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Twist and Shout: Audible Facing Angles and Dynamic Rotation

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In 2 experiments, blindfolded listeners estimated the facing direction of a sound source from 2 different listening distances. In Experiment 1, listeners estimated the stationary facing angle of a loudspeaker that projected a speech stimulus while facing 1 of 8 different directions. In Experiment 2, the loudspeaker sounded while rotating and also while stationary at its terminal orientation. Listeners then made judgments of the final facing angle. Although performance fell short of that typically found in minimum audible angle experiments, listeners made relatively accurate estimates of loudspeaker orientation and showed a significant advantage when dynamic rotation information was available. Listeners were also significantly better at perceiving facing angles when closer to the source and when the loudspeaker was directly facing the listener (0°). The enhanced sensitivity to this egocentric source orientation may be the result of the use of redundant binaural and monaural information at a facing angle of 0°. Human listeners tend to visually orient toward the source of speech as well as project speech directionally toward the intended recipient of the message. Thus, sensitivity to static and dynamic audible facing angles may have implications for complex perception–action relations that are instrumental in activities such as communication and navigation.

Intuitively, it seems reasonable to assume that listeners use acoustic information to determine the facing direction of a sound source. For example, most listeners can probably hear when someone who is speaking turns their head in midsentence or when a marching band turns away from the audience. Both of these examples represent a change in the "facing angle" of an acoustic source (Neuhoff, Rodstrom, & Vaidya, 2001). Biological sound sources may intentionally vary their facing angle to convey information. For example, a change in facing angle might be used by humans

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to specify more closely the intended recipient of an utterance or by other animals to direct specific acoustic warnings or alarms. Yet, despite the potential information available in the facing angle of a sound source and the anecdotal ease with which listeners seem to be able to detect this information, there has been almost no empirical investigation of the ability to perceive differences in audible facing angles.

An audible facing angle is formally defined by a line between a source and a listener, and a ray in the direction in which the source is radiating (Neuhoff et al., 2001; see Figure 1). Thus, only sources that radiate sound in one primary direction relative to the source have true audible facing angles. An omnidirectional source would radiate sound equally in all directions, and in theory, any rotation of such a source would be undetectable. Many low-frequency sounds can also radiate relatively equally in all directions despite a specific facing direction of the source. Nonetheless, in a natural listening environment, many important sound sources are directional and do radiate from one primary plane of dispersion relative to the source. For example, humans and many other animals tend to project sound more strongly into the hemifield that the organism is facing. In fact, human vocalizations have been shown to be even more directional than those of other primates (Brown, 1989). The high-frequency spectral characteristics of vocalizations are particularly directional and may be instrumental in the detection of the facing angle of the source.

Although there has been very little research conducted on the perception of audible facing angles, some related work has shown that, from an attentional perspective, human listeners visually orient toward a source of speech and that, during production, talkers tend to project speech toward the intended recipient of the message (Bertelson, Morais, Mousty, & Hublet, 1987; Brown, 1989; Ecklund

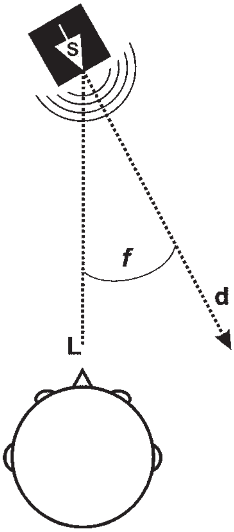

FIGURE 1 The audible facing angle *f* is defined by a line between the source *s* and listener *L*, and the ray *d* in the direction in which the source is radiating.

Flores & Turkewitz, 1996). Other organisms have also been shown to direct vocalizations such as alarm calls and territorial warnings (Fotheringham, Martin, & Ratcliffe, 1997; Herzog & Hopf, 1984; Munn, 1986; Sherman, 1977). Thus, perceiving the facing angle of a directional sound source may play a role in communication and perhaps in detecting warnings of potential environmental threats.

PREVIOUS WORK AND THE AVAILABLE ACOUSTIC INFORMATION

In one of the only studies to examine audible facing angles it was found that, under certain conditions, listeners could discriminate between facing angles that differed by as little as 9° (Neuhoff et al., 2001). In this study, a burst of broadband noise was played in an anechoic room through a small loudspeaker that directly faced the listener. After the stimulus was presented, the loudspeaker silently rotated on its axis either to the left or right. The same burst of noise was then played again. The task of the blindfolded listener was to determine the direction of rotation. A psychophysical function was derived by plotting the proportion of correct responses at each successively larger facing angle. The 75% correct point was then defined as the minimum audible facing angle and was found to be dependent on the distance between the source and the listener and also on the directivity (or pattern of acoustic dispersion) of the source. The closer the listener was to the source and the narrower the pattern of directivity, the better listeners could discern differences between facing angles.

