OCTOBER 13 2022

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J. Acoust. Soc. Am. 152, 2140–2149 (2022)
https://doi.org/10.1121/10.0014599

JASA ARTICLE

The pinna enhances angular discrimination in the frontal hemifield

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ABSTRACT:
Human sound localization in the horizontal dimension is thought to be dominated by binaural cues, particularly interaural time delays, because monaural localization in this dimension is relatively poor. Remaining ambiguities of front versus back and up versus down are distinguished by high-frequency spectral cues generated by the pinna. The experiments in this study show that this account is incomplete. Using binaural listening throughout, the pinna substantially enhanced horizontal discrimination in the frontal hemifield, making discrimination in front better than discrimination at the rear, particularly for directions away from the median plane. Eliminating acoustic effects of the pinna by acoustically bypassing them or low-pass filtering abolished the advantage at the front without affecting the rear. Acoustic measurements revealed a pinna-induced spectral prominence that shifts smoothly in frequency as sounds move from 0° to 90° azimuth. The improved performance is discussed in terms of the monaural and binaural changes induced by the pinna.

https://doi.org/10.1121/10.0014599

(Received 7 December 2021; revised 17 September 2022; accepted 19 September 2022; published online 13 October 2022)

[Editor: Matthew J. Goupell] Pages: 2140–2149

I. INTRODUCTION

Most measurements of the minimum audible angle (MAA) have concentrated on sound sources in the frontal hemifield. The experiments presented here contrast the magnitude of the MAA in the frontal and rear hemifields, demonstrating that MAAs are substantially smaller in front of the listener than behind, and investigate the source of the observed differences. The MAA is a direct measure of localization precision. It is important to note the distinction between precision, the ability to discriminate different sound directions, and accuracy, the ability to identify them. Precision may also be measured from response variability in localization judgements, but this approach is fraught with methodological problems (see Sec. VII A). Oldfield and Parker (1984) noted that sound localization was more accurate in the frontal hemifield than in the rear due to a systematic distortion of auditory space (Brimijoin, 2018), but the question of relative precision is fairly open because little attention has been paid to measurement of auditory precision in the rear hemifield.

The only previous studies of MAA at the rear appear to be those by Saberi *et al.* (1991), Aggius-Vella *et al.* (2020), and Fischer *et al.* (2020). The first two studies measured the MAA at 180° and found it to be similar in value to that at 0°. Saberi *et al.* (1991) did not make a direct comparison between the two directions but measured a value of 1° directly to the rear, which matches the best previous reports for directly in front (e.g., Mills, 1958). Aggius-Vella *et al.* (2020) measured front and back using the same protocol and observed MAAs of 5.5° and 7°, which did not differ significantly. It should be noted that the latter study used a different definition of threshold. Saberi *et al.* (1991) defined threshold as 75%, whereas the method by Aggius-Vella *et al.* (2020) is equivalent to 84.1%.[1] In addition to this difference, Aggius-Vella *et al.* (2020) drew their thresholds from a psychometric function with a relatively coarse resolution of 4.4°. These factors may explain the difference in the reported MAAs. Overall, both of these studies support the expected front/back symmetry. However, the third study (Fischer *et al.*, 2020) measured MAAs at 135°, 180°, and 225° and found these locations to produce larger MAAs, averaging 3.6°, than the equivalent locations in the frontal hemifield, averaging 2.2°.

In his definitive study of the MAA, Mills (1958) only measured the precision of sound localization for positions in front of and to the right of the listener. Regarding this decision, he remarked that "it is probably safe to assume that azimuth discrimination in the other quadrants is similar in all important respects," but he immediately acknowledged that "Because of the projection of the pinna and the asymmetry of the head, azimuth discrimination in the region behind the subject may be somewhat different at high frequencies" (Mills, 1958, p. 246). Pinna cues are most commonly thought of as monaural spectral cues because experiments that explore their role have generally involved listening to sources on the median plane that differ only in elevation (e.g., Hebrank and Wright, 1974) or listening with one ear blocked (e.g., Musicant and Butler, 1984). In either case, there is no binaural information that would be relevant to solving the task. However, the spectral changes introduced by the pinna could also be interpreted binaurally, effectively using the contralateral ear as a reference spectrum. Since the experiments we present here involved

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listening to sources away from the median plane and listening binaurally, we will consider the different potential ways that the acoustic effects of the pinna might be accessed.

In experiment 1, our measurements confirm the observations by Saberi *et al.* (1991) and Aggius-Vella *et al.* (2020) of front/back equivalence at 0°/180° but find smaller MAAs in front compared to those of the rear at other angles, a difference that becomes substantial for angles close to the interaural axis. In experiment 2, the possible influence of residual room acoustics is excluded by facing the listener in the opposite direction within the room. In experiments 3 and 4, the superior performance in the frontal hemifield is shown to be dependent on high-frequency pinna cues. The pinna, thus, substantially enhances the horizontal-plane MAA for oblique frontal sources during binaural listening.

II. GENERAL METHODS

The laboratory for this experiment contains a circular array of 48 loudspeakers that was designed for the presentation of moving sound sources without physical movement of the transducers. Sound sources are positioned and moved by using a spatially weighted Gaussian function with a specified center location and standard deviation to create "blobs" of controllable size, location, and movement. Effectively, the source is subjected to Gaussian smoothing analogous to that used in anti-aliasing for visual stimuli rather than using cross-fading between adjacent loudspeakers. Given that our methodology differs somewhat from that used by Mills (1958) and many subsequent authors who generally used point sources, an experiment in the Appendix evaluated the adequacy and limits of this form of presentation for measurements of MAAs.

A. Listeners

The listeners were all undergraduate and postgraduate students at Cardiff University, aged 18–27 years old with self-reported normal hearing.

