figure 1. Separate fits were performed for both HRTF conditions (own or other ears) and both source directions (0º or 90º). The parameters of these fitted functions are displayed in Figure 3. In order to evaluate these results statistically, two repeated-measures ANOVAs were performed; one with the fitted exponents, *a*, as the dependent measure, and the other with the constant values, *k*, as the dependent measure. HRTF conditions and source direction were within-subjects factors in both analyses. The results of these analyses revealed that the HRTF condition did not significantly affect either the exponent values, $F(1,5) = 0.173$, $p = .695$, or the constant values, $F(1,5) = 0.896$, $p = .387$. The interactions between HRTF condition and source direction were also non-significant for both exponent values, $F(1,5) = 2.907$, $p = .149$, and constant values, $F(1,5) = 2.788$, $p = .156$. This suggests that the use of non-individualized HRTFs does not bias distance localization when evaluated over the full range of source distances from 0.3 to 13.8 m or at either source direction. Average estimate standard deviations for each listener were also unaffected by the use of non-individualized HRTFs, as evaluated by a match-pair *t*-test, $t(5) = 0.738$, $p = 0.753$, and were similar to those displayed in Figure 2. Also of note, no "zero" estimates were encountered in either condition, suggesting that all sources were externalized.

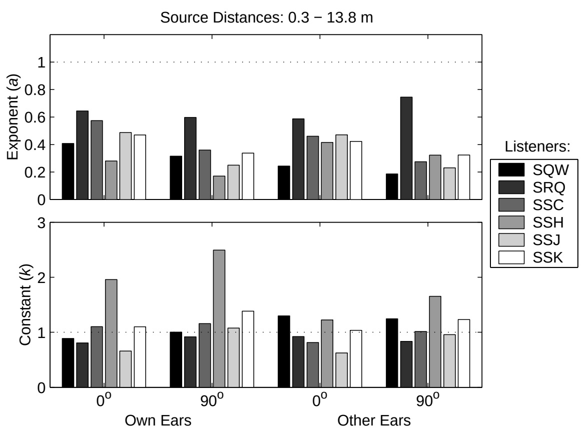


Figure 3. *Power function fit parameters (a, k) for virtual sound sources synthesized both with listeners' own ears and with another listener's ears. Data from azimuth angles of 0º and 90º relative to the midline are shown.*

Because the distance-dependent changes in HRTFs are only appreciable at very close distances (less than roughly 1 m), it is important to examine this region of source distances in the experiment more closely. Power functions were again fit to the individual listener data, but this time only for source distances between 0.3 m and 0.8 m. The parameters of these fitted functions are displayed in Figure 4. Although the exponent values were in general found to be higher in this analysis than in the previous analysis, a result that is consistent with the decreased estimate bias reported for close distances in [9], HRTF condition still did not have a statistically significant effect on either the exponent values, $F(1,5) = 0.0004$, $p = .986$, or the constant values, $F(1,5) = 1.447$, $p = .333$. The interactions between HRTF condition and source direction were also non-significant for both exponent values, $F(1,5) = 0.006$, $p = .942$, and constant values, $F(1,5) = 1.938$, $p = .223$.

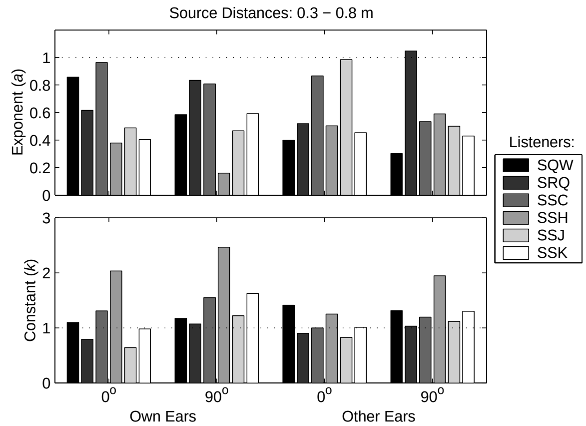


Figure 4. *Power function fit parameters (a, k) for near-field virtual sound sources synthesized both with listeners' own ears and with another listener's ears. Data from azimuth angles of 0º and 90º relative to the midline are shown.*

These results demonstrate that distance localization performance is not degraded through the use of non-individualized HRTFs, results that are perhaps surprising given the known performance-degrading effects of non-individualized HRTFs on directional localization [24].