There are several potential sources of acoustic information that listeners might use to perceive audible facing angles. Binaural information for facing angles such as interaural level differences (ILDs) and interaural time differences (ITDs) could provide listeners with specific information about both the degree and the direction of displacement from a facing angle of 0° (directly facing the listener). Monaural information such as the ratio of direct-to-reflected sound, overall differences in level that occur at different facing angles, and changing spectral information could provide general information about how far the source is displaced from 0° but could not be used to determine the direction of displacement.

ILDs can be created by different facing angles because of the directivity pattern of the source. 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 (Beranek, 1993). Directivity measurements for enclosed loudspeakers typically show peak levels directly in front of the source that drop off as the measurement point departs from 0°. High-frequency sounds are particularly directional and show greater “beaming” than low-frequency sounds (Beranek, 1993). Listeners may in part base their judgments of facing angle on ILDs that are created by the interaction of facing angle and the directivity of the source. For high-frequency sounds, ILDs are useful in localizing a sound source and are typically created when a source is closer to one ear than the other. The presence of the listener's head creates an acoustic shadow and prevents sound waves from traveling on a direct path from the source to the far ear. Sources in the median plane are equidistant from the two ears and thus typically do not create ILDs (but see Searle, Braida, Cuddy, & Davis, 1975). However, a directional source in the median plane fails to produce ILDs only if the source is directly facing the listener. A directional source in the median plane can produce ILDs if its facing angle is greater than 0°. For example, suppose that the level measured at 0° in front of a directional source is higher than that measured at 10°. If the source is in the median plane and is facing the listener directly, then the level at each ear will be the same because each ear is equally offset from the midline and thus equally displaced (in degrees) from the directivity pattern where the level is highest (assuming a reasonably symmetrical head and pattern of directivity). However, if the facing angle of the source is such that the source is rotated to directly face the right ear, for example, ILDs would be created because the right ear is now directly in the portion of the directivity pattern where the level is highest, whereas the left ear is in the portion of the directivity pattern where levels begin to drop off. Thus, listeners may be able to use the ILD created by the directivity of a source to determine its facing angle (Neuhoff et al., 2001).

Monaural sources of information might also be used to perceive facing angles. As the facing angle of a source departs from 0° the ratio of direct-to-reflected sound decreases, overall level decreases, and spectral information changes. Listeners may be able to use this information to perceive facing angle in a manner similar to that used to judge auditory distance (Bronkhorst, 1995; Bronkhorst & Houtgast, 1999; Little, Mershon, & Cox, 1992; Mershon & Hutson, 1991; Mershon & King, 1975; Zahorik & Wightman, 2001). All three types of information can signal that the facing angle of a source is different from 0°, but none of these sources of information alone provide information about whether the source has turned to the left or to the right. Binaural information such as directivity or ILD and ITD created by specific patterns of reflection would be required to provide directional information.

However, listeners may be able to make use of both monaural and binaural information to determine audible facing angles. The monaural information would provide information about whether the source is facing the listener directly and, if it is not, perhaps some information about how far the facing angle is displaced from 0° (without providing information about the direction of rotation). The binaural information could provide redundant information about the magnitude of facing angle displacement from 0° and, in addition, provide specific information about the direction of rotation. For facing angles of 0°, listeners might then have both monaural and binaural information that accurately specifies the facing angle of the source. Thus, we might expect greater accuracy in judging facing angles of 0° because listeners potentially would have more specific information on which to base their judgments.