B. Stimuli

Sounds were presented using a circular array of 48 Cambridge Minx satellite loudspeakers (London, UK) of 1.2 m radius. Groups of 6 loudspeakers were driven by Auna CH-06 car amplifiers (Berlin, Germany), and 2 groups of 24 loudspeakers were each controlled by a Motu 24-channel digital-to-analogue converter (Cambridge, MA). Each loudspeaker output was individually calibrated using a sound level meter at a fixed distance. The array is housed in a sound deadened listening room (3.2 m × 3.6 m) with acoustically absorbing panels on the walls and ceiling and a carpeted floor. The reverberation time of this room is approximately 60 ms, and the direct-to-reverberant ratio at the listening position was measured from an impulse response at 13 dB using a hand-fitted 4-ms window to isolate the direct sound from the earliest reflections.

Independent Gaussian noises of 500-ms duration were generated digitally in MATLAB (The MathWorks, Natick, MA) for all of the 48 channels and shaped with 10-ms raised-cosine onset and offset ramps. The noises had a sampling frequency of 44.1 kHz and were high-pass filtered at 200 Hz, using a 512-point linear-phase finite impulse response (FIR) filter. The 48 channels were then spatially weighted in power using a Gaussian function. Power rather than amplitude scaling was chosen because the independently excited channels were not in phase. The scale factors were, thus, drawn from a square-rooted Gaussian function. The center location and standard deviation of the Gaussian function could be arbitrarily specified to control the position and size of the source at a given moment.

The choice of this Gaussian-blob methodology had two motivations. First, we had some concern about conventional cross-fading between adjacent loudspeakers. There may be confounding factors introduced by having a mixture of point sources (when the stimulus is located in the exact position of a loudspeaker) and phantom sources (when the stimulus is located between two loudspeakers). A Gaussian-blob always involves the excitement of several loudspeakers at once. Second, the system was designed for use in cross-modal experiments for which blobs of light would be created using an array of light emitting diodes behind a diffuser. The Gaussian-blob method could, therefore, be used to define equivalent stimulus width in both modalities. In a trial, two stimuli were presented symmetrically on either side of a single tested direction, which was nominally 0° ("straight ahead") but was roved between trials over a range of ±7.5° (equal to ±1 speaker separation).

C. Procedure

In each session, the listener was seated and leaning forward with their chin on a chinrest such that the head was at the center of the loudspeaker ring. To verify that the head was correctly positioned, a cord connected to the loudspeaker at −90° was drawn across the top of the listener's head to the opposite loudspeaker. The cord was then used as a sightline to ensure that the interaural axis was aligned with the two loudspeakers. Finally, a Polhemus Liberty electromagnetic headtracker (Colchester, VT) was placed on the listener's head to monitor any deviation from this positioning.

The MAAs were measured using two-interval/two-alternative forced-choice trials controlled by two interleaved two-down, one-up adaptive sequences for the same test direction. A trial consisted of two stimuli in a random order, separated by a 100-ms interstimulus interval. Listeners pressed buttons on a gamepad to indicate the direction of displacement. Each adaptive track began at 10° difference in center location and continued until ten reversals were completed on that track (i.e., the other track may continue for a while after one was completed). The adaptation used a log-2 step size of 0.25 (i.e., a factor of 1.189). The geometric mean of the last eight reversals from each staircase was used to estimate the MAA for each staircase.

III. EXPERIMENT 1: MAA AT ALL AZIMUTHS

The MAA was measured at every azimuth around the full circle at 15° intervals.

A. Stimuli

The standard deviation of the Gaussian-blobs was fixed at 0.7 speaker separations (5.25°). Twenty-four different directions, covering the full circle in 15° steps, were examined.

B. Procedure

Because measurements were recorded in all of the four quadrants, the change in location from the first to the second interval could be leftward, rightward, forward, or backward. To provide listeners with an intuitive response interface that covered all of these options, the *ABXY* buttons of a gamepad, which are arranged in a diamond, were used: *X* for leftward; *B* for rightward; *Y* for forward, and *A* for backward. These buttons were active when the target stimulus fell within one of four overlapping 120° zones centered on the cardinal directions. For instance, the leftward and rightward buttons were active for stimuli between −60° and 60°, while the forward and backward buttons were active if the stimuli were presented between 30° and 150°.

Four listeners, all of whom were experienced in the measurement of MAAs, attended three 1-h testing sessions. During each session, they provided MAAs for a random subset of directions; two thresholds for each direction from 0° to 345° in 15° steps were provided by the interleaved adaptive tracks.

C. Results

The first four panels of Fig. 1 show the MAAs as a function of the source direction for each of the four listeners with error bars determined by a bootstrapping technique. Error bars were bootstrapped using the Palamedes toolbox. We first collated the psychometric function using the pair of staircases associated with each azimuth. We then selected the nonparametric bootstrapping option in the Palamedes toolbox, setting the number of bootstraps to 500 and allowing the threshold, slope, and lapse rate to vary in the fit. The maximum lapse rate was capped at 6% (Wichmann and Hill, 2001). Standard errors were then extracted from the distribution of bootstrapped thresholds using the 16th and 84th percentiles to yield the 68% confidence interval (Wichmann and Hill, 2001).

The final panel shows the mean and variability across listeners. Consistent with previous reports, mean MAAs directly in front and directly behind are very small and very similar (the mean across listeners was 1.5° and 1.7°, respectively). Away from the median plane, the MAAs tend to be substantially larger, particularly at the rear (black filled symbols).

