The audible facing angle

John G. Neuhoff, Mary-Alice Rodstrom, Tanaya Vaidya

Department of Psychology, The College of Wooster, Wooster, OH 44691
jneuhoff@wooster.edu

Abstract: The ability to perceive the facing orientation of a directional sound source was explored. Broadband noise was presented from a loudspeaker directly facing the listener and then from one of six rotated facing angles. Blindfolded listeners judged the direction of rotation at two different distances. The "minimum audible facing angle" (MAFA) was defined as the angle at which listeners reached 75% correct. However, MAFA varies with source distance and directivity. Thus, the "minimum audible facing index" (MAFI) was termed a measure of facing angle that takes into account these factors. Results are consistent with interaural level difference (ILD) as a cue to facing angle for sources in the median plane.

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1. Introduction

By almost any measure, resolving the spatial location of objects in the environment is a primary task of most perceptual systems. Auditory estimates of spatial location can facilitate navigation, enable precise interaction with objects and organisms, and help direct the visual system toward critical targets (Dallenbach, 1941; Griffin, 1958; Guski, 1992; Rice et al., 1965; Rosenblum, 1993; Rosenblum et al., 1996). There has been a good deal of research on the ability of listeners to locate sound sources (for reviews see Blauert, 1997; Gilkey and Anderson, 1997; Middlebrooks and Green, 1991; Phillips and Brugge, 1985). Yet, almost every study of localization to date has employed sources of sound that point directly at the listener. There are obviously good reasons to hold the facing direction of a loudspeaker constant relative to the listener when investigating localization abilities. Still, it is curious that the perception of acoustic facing direction itself has received little or no attention in the literature.

Enclosed loudspeakers (as well as many biological sound sources) primarily project sound into the hemifield that the source is facing (Studebaker, 1985). Here we refer to these types of sources as *directional sources*. High frequency sounds are particularly directional and show greater "beaming" than low frequency sounds (Beranek, 1993). Although most sources are audible even when they do *not* face the listener directly, there may be information conveyed by the facing angle of a source to which listeners are sensitive. For example, the perception of facing angle may be of particular importance with sounds produced by biological organisms. Human listeners visually orient toward the source of speech as well as project speech toward the intended recipient of the message (Bertelson et al., 1987; Brown, 1989; Ecklund Flores and Turkewitz, 1996). Other organisms direct vocalizations such as alarm calls and territorial warnings (Fotheringham et al., 1997; Herzog and Hopf, 1984; Munn, 1986; Sherman, 1977). Thus, detecting the facing angle of a directional source may play a role in communication and perhaps in warning of potential environmental threats.

The directivity characteristics of a loudspeaker can be obtained by measuring levels directly in front of the source and at equidistant angles around the source or simply rotating the source while taking measurements from one position (Beranek, 1993). Broadband directivity measurements for enclosed loudspeakers often show peak levels directly in front of the source that drop off as the measurement point departs from 0^o. It is often stated that interaural level differences (ILDs) do not exist when a sound source is in the median plane of the listener. However, there are at least two important qualifications to this statement. One is the lack of exact bilateral symmetry (see Searle et al., 1975). The other is that directional sources in the median plane fail to produce ILDs only if the source is *directly facing* the listener. A directional source in the median plane *can* produce ILDs if it does not directly face the listener because of directivity characteristics. For example, if the level measured directly in front of a source is higher than that measured at 10^o, then we might expect ILDs when the source is directly in the median plane but facing 10^o to one side of the listener. Thus, listeners may be able to use the ILD created by the directivity of a source in the median plane as a cue to facing angle. Furthermore, if listeners do use directivity related ILD to perceive facing angle, we would predict that they would be more sensitive to facing angle when closer to the source. Given this potential cue, we sought to examine the ability to perceive the facing angle of a directional sound source at two different listening distances.

2. Method

2.1 Participants

Fifteen undergraduates served as participants. All had normal hearing and were between eighteen and twenty years of age.