DYNAMIC VERSUS STATIC FACING ANGLES

There is a considerable amount of research that shows that perceptual judgments made with access to dynamic information are more accurate than those made with only static information. However, the effects of dynamic motion on the perception of auditory space are somewhat paradoxical. In the localization literature, differences have been found between the minimum audible angle (MAA; Mills, 1958) and the minimum audible movement angle (MAMA; Chandler & Grantham, 1992; Harris & Sergeant, 1971; Mills, 1958; Perrott & Musicant, 1981; Perrott & Saberi, 1990; Strybel, Manligas, & Perrott, 1992). The MAA is a measure of auditory localization precision that differs from the minimum audible facing angle. Essentially, it is the minimum separation in degrees of azimuth that is required for two sound sources to be perceived as being in different locations. Listeners are typically seated in an anechoic chamber and played sounds from a loudspeaker mounted on the end of a boom. The initial sound is followed by a second sound that is played after the boom has been moved to the left or right. The task of the listener is to determine the direction in which the sound source has been moved. The angle at which listeners achieved an accuracy rate of 75% is termed the MAA. The MAMA is a similar measure of precision for detecting auditory motion where the loudspeaker plays while it is in motion to the left or the right. Research on MAAs has shown that some stimuli can be localized to within plus or minus 1° of azimuth (Mills, 1958). Yet, some work on the MAMA has shown that under some circumstances a sound source in motion can travel up to 10 times this distance before the motion can be detected (Harris & Sergeant, 1971; Perrott & Musicant, 1981; but see Elfner & Howse, 1987). In this case, listeners exhibit greater precision when making judgments of stationary audible angles than they do when making judgments of audible angles produced by source motion. On the other hand, when listeners are asked to judge the distance to a sound source or to estimate the time of arrival of an approaching source, the more dynamic motion information that listeners have available, the more accurate their judgments appear to be (Ashmead, Davis, & Northington, 1995; Rosenblum, 1993; Rosenblum, Gordon, & Jarquin, 2000). So far, the work on audible facing angles has examined only stationary differences in the facing angle of a sound source. However, in natural listening environments biological sound sources often emit sound while changing facing angle. This type of motion information may affect the ability of listeners to perceive the facing angle of the source.

THE PRESENT EXPERIMENTS

In this work, the ability to determine the facing angle of a loudspeaker was examined under stationary and dynamic rotation conditions. In Experiment 1, a loudspeaker silently rotated on its axis to one of eight facing angles, and a speech stimulus was played. Blindfolded listeners made estimates of the terminal facing angle of the loudspeaker. In Experiment 2, the effects of dynamic rotation were investigated. Thereby, the loudspeaker rotated while the speech stimulus was playing, and listeners estimated the terminal facing angle once the rotation and the speech stimulus had stopped. It was hypothesized that if listeners could take advantage of the changing acoustic information that occurred when a sounding source changed its facing angle, then they would exhibit better performance in the dynamic rotation experiment than in the stationary experiment. Both experiments were conducted with a speech stimulus in a reverberant room, and listeners estimated facing angles from two different distances. To summarize, it was hypothesized that listeners would show better performance at closer listening distances under dynamic rotation conditions, and due to the redundant monaural and binaural information at 0°, listeners would show better performance when the sound source faced the listener directly.

EXPERIMENT 1

Method

Participants. Thirty undergraduate students between the ages of 18 and 25 years served as participants. All listeners reported normal hearing and received class credit for participation.

Apparatus and stimuli. The experiment took place in a 2.74 m × 3.66 m room with painted gypsum sheetrock walls, a 2.44-m-high acoustical tile ceiling, and a carpeted floor. Room reverberation time was $RT_{60} = .45$ sec (using band limited noise with cutoff frequencies of 200 and 10,000 Hz). Speech stimuli were digitally recorded in an anechoic room onto a PC hard drive with a Sure SM-57 microphone through a Turtle Beach Santa Cruz sound card at a sampling rate of 44.1 kHz. The recordings were then transferred onto a CD and presented with a Koss portable CD player (Model HG 900). The stimulus was a male voice counting "one, two, three, four, one, two, three, four" at approximately 65 dB-A measured 1 m from the source. Stimulus duration was 4 sec with one digit voiced every 0.5 sec (see Figure 2). The stimulus was presented from a Radio Shack Optimus XTS 40 loudspeaker with height, width, and depth dimensions of 12.5 × 12.5 × 11.4 cm, respectively, and a frequency response of 150 to 18,000 Hz. Directivity measurements for the loudspeaker at three frequencies are shown in Figure 3. The loudspeaker rested on a 91.4 × 61 cm table from which a 3 cm steel dowel 6.25 mm in diameter protruded. A 6.25 mm hole was drilled in the center of the bottom of the loudspeaker, and the speaker was placed on the table over the protruding steel dowel, thus allowing it to rotate freely in any direction (see Figure 4 for specific room configuration). The tabletop was 77.5 cm from the floor. Participants were

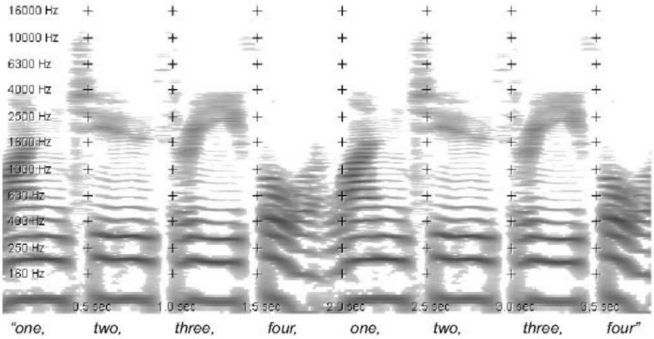

FIGURE 2 Spectrogram of the speech stimulus used in Experiments 1 and 2.