A feature of the data is that the variability of thresholds tended to be higher the greater the average threshold. Maulchy's test confirmed that the sphericity assumption for analysis of variance was violated. This problem was resolved by applying a log transform to the threshold data. A repeated-measures analysis of variance of the log-transformed data from the non-cardinal directions was conducted with factors of direction (15°, 30°, 45°, 60°, and 75° from the median plane), left and right hemifield, and front and rear hemifield, and the two repeated measurements arising from the use of interleaved staircases. Cardinal directions were excluded from the analysis because they cannot be classified into left/right and front/back categories. The analysis revealed significant effects of direction [$F(4,12) = 32.5$, $p < 0.001$] and front/rear hemifield [$F(1,3) = 744.0$, $p < 0.005$] but no effect of left/right hemifield or repeat.

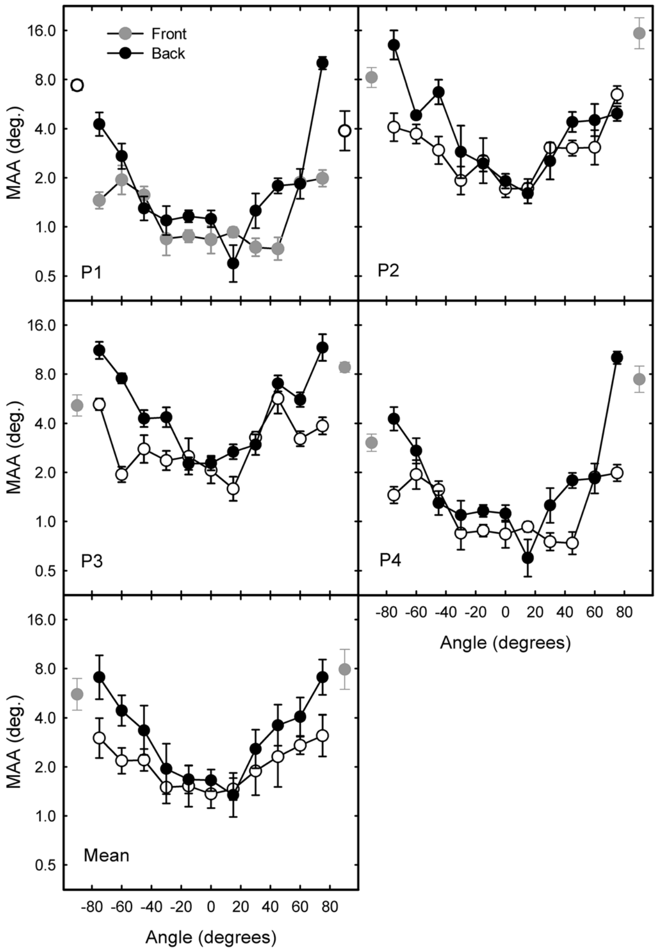

FIG. 1. The MAAs in degrees as a function of the sound-source direction for each individual listener and their mean. Black symbols are in the rear hemifield. Open symbols are in the frontal hemifield. Gray symbols are ±90°. Error bars are one standard error.

There was also one significant interaction between direction and hemifield [$F(4,12) = 5.4$, $p < 0.01$], which reflected greater inflation of the MAA with direction in the rear hemifield. This front/back difference in MAA increases progressively for directions away from the median plane and closer to the interaural axis. Simple main effects tests revealed that the difference was significant at $p < 0.01$ for 30°/150°, 60°/120°, and 75°/120° and at $p < 0.05$ for 45°/135°. Note that with Bonferroni correction for five comparisons, $\alpha = 0.01$, leaving only the first three of these comparisons as significant. For each of these differences, the MAAs were at least 35% larger in the rear hemifield than in the

https://doi.org/10.1121/10.0014599

front hemifield (38.5%, 56.7%, 76.7%, and 133% for each difference, respectively, from 30°/150° to 75°/105°).

D. Discussion

The experiment replicated the observations by Mills (1958) with regard to the first quadrant; the MAAs averaged 1.5° directly in front and grew steeply as the azimuth increased up to 90°. At 90°, the MAA became very large. The results also confirm the observation by Saberi *et al.* (1991) that MAAs at 180° are similar (1.7°) to those at 0° (1.5°). However, at other angles, the MAAs at the rear are, as reported by Fischer *et al.* (2020), substantially larger than those in the front. The differences grow monotonically with the angle away from the median plane and exceed 50% for most of these oblique directions.

IV. EXPERIMENT 2: CONTROLLING FOR ROOM ACOUSTICS

Experiment 1 found a marked difference in the MAA between the front and rear hemifields, suggesting that listeners have a superior ability to discriminate locations at the front. However, the listening room used for the experiment was not entirely anechoic, and the location of the ring is offset by 0.3 m from the center of the room on its longer axis. In consequence, the loudspeaker directly in front of the listener was 0.3 m from the wall while that directly behind the listener was 0.9 m from the wall. These factors raise the possibility that asymmetries in the room acoustics may have made the task easier for sound sources at one end of the room than for sound sources at the other end. To address this potential confound, a control experiment was conducted in which the listener was seated in different orientations with respect to the room such that any advantage of the room acoustics would be conferred to different hemifields in different conditions.

A. Stimuli

The stimuli were identical to those of experiment 1 except that only sources at 45°, 135°, 225°, and 315° were tested. These four directions were tested with each listener in two different orientations in the room.

B. Procedure

Four naive listeners attended a 1-h session to measure the eight MAAs, each based on two interleaved staircases per direction while seated in each orientation. The orientation of the listener within the room was reversed after every second MAA, resulting in an *AABBAABB* orientation sequence. Two listeners began by facing in the same direction as in experiment 1 and the other two began by facing in the reverse orientation.