## 5. NON-ACOUSTICAL FACTORS

Even though acoustical factors contributing to perceived distance are of primary interest for auditory display, it is important to recognize the contributions of other non-acoustical factors. Vision has long been known to affect percepts of auditory space, including perceived distance. The existence of visible targets has been shown to attract, or capture, the perceived location of a sound source under certain conditions. For directional localization, this effect is known as the "ventriloquism effect", and can cause the perceived direction of an auditory target to be pulled in the direction of a plausible visual target over angular separations of 30º or more [25]. For distance localization, similar effects have been observed [26, 27]. The presence of visual targets has also been shown to increase auditory distance accuracy and lower judgment variability under other conditions where multiple visual targets are present [28].

Recent preliminary research also demonstrates the effects of visual targets on auditory distance perception by examining listener judgments of spatial coincidence. In this experiment virtual sound sources were varied in distance from 1 to 5 m in .25 m steps. A visual target was placed at a distance of either 1.5, 3, or 4.5 m during a block of trials. Spatial coincidence judgments were made via a 2-alternative forced-choice procedure. Results demonstrate relatively large regions of spatial coincidence, which suggests that a form of visual capture of the auditory target may operate over a broad range of distances. Interestingly, sources at distances greater than the visual target were more likely to be judged as coincident than sources at equally lesser distances. This later result may be consistent with past results in anechoic space showing significant biases to judge the position of an auditory target at the position of a closer visual target [26].

Perceptual organization factors may also affect perceived distance. This type of psychological factor has been shown to affect visual distance percepts [29] and has been hypothesized to similarly affect auditory distance [21]. Known as *specific distance tendency*, this factor describes a tendency towards a specific "default" distance estimate under stimulus conditions in which all distance cues have been removed. The addition of cues that provide relative source distance information results in a distance psychophysical function that pivots about the specific distance tendency value. As a result, an organization factor such as this may also account for listener tendencies to perceptually compress far distances and expand close distances [21]. This effect may also be at least partially related to the concept of an *auditory horizon*, which, just as in vision, marks an upper limit on perceived distance [11].

Listener familiarity with the particular source signals being localized may also be a significant factor in auditory distance perception. Past research has demonstrated that estimates of source distance are more accurate for familiar sound signals than for unfamiliar sounds [30] and that accuracy with unfamiliar sounds improves with repeated exposure to those sounds [31]. Familiarity with the source signal may allow listeners to process certain acoustic distance cues, such as intensity or spectrum, somewhat differently. Consider a whispered speech signal, which is normally associated with a very low acoustic source power. Listeners can perhaps use this knowledge along with information as to the intensity of the signal reaching their ears to make inferences about the distance of the source. At least three studies have now demonstrated effects of the perceived source power of speech (e.g. whispers, shouts, etc.) on perceived distance [19, 32, 33]. Although not demonstrated, these effects would be unlikely with unfamiliar source signals, as it is highly doubtful that listeners could have learned to associate these signals with any sort of meaningful acoustic power values.

The sometimes significant contributions of non-acoustical factors on distance perception also underscore the importance of careful experimental design, as well as the need for cautious comparisons among results from different studies. The seemingly innocuous use of visual targets in an experimental response method, for example, can have profound effects on auditory distance judgments. It may also make for difficult comparison to related work using other response methods that do not rely on visual targets. Similar issues may potentially exist for the use of familiar sound sources or restricted ranges of source distances.