seated at a 91.4 × 61 cm response table, the surface of which was 72.4 cm from the floor. A 3 cm steel dowel 6.25 mm in diameter also protruded from the center of the response table. A hole was drilled in the center of the bottom of a second Optimus XTS 40 loudspeaker, and the loudspeaker was placed over the protruding dowel in the response table so that it, too, was free to rotate in any direction. Both the stimulus and response speakers were fitted with flat plastic pointers 6 in. (15 cm) in length that indicated the facing angle of each speaker by pointing to marks on the table surrounding each speaker. The response table was moved between blocks of trials so that, in two separate conditions, the distance between the two loudspeakers was 0.91 m and 1.82 m, respectively.

Design and procedure. Participants entered the experimental room and were seated at the response table. They were then blindfolded and told that they would hear a voice emanating from the stimulus loudspeaker and that the loudspeaker could be facing any direction. The listener's task was to indicate the facing angle of the stimulus loudspeaker by rotating the response loudspeaker to match the perceived facing direction of the stimulus loudspeaker. There were two trials from each of eight facing angles (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°). This provided for a total of 16 randomly presented trials at each of the two listening distances.[1] Half of the listeners provided responses from the 0.91 m listening distance first; the other half provided responses from the 1.82 m listening distance first.

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[1] Between-trial masking of apparatus noise is critical in auditory distance and localization experiments because the information in the incidental noises produced by moving the apparatus can specify target location and distance. However, this is not the case in facing angle estimates. Nonetheless, to prevent listeners from potentially using the between-trial sound of the loudspeaker rotation, the stimulus loudspeaker was rotated 360° prior to each trial when moving to its starting position. Furthermore, an additional experiment was conducted with 8 new participants to assess the ability of listeners to use only the between-trial rotation sounds to determine facing angle. Performance was at chance levels.

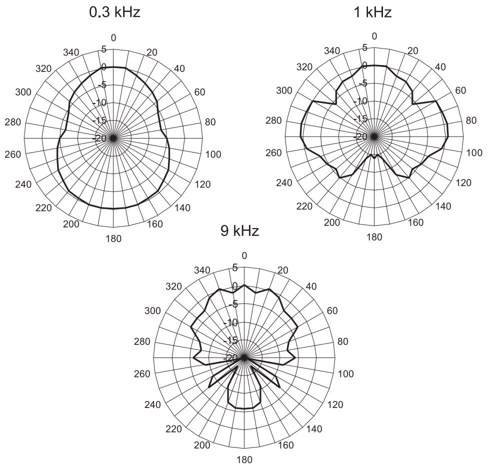

FIGURE 3 Directivity measurements at three frequencies for the loudspeaker used in Experiments 1 and 2.

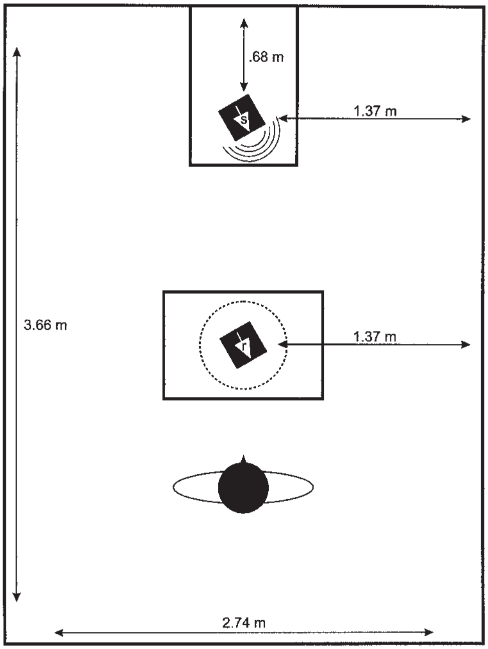

FIGURE 4 Experimental setup used in Experiments 1 and 2. Listeners used the response loudspeaker *r* to indicate the perceived facing angle of the stimulus loudspeaker *s*. The response table was moved between blocks of trials so that the distance between the two loudspeakers was 0.91 m and 1.82 m.