2.2 Apparatus and Stimulus

The experiment was conducted in a 2.74 x 3.66 x 2.43 m semi-anechoic room (reverberation time with stimulus broadband noise: RT_{60} = .15 s). The stimulus was white noise generated by a 16-bit soundcard in a Pentium PC compatible computer at a sampling rate of 44.1kHz. The noise was band pass filtered with cutoff frequencies of 220 Hz and 10 kHz. Stimuli were transferred to an audio compact disc and presented from a Sony portable CD player (Model CFD-ZW755) connected to an Optimus XTS 40 loudspeaker (Radio Shack part #40-1991) with the metal grill removed. The loudspeaker enclosure was 12.5 x 12.5 x 11.4 cm and had a frequency response of 150-18,000 Hz. The loudspeaker was mounted 91 cm above the floor on a microphone stand that allowed it to rotate freely and quietly in the horizontal plane. The loudspeaker was centered in the median plane of the listener 1 m from the rear wall that the listener faced. On half of the trials, listeners were seated 0.91 m from the loudspeaker. On the other half, they were seated 1.82 m from the loudspeaker. On each trial the broadband noise occurred in five 100 ms bursts with a 100 ms inter-burst interval. Stimuli were presented at 70 dB-A (measured at a distance of 1.82 m). Directivity measurements from -30^o to 30^o were taken 1.5 m from the source at four different frequencies (see Fig. 1).

2.3 Design and Procedure

Listeners were blindfolded such that no part of the blindfold touched the ear. Each listener first heard the stimulus at 0^o (directly facing the listener). The loudspeaker was then rotated either left or right to one of six facing angles (5^o, 10^o, 15^o, 20^o, 25^o, 30^o), and the stimulus was played again. The interstimulus interval was 1 s. The task of the listener was to indicate the direction of rotation by raising either the left or right hand. There were ten trials at each of the six facing angles at each distance for a total of 120 trials. Half of the rotations were to the left and half were to the right. Trials were blocked by listening distance with half of the listeners listening from .91 m first, and the other half listening from 1.82 m first. Trials were randomly ordered within blocks of listening distance.

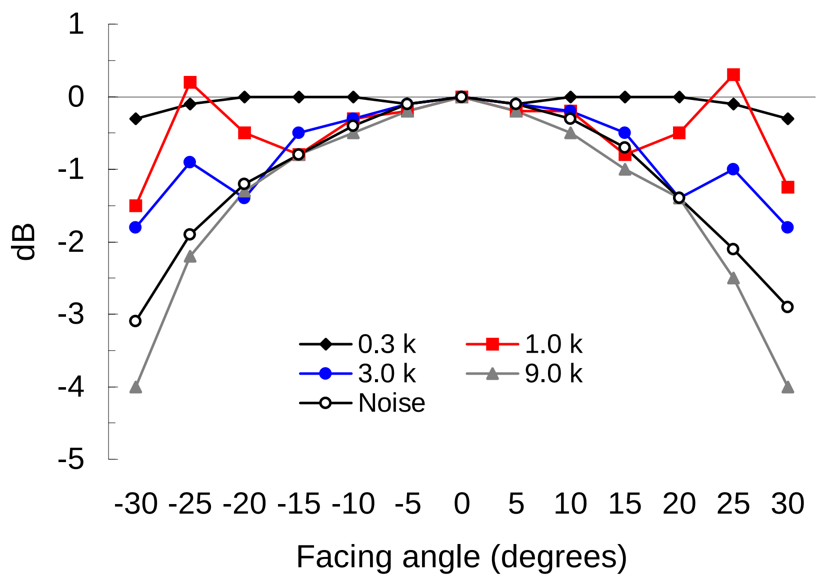

Fig. 1. Loudspeaker directivity measurements 1.5 m from the source at four frequencies and using the broadband noise stimulus.