C. Results

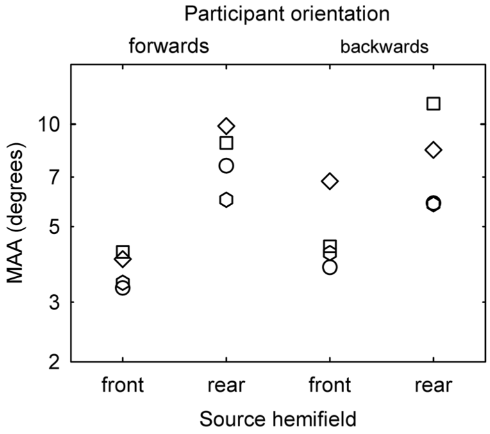

FIG. 2. The mean MAA for sources to the front (45° and 315°) and rear (135° and 225°) of each listener while facing toward each end of the room. Each listener has a different symbol. Each point is the mean of four thresholds for a single listener.

Figure 2 shows that the MAAs in the listeners' frontal hemifields were consistently lower than those in their rear hemifields, regardless of their orientation within the room. In fact, the difference in mean MAA was slightly (although not significantly) larger with the reversed orientation. A repearted-measures analysis of variance of the log-transformed data with factors side (left/right), hemifield (front/back), and orientation (forward/backward) revealed a corresponding main effect of source hemifield [$F(1,3) = 45.1$, $p < 0.01$] and no other significant effect.

D. Discussion

The results replicated the front/back asymmetry observed in experiment 1 and demonstrated that the effect was independent of orientation within the room. This outcome rules out a potentially confounding influence of the room acoustics.

V. EXPERIMENT 3: EFFECTS OF HIGH FREQUENCIES

Experiments 1 and 2 found a marked difference in the MAAs in the front and rear hemifields. An obvious possibility is that the pinna has a greater influence on horizontal-plane localization during binaural listening than had previously been thought. Due to its physical dimensions, the pinna has minimal influence at frequencies below about 4 kHz. Experiment 3, therefore, tested whether the front/back asymmetry was dependent on frequencies above 4 kHz, which can be affected by the pinna, or whether the effect was still present at low frequencies, where ITDs have been shown to dominate perception of laterality (Wightman and Kistler, 1992).

A. Stimuli

The stimuli were similar to those of experiments 1 and 2 except that the spectrum of the noise was filtered into different frequency bands using a 512-point FIR filter. The three conditions used were low-pass filtered at 4 kHz (0.2–4 kHz), high-pass filtered at 4 kHz (4–20 kHz), and broadband (0.2–20 kHz). To test front/back asymmetry, these stimuli were presented at around 45° or 135°, subject to the same ±7.5° rove used in previous measurements.

B. Procedure

The experimental procedure was identical to those in experiments 1 and 2 but with six conditions. Ten naive listeners with no known hearing impairments attended a 1-h session to measure the six MAAs. Each MAA was measured using two interleaved staircases.

C. Results

The log-transformed data were subjected to a repeated-measures analysis of variance with the factors frequency band (high-pass, low-pass, and broadband) and azimuth (45° and 135°). Figure 3 shows that the MAAs were much larger when low frequencies were removed (open symbols), resulting in a significant main effect of frequency band [$F(2,18) = 29.3$, $p < 0.001$]. Consistent with experiment 1, the MAAs were also lower at 45° than at 135° [$F(1,9) = 9.6$, $p < 0.05$]. This front/back asymmetry was largely abolished when high frequencies were removed (gray symbols), but this interaction was nonsignificant [$F(2,18) = 3.3$, $p = 0.06$]. The MAAs for broadband and low-pass-filtered stimuli were almost identical at 135°, suggesting no benefit from high frequencies at the rear. Bonferroni-corrected, two-tailed *t*-tests on the log-transformed data showed that the high-pass condition differed from the low-pass [$t(9) = 4.2$, $p < 0.005$] and broadband [$t(9) = 6.7$, $p < 0.01$] conditions.

D. Discussion

The larger MAAs for high-pass-filtered stimuli support previous observations that low frequencies provide stronger sound-localization cues than high frequencies, consistent with the dominance of low-frequency interaural time delays (ITDs) in sound localization (Wightman and Kistler, 1992). However, high frequencies (above 4 kHz) were found to make a substantial contribution to precision in the frontal hemifield because the MAAs for full spectrum stimuli were significantly lower than for those that only have frequencies below 4 kHz. Moreover, the removal of high frequencies was found to have no effect at the rear (gray and black symbols overlap for 135° in Fig. 4). This pattern of results is consistent with the existence of a high-frequency cue that enhances sound localization but only in the frontal hemifield.

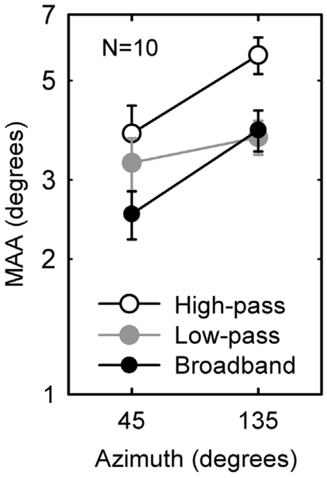

FIG. 3. The mean MAA for band-limited stimuli at 45° and 135°. High- and low-pass stimuli were filtered with a 4 kHz cutoff. Error bars are one standard error of the mean.

The experiment has some features in common with a previous study by Musicant and Butler (1984). They used similarly filtered noise bursts in front and rear hemifields but in an absolute sound-localization task. Consistent with experiments 1–3 of the current study, Musicant and Butler (1984) found that the sound-localization error was much smaller in the frontal hemifield. They also identified high frequencies as being important to optimal performance, albeit on the basis of poorer performance in the low-pass-filtered condition than that in the other two. However, since they used a loudspeaker identification task, their result could be explained by a spatial registration problem in which listeners have greater difficulty identifying loudspeakers at the rear that they could not see.