Prior to beginning experimental trials, listeners were given two familiarization trials in which they were exposed to the stimulus sound and the acoustical properties of the room. On familiarization trials, listeners heard the stimulus two times in succession while the speaker was rotated 360° starting and ending at 0° (facing the listener). On one familiarization trial the direction of rotation was clockwise; on the other trial the direction of rotation was counterclockwise. Listeners indicated their response by rotating the response speaker to the desired orientation and removing their hand from the speaker. The experimenter then recorded the facing angle of the response speaker.

Results and Discussion

Each listener made two estimates at each of eight facing angles. Estimates were averaged to obtain a single score at each facing angle. A mean error score for each condition was calculated by taking the absolute value of the difference between the perceived and the actual facing angle. The mean error scores in each condition are shown in Figure 5a. A 2 (distance) × 8 (facing angle) analysis of variance (ANOVA) on the error scores showed a significant effect for facing angle, $F(7, 203) = 6.30$, $p < .001$. Listeners showed the best performance when the loudspeaker was oriented at 0° (directly facing the listener). Listeners also showed significantly better performance at the closer listening distance, $F(1, 29) = 11.32$, $p < .01$ (0.91 m: $M = 47.0$, $SD = 37.1$; 1.82 m: $M = 52.5$, $SD = 37.3$). In a separate analysis, errors that were between 165° and 180° were defined as reversals. Averaged across all conditions, only 4.6% of the trials were reversals. However, the large majority of these occurred at 180°, with listeners mistaking the 180° facing angle for 0°. A chi-square test showed a significant difference in the number of reversals between facing angles, $\chi^2(7, N = \text{XXX}) = 125.48$, $p < .001$ (see Figure 6). These reversals are likely due to room reflections from the wall that the loudspeaker was facing. The reflections from the wall at 180° would provide the same interaural information as the loudspeaker facing directly toward the listener at 0°.

Thus, to summarize the results of Experiment 1, listeners could detect differences in the facing angle of the loudspeaker and showed the best performance when closer to the source and when the source was oriented at 0°. This latter finding is consistent with the hypothesis that listeners use redundant binaural and monaural information when detecting the facing angle of a source at 0°. These results are discussed further in conjunction with the dynamic rotation results of Experiment 2.

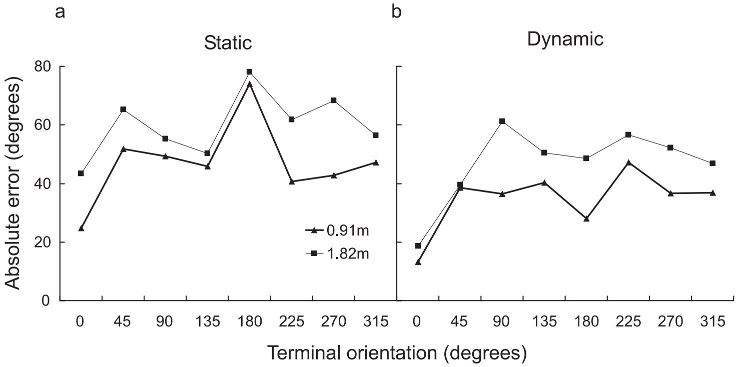

FIGURE 5 (a) Mean error in static facing angle estimates in Experiment 1, and (b) dynamic facing angle estimates in Experiment 2.

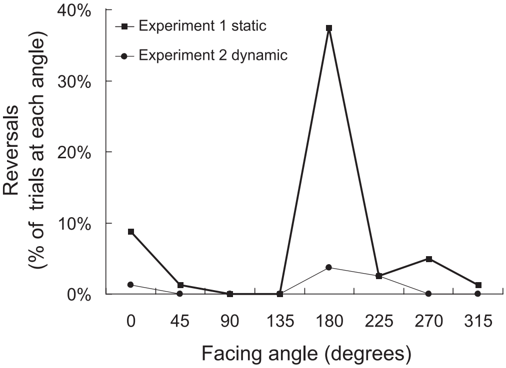

FIGURE 6 Percentage of reversals (errors greater than 165°) at each angle for static facing angle estimates in Experiment 1 and dynamic facing angle estimates in Experiment 2.

EXPERIMENT 2

Method

Participants. Twenty undergraduate students between the ages of 18 and 25 years served as participants. All listeners reported normal hearing and received class credit for participation.

Apparatus and stimuli. The apparatus and stimuli used in Experiment 2 were identical to those used in Experiment 1.