3. Results and Discussion

The mean proportion of correct responses at each facing angle and distance across all fifteen listeners is shown in Fig. 2. In this type of experimental design, the halfway point between perfect performance and chance performance is usually considered the minimum threshold for detection (75% correct), or, in this case, what we might call the "minimum audible facing angle" (MAFA). The 75% correct point at listening distances of 0.91 m and 1.82 m occurred at 7.5^o and 12.5^o respectively. However, given that our listeners did not reach perfect performance at any angle and were still above chance performance at the smallest angle tested, identifying these points as minimum auditory facing angles may be somewhat premature.

Nonetheless, listeners showed an appreciable sensitivity to the facing angle of our loudspeaker. Our results are consistent with an interpretation of ILD as a primary cue. Interaural intensive thresholds vary as a function of frequency. However, at most frequencies, the threshold is between 0.5 and 1 dB (Mills, 1960; Yost and Dye, 1988). The broadband directivity of our loudspeaker between -30^o and 30^o is approximately quadratic and can be represented by:

$$D = D_0 - D_2 f^2 \qquad (1)$$

where D = the broadband directivity of the source, D_0 = the reference level at 0^o facing angle, D_2 = .0034 dB/deg^2 (or 11 dB/rad^2), and f = the facing angle of the source. ILD is created by the change in directivity across the listener's head. Using small-angle approximations, MAFA based on ILD threshold can be predicted by the following equation:

$$MAFA = \frac{ILD_0 r}{2 D_2 d} \qquad (2)$$

where ILD_0 = the threshold for ILD, r = the distance between the source and the listener, and d = the diameter of the listener's head. Plugging in values of ILD_0 = 0.5 dB, D_2 = 11 dB/rad^2, and d = 0.175 m, at a listening distance of r = 0.91 m we find a predicted MAFA based on

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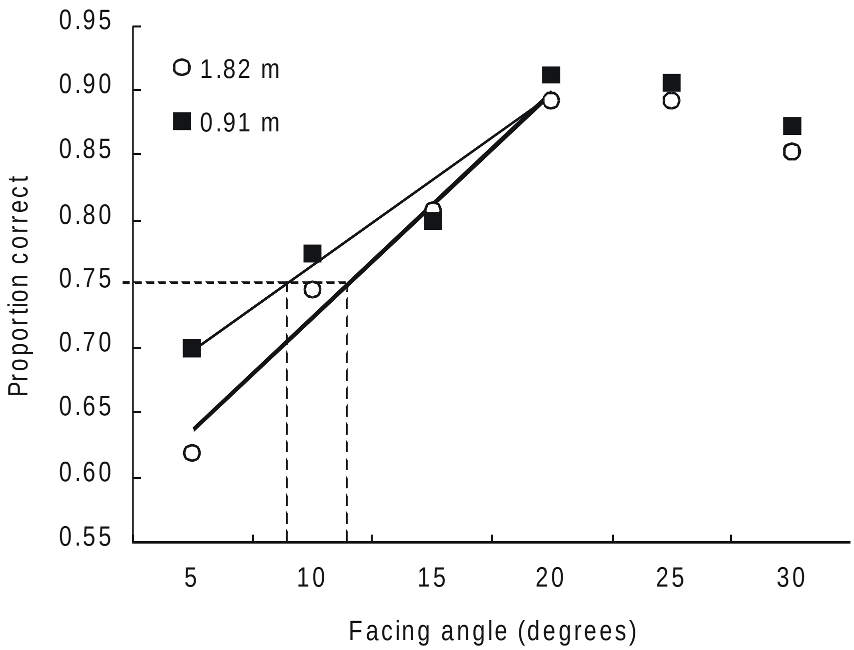

Fig. 2. Mean proportion correct at each facing angle and distance. Minimum audible facing angles (75% correct points) for .91 m and 1.82 m distances are 9° and 12° respectively. Trend lines show linear regression for the first four facing angles. The function is non-monotonic beyond 20° (see text).

ILD of 0.118 rad or 6.8°. At our farther listening distance where r = 1.82 m, the predicted MAFA is 0.236 rad or 13.5°. These predicted MAFAs based on ILD are in reasonably good agreement with our obtained values of 9° and 12° respectively.