High-frequency cues may come from the acoustic influences of the pinnae and head, either of which might display a front/back asymmetry at these high frequencies. Moreover, the effect of the pinnae will be different at the ipsilateral and contralateral ears, producing a modification of the interaural level differences (ILDs), which may, thus, be considered an additive combination of pinna and headshadow effects. Carlile and Pralong (1994, p. 3453) observed that the pattern of ILDs from head-related transfer functions (HRTFs) "was basically symmetrical about the interaural axis," suggesting that they are a less likely source for the front/back asymmetry in MAAs. The HRTFs from Carlile and Pralong (1994) were collected from human listeners with intact pinnae. To more directly test the front/back symmetry of ILDs produced by headshadow and any contribution to them from asymmetric pinna influences, we used the ring of loudspeakers to measure HRTFs from KEMAR (Burkhard and Sachs, 1975) with the pinnae in place or removed (Fig. 4). With the effect of the pinnae removed, some front/back asymmetry might be caused by KEMARs facial features or by eccentricity of the ear-canal openings on either side of the head. Despite these possibilities, Fig. 4(a) shows that the pattern of ILDs produced by the head and shoulders alone is strikingly front/back symmetric. Moreover, there is no discernible structure to the front/back differences that exist. Figure 4(b) shows the additional ILDs introduced by the pinnae, which were derived by subtracting the pattern with pinnae in place from the pattern without them. Figure 4 confirms that the effects of the pinnae are limited to frequencies higher than 4 kHz (Musicant and Butler, 1984) and also shows some differences in the pattern of ILDs in the frontal and rear hemifields. However, it is not clear that the pattern in the front is in any way stronger or more easily interpreted; indeed, it seems to be less azimuth dependent in front than it is at the rear.

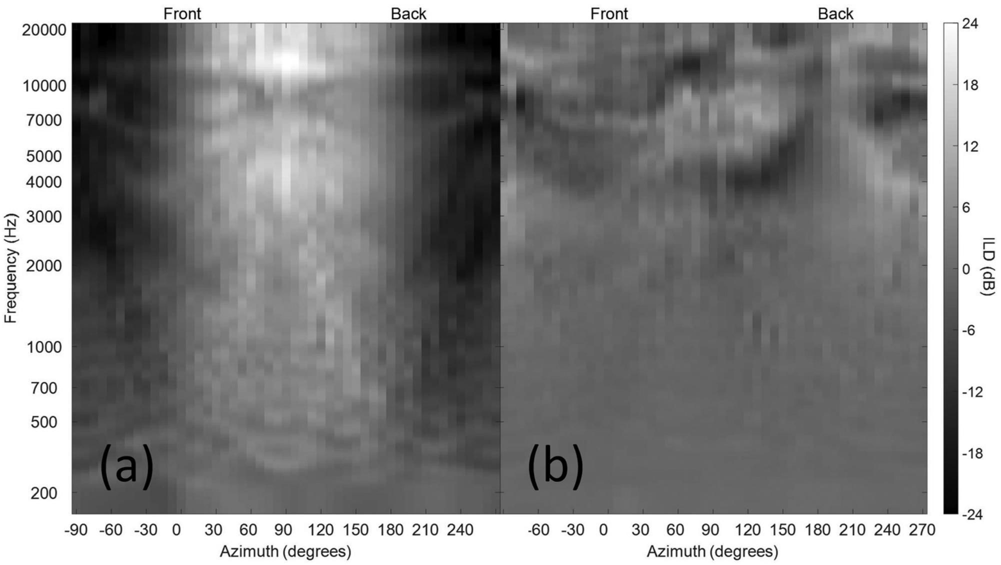

FIG. 4. (a) The headshadow-generated interaural level differences (ILDs) as a function of frequency and azimuth, measured from a KEMAR manikin without pinnae; and (b) pinna-generated ILDs as a function of frequency and azimuth, measured from a KEMAR manikin by subtracting ILDs with pinnae in place from ILDs with pinnae removed are depicted. Frequency smoothing is produced by calculation of cochlear excitation patterns (Moore and Glasberg, 1983).

VI. EXPERIMENT 4: EFFECT OF PINNAE

The results of experiment 3 confirm that the removal of high frequencies can substantially reduce the front/back asymmetry, but it is at the front rather than at the rear where the effect is evident. Experiment 4 tested more directly whether the pinna was responsible for the enhanced MAAs in the frontal hemifield by using extension tubes inserted into the ears to bypass the acoustic effect of the pinnae.

A. Stimuli

The stimuli were identical to those of the broadband conditions of experiment 3 with source directions of 45° and 135°.

B. Procedure

Ten naive listeners attended a single hour-long experimental session. The experimental procedure was identical to the preceding experiments except that, borrowing a technique from Fisher and Freedman (1968) and Perrett and Noble (1997), the listeners' ears could be fitted with extension tubes to bypass the effect of pinna acoustics (Fig. 5). The extension tubes were formed from disposable audiological specula and fitted with silicone ear buds from commercial earphones to create a snug and comfortable fit to the auditory meatus. The specula were 36 mm in length. With two source directions and conditions with and without specula, there were four conditions in all.

C. Results

Figure 6 shows that the front/back asymmetry was completely abolished by the acoustic bypass of the pinna. As in experiment 3, there was no change in the MAAs in the rear hemifield when the acoustic influence of the pinna was foiled. A 2×2 repeated-measures analysis of variance for the log-transformed thresholds (factors: source azimuth, 45°/135°, and pinna acoustics, intact/bypassed) confirmed a significant interaction between the source azimuth and the use of the acoustic bypass tubes [$F(1,9) = 5.7$, $p < 0.05$]. Bonferroni-corrected *t*-tests showed that there was a significant difference between front and back when the pinna was intact but not when it was bypassed [$t(9) = 3.1$, $p < 0.05$].