Design and procedure. Participants entered the experimental room and were seated at the response table. They were then blindfolded and told that they would hear a voice emanating from the stimulus loudspeaker. They were also told that the loudspeaker would rotate when the voice began. The listener's task was to indicate the terminal facing angle of the stimulus loudspeaker by rotating the response loudspeaker to the same orientation. Prior to each trial, the facing direction of the response loudspeaker was aligned with that of the stimulus loudspeaker. Listeners were instructed to feel the response loudspeaker prior to each trial so that they knew the starting orientation of the stimulus loudspeaker. There were two trials from each of eight starting trajectories (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°). One trial was in the clockwise direction, and one was in the counterclockwise direction. On each trial, the loudspeaker rotated 180°. However, the listeners were unaware of this fact. The eight starting trajectories and two rotation directions provided for a total of 16 randomly presented trials at each of the two listening distances. Half of the listeners provided responses from the 0.91 m listening distance first; the other half provided responses from the 1.82 m listening distance first. The rotation speed was 90°/sec, the stimulus was 4 sec duration, and the loudspeaker always rotated 180°. Thus, the first 2 sec of the stimulus sounded during the rotation and the second 2 sec of the stimulus sounded when the loudspeaker was stationary at its terminal facing angle. Prior to beginning experimental trials listeners were given two familiarization trials in which they were exposed to the stimulus sound, the speaker rotation, and the acoustical properties of the room. On familiarization trials, listeners heard the stimulus two times in succession while the speaker rotated 360°, starting and ending at 0° (facing the listener). On one familiarization trial the direction of rotation was clockwise; on the other trial the direction of rotation was counterclockwise. Listeners indicated their response by rotating the response speaker to the desired orientation and removing their hand from the speaker. The experimenter then recorded the facing angle of the response speaker.

Results

The difference between perceived facing direction and actual facing direction was calculated for each trial. These scores were converted to absolute vales, and mean error values were calculated in each condition. A 2 (listening distance) × 2 (rotation direction) × 8 (facing angle) repeated measures ANOVA was performed. Errors in perceived facing angle were significantly affected by actual facing angle, $F(7, 133) = 5.30$, $p < .001$. This effect appears to stem from greater accuracy when the speaker was oriented at 0° (directly facing the listener; see Figure 5b). When perceived facing angle was examined with 0° removed, there was no significant difference between angles. Listeners were also significantly more accurate at estimating facing angle when they were closer to the source, $F(1, 19) = 8.02$, $p < .05$ (M error for 0.91 m = 33°, $SD = 24.5$; M error for 1.82 m = 42° , $SD = 24.5$). Finally, there was a significant interaction between rotation direction (clockwise–counterclockwise) and facing angle, $F(7, 133) = 3.19$, $p < .01$. The interaction stemmed from better performance on clockwise rotations at angles of 225°, $t(19) = 3.08$, $p < .01$, and 315°, $t(19) = 2.70$, $p < .05$, and better performance on counterclockwise rotations at 135°, $t(19) = 2.56$, $p < .05$. The pattern of interaction suggested better performance on trials where the loudspeaker passed through 0° at some point during its rotation.

To examine this hypothesis, the type of rotation was divided into two different groups, those trials in which the speaker at some point in its path of rotation directly faced the observer and those trials in which it did not. For example, a clockwise trial that began at 90° and ended at 270° would rotate through 0°, directly facing the listener at the midpoint of the rotation. However, the same angular rotation in the counterclockwise direction would rotate through 180° and would not face the listener at any point in its rotation path (see Figure 7). For trials beginning at 270° and ending at 90°, the pattern would be reversed. Excluded from this analysis were trials that ended at 0° and 180°. Thus, a 2 (path) × 6 (angle) ANOVA was performed. The results showed that listeners were significantly more accurate in determining facing direction when the loudspeaker rotated toward them through 0° than when it rotated away from them despite identical terminal orientation, $F(1, 19) = 22.77$, $p < .001$ (see Figure 8). There were no significant differences in accu-

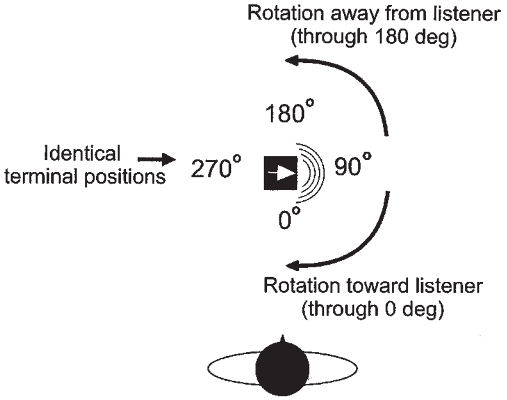

FIGURE 7 "Toward" and "away" rotation paths for estimating dynamic audible facing angles in Experiment 2. Listeners were significantly better when the loudspeaker rotated toward the listener and passed through 0°.