## 6. IMPLICATIONS FOR AUDITORY DISPLAY

Many commercially available spatial auditory displays do not do a very good job of creating realistic distance percepts. This is because accurately reproducing the stimulus at a listener's ears that would result from a distant source in a real environment is quite technically demanding. In the laboratory, however, we are able to precisely measure at-the-ear responses to distant sound sources and empirically derive transfer-functions that include not only the acoustic properties of the listener's head and ears, but the properties of a given acoustic environment as well. These enhanced head-related transfer-functions (HRTFs), which are equivalently referred to as binaural room impulse-responses (BRIRs), can then be used to filter the desired source signals in order to produce very high-quality distance displays when presented over equalized headphones. Distance judgment performance with this type of virtual display does not differ significantly from that observed with real sources in similar conditions [9].

Because this type of display method offers both realistic distance simulation and the ability to strictly control and manipulate the stimulus reaching the listener's ears, it is a valuable scientific tool and has been used extensively in many of the experiments mentioned in this article. Most practical display applications will place more stringent constraints on the methods used to create the display than laboratory applications. It is simply not feasible, in most applications, to measure BRIRs for all of the desired simulation configurations (source locations and environments) and users (although this latter factor has been shown to be less important for distance than directional rendering). Results of psychophysical research discussed in this article have a number of implications for developing feasible high-quality auditory distance displays. These implications may be summarized as the following set of guidelines:

a. Because real environments typically provide multiple and consistent distance cues to the listener, spatial auditory displays should try to do the same. For proper simulation of distance in room environments, consistent changes in direct-to-reverberant ratio as well as intensity are necessary, since studies have shown that listeners extract information from both of these cues [9]. Displays that provide listeners with distance information from only a single cue, such as intensity or direct-to-reverberant ratio, can lead to highly inaccurate distance percepts. Although implementing changes in intensity to cue distance is quite easy, providing realistic changes in direct-to-reverberant ratio is substantially more demanding, and an area in need of further scientific research. Relatively simple modeling of room acoustics using principles of geometric acoustics and statistical modeling of late reverberation may perhaps provide acceptable results. Developers should be aware, however, that some research suggests that reflections and reverberation can degrade directional localization accuracy [34], although other research does not show this effect [35].

b. Realistic simulation of distance does not require that the display be tailored to the acoustics of the individual user's head and ears (i.e. head-related transfer function, or HRTF), provided that other distance cues are available to users, such as a high-quality direct-to-reverberant energy cue. This result is important because it greatly simplifies effective implementation of distance simulation in virtual auditory displays. The use of non-individualized HRTFs can have a significant negative impact on directional localization accuracy, however [24].

c. Since vision is known to facilitate auditory distance perception, incorporating a visual component into the display system can reduce errors (both in terms of estimate bias and estimate variability) in perceived distance of the auditory source. When vision is not included in the display, developers and users should be aware that the visual objects in the environment may possibly have the undesired effect of modifying perceived sound source location, as a result of phenomena related to the "ventriloquism effect".

d. The use of source signals that are familiar to the listener, such as speech, can facilitate distance localization. Where possible, these types of signals should be used in auditory displays. Although the use of familiar source signals is probably most beneficial when other acoustic distance cues are available to listeners, recent results suggest that the familiar aspects of speech can be used exclusively to provide source distance information [33].

e. Finally, developers of spatial auditory displays are urged to not be overly optimistic in terms of perceived distance accuracy. Even under the best of conditions with real sound sources, significant perceptual errors are the norm: far sources are (exponentially) underestimated and very close sources overestimated. The best one can hope for is a level of display accuracy that is comparable to an analogous real-word situation.

## 7. CONCLUSIONS

Just as the psychoacoustical study of directional localization has led to improved display technology, so too can the study of distance localization. Description and review of recent research on distance localization in this article has resulted in a number of guidelines that will hopefully facilitate more realistic 3-dimensional reproductions of acoustic space, reproductions that include a compelling rendering of sound source distance.

## 8. ACKNOWLEDGMENTS

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