D. Discussion

The effect of bypassing pinna acoustics in experiment 4 was very similar to that of removing high frequencies in experiment 3, suggesting that the two manipulations were both influencing the same phenomenon. In experiment 4, bypassing pinna acoustics completely removed the front/back asymmetry, directly implicating their role. This outcome also reinforces the conclusion of experiment 2. If

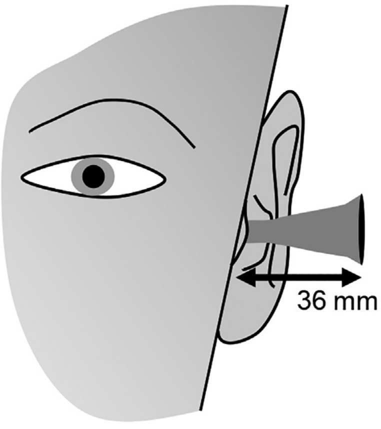

FIG. 5. An illustration of an audiological speculum inserted to bypass the pinna acoustics.

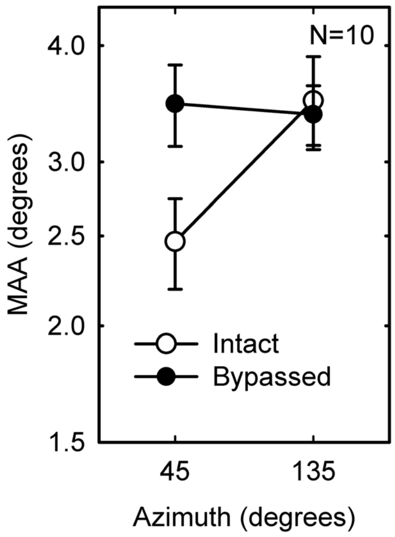

FIG. 6. The mean MAA at 45° and 135° with and without extension tubes that acoustically bypassed the pinna. Error bars are one standard error of the mean.

room acoustics had been responsible for the front/back asymmetry, then one would have expected the effect to at least partially survive the use of acoustic bypass tubes.

The experiment was foreshadowed by Musicant and Butler (1984) who found in their sound-localization study that the advantage of the frontal hemifield was partially removed when the pinna folds were occluded with ear mold material.

VII. GENERAL DISCUSSION

The present experiments have demonstrated that there is a front/back asymmetry in the precision of sound localization as measured through the MAA, which is generated by the pinna. The effect is quite substantial for oblique azimuths. These observations contrast with the consensus view (e.g., Balachandar and Carlile, 2019) that binaural cues are overwhelmingly precise in the horizontal plane but leave a cone of confusion (Oldfield and Parker, 1984) that the pinna serves to disambiguate. It appears that while the pinnae on their own do not encode sound direction in the horizontal plane very accurately (Oldfield and Parker, 1986), they can enhance precision substantially during binaural listening.

For sources directly in front of (or behind) the listener, binaural cues are overwhelmingly dominant, but as the source moves away from the median plane, these cues become less effective (Mills 1958; Kuhn, 1977). This decline is partly attributable to geometry and acoustics, and partly to central processing by the brain. As the azimuth increases the rate of change in path distance to the two ears and, therefore, the rate of change of ITD progressively decreases, falling eventually to zero at 90°. An ever larger change in azimuth is, thus, needed to generate the same change in ITD. In addition, due to constructive and destructive interference between waves that diffract around different sides of the head, the spectral pattern of ILDs is increasingly chaotic as a source approaches the interaural axis. Even if averaged across frequency, it undergoes a counterintuitive reversal close to 90° (Macaulay *et al.*, 2010), hence, the ILD cue is a non-monotonic function of azimuth. In addition to these acoustic factors, the brain is less sensitive to increments in ITD and ILD with increasing reference value (Mossop and Culling, 1998; Yost and Dye, 1988), so, the detectable ITD or ILD change becomes larger with azimuth as well. It would appear, therefore, that pinna cues increasingly compensate for this decline in precision for sources in the frontal hemifield.

A. Evidence of front/back differences from sound-localization studies

Although few direct precision measurements (using the MAA task) have previously been made at the rear, studies investigating absolute sound localization have inferred coarser precision in the rear hemifield because the sound-localization error is greater there (Oldfield and Parker, 1986; Carlile *et al.*, 1997; Makous and Middlebrooks, 1990; Majdak *et al.*, 2010). Unfortunately, none of these studies give reliable evidence in this regard. There are two problems.

First, localization studies usually report only accuracy (a measure that includes bias) rather than precision data (i.e., response variability around the mean response, which excludes bias). Where precision metrics have been extracted, they are almost always calculated in a manner that is contaminated by bias because the experiment is focused on angular error, that is, the differences between the actual location and the response, rather than response variability (Stevens and Newman, 1934; Oldfield and Parker, 1984; Musicant and Butler, 1984; Gilkey *et al.*, 1995). As others have noted, this confounds accuracy and precision (Kolarik *et al.*, 2021).

Second, even when precision has been measured by using response variability in a localization study (Makous and Middlebrooks, 1990; Carlile *et al.*, 1997, 1999; Majdak *et al.*, 2010), the data still tend to be confounded by the mode of response. Pointing of the hand or the nose toward a perceived source of sound at the rear requires a larger motor action, including rotation of the torso, which would itself increase variability in response. Other localization experiments have required naming of a direction or identification of a source loudspeaker that is not in view (e.g., Musicant and Butler, 1984). In these cases, acoustic sources in the rear hemifield may be less well aligned with the listener's spatial map than locations in the visible hemifield.

Oldfield and Parker (1984) noted the problem of motor noise and attempted to factor out its influence by making separate measurements of it. After removal of the motor influence, they found that listeners made systematic errors, wherein the azimuth was mildly overestimated in the frontal hemifield and more strongly underestimated in the rear hemifield. This bias makes the pattern of performance less accurate at the back, but it does not necessarily affect the precision. Unfortunately, Oldfield and Parker (1984) is one of the studies that reported response error rather than variability.