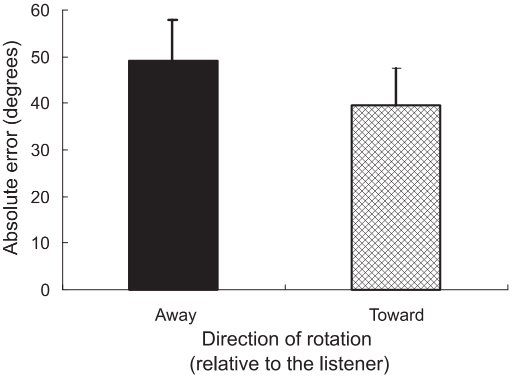

FIGURE 8 Path results from Experiment 2. Listeners were significantly better when the loudspeaker rotated toward the listener and passed through 0°. Error bars represent 1 standard error.

racy between facing angles (keeping in mind that 0° and 180° were removed from this analysis), and the interaction between rotation path and facing angles was not significant.

To examine the influence of dynamic rotation on the perception of facing angles, mean errors in Experiment 1 were compared with those in Experiment 2 in a 2 (rotation) × 8 (facing angle) ANOVA. The effect of facing angle was statistically significant, $F(7, 48) = 6.73, p < .001$, and listeners were significantly more accurate at estimating facing angles when presented with dynamic rotation information, $F(1, 48) = 25.23, p < .001$ (dynamic $M = 37.8$, $SD = 27.0$; static $M = 52.5$, $SD = 37.3$). The overall proportion of reversals (errors greater than 165°) in Experiment 2 was less than 1%. A chi-square analysis failed to show a significant difference in the number of reversals across the eight different terminal orientations, $\chi^2(7, N = \text{XXX}) = 12.67$, *ns*. An analysis of reversals between Experiments 1 and 2 showed significantly more reversals in the static condition employed in Experiment 1 than in the dynamic condition employed in Experiment 2, $\chi^2(1, N = \text{XXX}) = 76.92, p < .001$ (see Figure 6).

DISCUSSION

In two experiments, listeners made relatively accurate estimates of loudspeaker facing angle and showed a significant performance advantage when dynamic rotation information was available. Although it may seem optimistic to call perceptual judgments relatively accurate in an experiment where the best performance showed errors of 15°, this level of precision is probably sufficient for listeners to determine the intended recipient of an utterance, for example, in a three-person communication setting. In almost all conditions (excluding those in which the source faced directly away from the listener) errors were almost always less than 60°. Although performance fell short of that typically found in MAA experiments, listeners did appear to have a good sense of the "general direction" that the loudspeaker was facing. Facing angle performance was particularly good when the loudspeaker faced the listener directly and when the listener was closer to the source. Performance in this experimental setting may have been enhanced slightly by listeners becoming familiar with the source as the trials progressed. However, this is not unlike naturally occurring conversations in which listeners become accustomed to the characteristics of a particular speaker and acoustic environment.

The enhanced ability of listeners to localize egocentric source orientation (0°) may be the result of the use of both binaural and monaural information. A primary monaural source of information at 0° is the fact that the stimulus would be loudest at this angle. In addition, both binaural and monaural information would specify the correct facing angle. The combination of monaural and binaural information may also be responsible for the better accuracy at other facing angles when the source rotated through 0°.

Listeners were also better at determining facing angle when they were closer to the loudspeaker. At closer listening distances, the ratio of direct to reflected sound is higher. Thus, this finding is consistent with the interpretation that listeners may in part rely on the change in this ratio in making determinations of the facing angle of directional acoustic sources. If so, an avenue for future studies would be to examine whether facing angle estimates based on dynamic rotation information rely on a tau-like function for change in the ratio of direct to reflected sound, similar to those suggested for intensity change in sound source approach (Shaw, McGowan, & Turvey, 1991) and frequency change in vessel filling (Cabe & Pittenger, 2000).

Better performance at closer distances is also consistent with the hypothesis that listeners can use ILDs in perceiving facing angle. For example, the directivity characteristics of the loudspeaker were such that levels were generally attenuated as the facing angle departed from 0°. At 0° then we would expect zero ILD. However as the loudspeaker was turned, the directivity pattern created ILDs that listeners may have used to perceive facing angle. At closer distances the amount of rotation required to create ILDs is smaller than that required at farther distances. Thus, our finding of greater precision at closer listening distances is also consistent with ILD as a source of information for perceiving facing angle.