If listeners do use ILD created by the directivity of the loudspeaker to perceive facing angle then MAFA should vary as a function of source distance and directivity. As our results show, MAFA increases as the distance between the source and listener increases. In addition, the more directive the source, the more sensitive listeners should be to facing angles. Given the dependence of MAFA on source distance and directivity, the perception of facing angle might be more appropriately characterized by a measure that takes into account both the distance between the source and the listener as well as the directivity of the source. We term this measure the minimum audible facing index (MAFI):

$$MAFI = \frac{MAFA}{r\theta_{ILD}^{2}} \tag{3}$$

where *MAFA* = the minimum audible facing angle, *r* = the distance between the source and the listener, and θ_{ILD} = the facing angle at which the difference in level from that measured at 0° first equals the threshold for ILD (approximately 10° for our loudspeaker and stimulus). Using θ_{ILD} = 10°, our results show a MAFI of 0.099 /m at r = 0.91 m and 0.066 /m at r = 1.82 m. This discrepancy suggests that listeners may use other information in addition to ILD to discriminate audible facing angles at varying distances.

The directivity characteristics of a source also depend on frequency (Beranek, 1993). Because low frequencies provide little information about the facing angle of a source, listeners may rely on specific spectral regions within broadband stimuli. Our results show that sensitivity to facing angle leveled off and declined between 20° and 30°. This may be due to the directivity characteristics of the loudspeaker at midrange frequencies. Fig. 1 shows that midrange frequencies (1kHz and 3 kHz) increase in level between 20° and 30° with a peak at 25°. Thus, between 20° and 30°, ILD in this frequency range decreases and becomes less informative. This finding suggests that the perception of facing angle for broadband sources may depend more on the directivity of these midrange frequencies than the overall broadband directivity of the source. Thus, future work in this area may suggest frequency specific modifications to our development of the MAFI.

Implicitly, we have suggested that listeners can use a disparity between interaural time differences and ILDs to recognize that a source is not facing them directly. We realize that such disparity has also been proposed as a cue to source elevation (Searle, et al., 1975) as well as to the distance of nearby sources (Brungart, 1999; Brungart, et al., 1999; Brungart and Rabinowitz, 1999). Furthermore, we acknowledge that there are a host of other possible cues that listeners may use to perceive facing angle. Thus, as with any preliminary finding, there are numerous parameters yet to be investigated. Some of these include effects of frequency, intensity, the reference point from which the facing angle is measured, and the reverberant characteristics of the environment. In reverberant environments, listeners may use reflected sound in a manner analogous to that used to judge auditory distance (Bronkhorst and Houtgast, 1999; Little et al., 1992; Mershon et al., 1989; Mershon and King, 1975). Also of interest is the effect of dynamic change in facing angle. In the localization literature, differences have been found between the minimum audible angle (MAA) and the minimum audible movement angle (MAMA) (Chandler and Grantham, 1992; Harris and Sergeant, 1970; Mills, 1958; Perrott and Musicant, 1981; Perrott and Saberi, 1990; Strybel et al., 1992). It may be that differences between static and dynamic audible facing angles also exist. For example, dynamic rotation of a directional source would provide an ongoing change in the ratio of direct to reflected sound (Neuhoff, 2001) as well as dynamic changes in amplitude, spectral content, and ILD. Thus, facing angle estimates based on rotation cues might rely on a tau-like function for change in the ratio of these characteristics, similar to those functions suggested for amplitude change in sound source approach (Shaw et al., 1991) and frequency change in the acoustic guidance of vessel filling (Cabe and Pittenger, 2000). At faster rates of rotation, Doppler cues may be useful. In music, such sounds have been produced since the 1940s by the Leslie loudspeaker, famous among organists for its rotating horn that creates a spatial tremolo and vibrato effect with the frequency and amplitude variation that result from the horn's rapid rotation (Henricksen, 1981).

4. Conclusions

Within the limitations of the current experimental conditions, listeners showed appreciable sensitivity to the facing angle of a directional sound source in the median plane. The results are consistent with an interpretation of directivity dependent ILD as a primary cue used to accomplish this task.

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