The problems with the mode of response are well illustrated by the fact that such studies also report large response variability for sources at 180°. In contrast, when measured more directly using the MAA (Saberi *et al.*, 1991; Aggius-Vella *et al.*, 2020; experiment 1 of the present study), precision at 180° can rival that at 0°, indicating that these non-psychoacoustic sources of error in a sound-localization task can substantially inflate the measured precision in the rear hemifield.

In summary, while it is theoretically possible to measure the precision of sound localization by reporting the variance of the listeners' directional responses, most studies only report localization error. Where localization variance is reported, it is generally contaminated by other influences, such as motor-response noise. Consequently, reports of front/back differences in localization precision based on sound localization are all unreliable compared to direct measurement using the MAA.

B. The role of the pinna

The pinna is thought to provide monaural spectral cues to sound-source elevation in the form of spectral notches (Hebrank and Wright, 1974; Watkins, 1978) or the overall spectral shape (Baumgartner *et al.*, 2014; van Opstal *et al.*, 2017; Balachandar and Carlile, 2019). What cues might it provide in the horizontal plane? A clue comes from Butler and Flannery (1980) who found that listeners experienced changes in the perceived lateral position of a 1-kHz-wide band of noise as a function of its center frequency between 4 and 8 kHz. A virtual simulation of such a stimulus [Mm. 1] is included.[1] The experiment was concerned with monaural listening, so listeners had one ear plugged and the stimuli were presented from a loudspeaker at 45° on the unoccluded side. The fact that this effect occurs at frequencies above 4 kHz is consistent with the possibility that the stimuli may be mimicking aspects of the pinna response. Supporting that suggestion, Carlile and Pralong (1994) and Shub *et al.* (2008) described a peak in the HRTF for the ear ipsilateral to the source that varied systematically as a function of the horizontal location in the frontal hemifield. To illustrate the specific role of the pinna in this effect, we measured HRTFs from KEMAR with and without its pinnae.

Mm. 1. Butler and Flannery stimulus. This is a file of type wav. (700 kB).

Figure 7 shows the gain introduced by the pinna as a function of the source azimuth. Pinna gain is the difference between excitation patterns (Moore and Glasberg, 1983) with and without pinnae. Pinna gain is predominantly positive, consistent with a sound-gathering role for the pinna. Particularly high gain (∼10 dB) is seen in exactly the region described by Carlile and Pralong (1994) and Shub *et al.* (2008), showing explicitly that the effect is produced by the pinna rather than by the head. It, thus, seems likely that the noise band in Butler and Flannery (1980) was mimicking an effect of pinna acoustics, and this cue provides the listener with supplementary lateral-position information in the frontal hemifield. In the rear hemifield, less systematic changes are observed, and this contrast may explain the observed front/back difference.

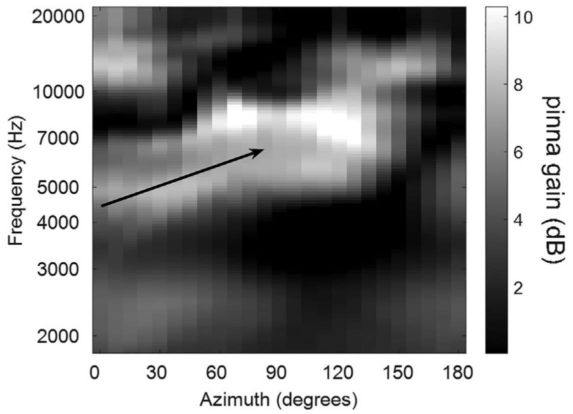

FIG. 7. The pinna gain as a function of frequency and azimuth, measured from the right ear of KEMAR. The black arrow indicates how the high-frequency spectral peak introduced by the pinna changes in frequency with the azimuth.

The spectral changes introduced by the pinna may influence horizontal-plane localization in two different ways during binaural listening. First, they may provide monaural spectral cues at the ipsilateral ear in the same fashion as when listening monaurally, which may then be integrated with binaural information. Second, they may act to enhance the magnitude of the ILDs produced by headshadow. The present study is not able to distinguish these two possibilities. An examination of the potential cues available in Figs. 5(b) and 7 suggests that the monaural cues may be more readily accessible in our experiment. This said, our experiment involves stimuli with exactly the same spectrum across intervals. During real-world listening, the source spectrum may be unpredictable and the use of the contralateral ear as a reference for the source spectrum may be important.

Our experiments show substantially improved precision when pinna cues are available in combination with congruent binaural cues. In contrast, pinna cues appeared rather ineffective in the horizontal plane when Shub *et al.* (2008) measured monaural MAAs. In particular, they found that MAAs were relatively poor when pinna cues alone were available because they produced psychometric functions that were highly idiosyncratic to individual listeners and often non-monotonic.

Pinna cues have also been found to have negligible influence when placed in competition with binaural cues using virtual acoustics (Macpherson and Middlebrooks, 2002). The effectiveness of pinna cues in that competition study may have been limited by the large discrepancies used (30° and 60°). Effective integration of conflicting cues often requires relatively small discrepancies, such as those used in perturbation analysis (Landy *et al.*, 1995). When using small discrepancies between cues, it has been shown that the relative precision of cues predicts the weighting in the compromise percept and the weighting changes in predictable ways when precision is manipulated. For instance, Ernst and Banks (2002) showed that the relative contributions of visual and haptic input to perception of height were weighted in proportion to their precision; and Alais and Burr (2004) described a similar effect in judgements of audiovisual location with the ventriloquist effect reversing when vision was made less precise than hearing. It remains to be determined whether the different cues contributing to sound localization are weighted in this fashion.

VIII. CONCLUSION

The MAA is smaller in the frontal hemifield than it is in the rear. The difference is negligible at 0° but increases monotonically and substantially with increasing azimuth up to 90°. The benefit to the frontal field is produced by spectral changes introduced by the pinna.