Earlier work has also implicated ILD as a source of information in detecting audible facing angles (Neuhoff et al., 2001). The minimum audible facing angles found in this previous work show considerably better performance than that displayed here. However, there are considerable methodological differences between the two studies that may account for this disparity. First, Neuhoff et al. (2001) used a discrimination task in an anechoic environment. Listeners simply had to indicate whether the source that emitted a broadband noise stimulus was rotated to the left or right. The work reported here used a method of adjustment with a speech stimulus in a reverberant environment. Although there is some work to suggest that speech may be localized differently than other sounds (Gardner, 1969), it appears that the experimental task used here as well as the reverberation may contribute to somewhat poorer performance.

The perception of facing angle may be of particular importance with speech. Human listeners tend to visually orient toward the source of speech as well as project speech directionally toward the intended recipient of the message (Bertelson et al., 1987; Brown, 1989; Ecklund Flores & Turkewitz, 1996). The fact that listeners are sensitive to facing angle suggests that incorporating facing angle in virtual environments might enhance intelligibility and more realistically approximate face-to-face communication, an ideal toward which many virtual communication systems strive (Palmer, 1995). Future studies might employ a setting in which a three-person conversation is simulated. Other potential variables of interest include the effects of room reverberation and visual information about the room.

Psychoacoustics and Sound Source Characteristics

The majority of psychoacoustic research has examined the perceptual characteristics of the acoustic signal per se (e.g., pitch, loudness, and timbre) rather than the acoustically perceived physical characteristics of a sound source such as shape, size, and orientation. Yet, Helmholtz (1866/1925) observed that perceivers easily attend to objects and events in the environment that give rise to sensations but generally have difficulty attending to those sensations per se. Gaver (1993) echoed this view, suggesting that listeners identify the physical characteristics of sound sources and events at particular spatial locations. Detecting the facing angle of a sound source may involve perceiving some of these physical source characteristics in conjunction with the perception of auditory space. There is a large body of work on spatial hearing and auditory localization (for reviews, see Blauert, 1997; Gilkey & Anderson, 1997; Hirsh & Watson, 1996; Knudsen & Brainard, 1995; Middlebrooks & Green, 1991). However, there is less work on perceiving the physical properties of sound sources. Nonetheless, some recent studies have shown that listeners can make reasonable estimates of many physical characteristics of an acoustic source. Often the perception of these sound source characteristics is not based on simple isomorphic relations between the auditory dimensions and the physical properties of the source. Rather, listeners appear to use complex, higher order acoustic variables.

For example, listeners can use sound to discriminate object length (Carello, Anderson, & Kunkler-Peck, 1998). Yet, the ability to do this task with remarkable accuracy is not well predicted by differences in frequency, amplitude, or the spectral centroid of the various sources. Instead, listeners appear to use higher order acoustic variables that are correlated with an object's inertia tensor. Other work has shown that listeners can correctly identify sound source shape (Kunkler-Peck & Turvey, 2000) and discriminate among sources with different width-to-height ratios (Lakatos, McAdams, & Causse, 1997). Russell and Turvey (1999) showed that listeners could determine whether there is room to pass between a sound source and a barrier. Still other work has shown that acoustic information can be used to perceive an occluding object between a sound source and a listener (Ader, 1935; Russell, 1997), and whether a sound source is within the reach of a listener (Rosenblum, Wuestefeld, & Anderson, 1996). Listeners can even use higher order temporal properties to perceive and categorize dynamic events such as breaking, bouncing, and vessel filling (Cabe & Pittenger, 2000; Warren & Verbrugge, 1984). All of these abilities have implications for the identification and localization of sound sources as well as for complex perception–action relations that are instrumental in activities such as navigation and communication. The perception of audible facing angles may have similar implications.

Finally, these results underscore the facilitory nature of dynamic information in making perceptual judgments. Listeners performed significantly better when they had access to the dynamic information about source rotation. Similar findings have been found in a number of other areas including time-to-arrival estimates and echolocation (Ashmead et al., 1995; Rosenblum, 1993; Rosenblum et al., 2000). Dynamic information has also been implicated in performance improvements in other modalities including vision (Kleiss, 1995) and haptics (Menier, Forget, & Lambert, 1996; Rochat & Wraga, 1997). Taken together these findings underscore the importance of employing dynamic stimuli in the study of sensory processes and perception–action relations. Given that perceptual systems have evolved in an environment that is rich with dynamic information, it should come as no surprise that dynamic information is important in making perceptual judgments.

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