ACKNOWLEDGMENTS

We are grateful to the late Bill Macken for suggesting the use of extension tubes and Petroc Sumner for useful comments on earlier versions of the manuscript. The studentship of J.O.S.-H.was directly funded by Cardiff University.

APPENDIX: BLOB SIZE AND LOUDSPEAKER SPACING

Given that our methodology differs somewhat from that used by Mills (1958) and many subsequent authors who generally used movable point sources, a supplementary experiment evaluated the adequacy and limits of this form of presentation for measurement of MAAs. Specifically, we tested what effect the spacing of loudspeakers used and the standard deviation of the blob (blob size) had on the measured MAA. For the blob size, a standard deviation of 0.7 times the speaker spacing (i.e., 5.25° using all 48 loudspeakers) is the smallest width that can be used without spatial aliasing. One would intuitively expect a small blob size to be beneficial but that there would be some size below which no greater improvement would occur. The effect of aliasing was less certain with the fluctuations in level potentially producing a confounding cue. We, therefore, used a range of blob sizes that extended above and below a blob size of 0.7 times the speaker spacing for each speaker spacing to test these effects on performance.

1. Stimuli

In different conditions, either 24 or 48 loudspeakers were active, leaving angular spacings between successive loudspeakers of 7.5° or 15°, respectively. The standard deviation of the spatial-weighting function was varied from 0.35 to 2.8 times the speaker separation. At smaller separations, the spacing of the loudspeakers under-samples the Gaussian function.

2. Procedure

Five listeners with self-reported normal hearing each attended two 1-h experimental sessions on different days.

3. Results

The results are shown in Fig. 8 as a function of the angular size of the blobs for the 24-loudspeaker and 48-loudspeaker conditions. For each number of loudspeakers, the MAA as a function of the blob size is *U*-shaped with a minimum at 0.7 times the angular spacing of the loudspeakers (5.3° for 48 loudspeakers; 10.5° for 24 loudspeakers). Since the set of blob sizes for each number of loudspeakers is the same when scaled by speaker separation, the analysis of variance uses this scaling as a factor.

An analysis of variance of the log-transformed MAAs confirmed that 48 loudspeakers produced significantly smaller MAAs than 24 loudspeakers [$F(1,9) = 12.5$, $p < 0.01$]. It also confirmed the significant main effect of blob size [$F(6,54) = 129.5$, $p < 0.001$]. Finally, there was also a significant interaction between the two [$F(6,54) = 13.5$, $p < 0.001$]. The variation in the MAA with blob size appears similar for both speaker separations, but there is a marked increase in MAAs for the two largest blob sizes when using 24 loudspeakers, which is presumably responsible for this interaction. Holm-corrected *post hoc* comparisons showed that the MAAs for a blob size of 0.7 times the speaker separation differed significantly at 0.35, 1.4, 2, and 2.8 times the speaker separation.

4. Discussion

Using both 24 loudspeakers and 48 loudspeakers, the MAA reaches a minimum value when the standard deviation of the Gaussian-blob is 0.7 times the speaker separation i.e.,

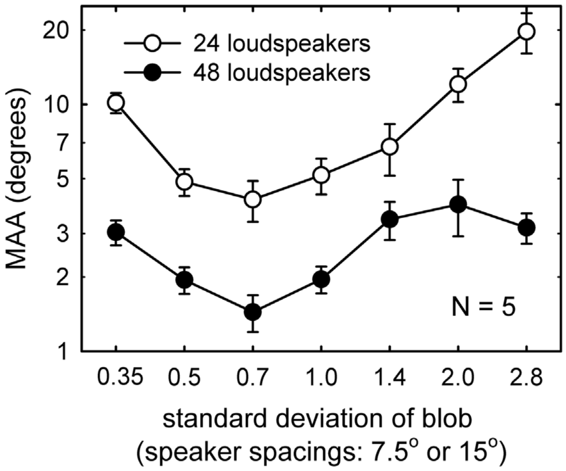

FIG. 8. The MAA as a function of the Gaussian-blob size (standard deviation in multiples of the speaker spacings) for loudspeaker rings with 24 or 48 loudspeakers. Error bars are one standard error of the mean.

https://doi.org/10.1121/10.0014599

5.25° with 48 loudspeakers and 10.5° with 24 loudspeakers. These values correspond to the minimum blob size that avoids spatial aliasing and, so, produces a consistent sound level as a function of the blob's center location. Using 0.7, the change in the sum of the weights between having a center location directly on a loudspeaker and midway between is 0.03%, which we regarded as acceptably small. At 0.5, the change is 3%, which is comparable with modulation detection thresholds and intensity difference limens. It, thus, appears that, up to a point, listeners are more precise when the blob is smaller. However, below 0.7 times the speaker separation, variations in sound level due to undersampling of the blob shape in the spatial domain introduced error rather than producing a confounding cue. The best MAAs are 1.4° with 48 loudspeakers and 4.9° with 24 loudspeakers. The former value is consistent with previous estimates of the MAA at 0° using point sources (e.g., Mills, 1958), so the results indicate that 48 loudspeakers and a standard deviation of 5.25° is sufficient to measure MAAs accurately. In contrast, 4.9° is a relatively poor MAA for 0° azimuth, indicating that a 24-loudspeaker system or one with loudspeakers separated by 15° would be inadequate for the Gaussian-blob methodology.

[1] The virtual simulation of the stimulus of Butler and Flannery (1980) was produced by generating a pure tone that sweeps back and forth between 4 and 8 kHz and modulating it with a low-pass noise to create a frequency-modulating, 1-kHz-wide band of noise. It was then convolved with a head-related impulse response for the right ear at 45°. The right channel contains this stimulus and the left channel is silent.

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