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1 **The pinna enhances angular discrimination in the frontal hemifield.**

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7

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10 Received:

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ABSTRACT

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

24

25

26 INTRODUCTION

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

39 The only previous studies of MAA at the rear appear to be Saberi et al. (1991), Aggius-
40 Vella et al. (2020), and Fischer et al (2020). The first two studies measured the MAA at 180° and
41 found it to be similar in value to that at 0° . Saberi et al. did not make a direct comparison between
42 the two directions, but measured a value of 1° directly to the rear which matches the best previous
43 reports for directly in front (e.g., Mills, 1958). Aggius-Vella et al. measured both front and back
44 using the same protocol and observed MAAs of 5.5° and 7° , which did not differ significantly. It
45 should be noted that the latter study used a different definition of threshold. Saberi et al. (1991)
46 defined threshold as 75%, while Aggius-Vella et al.'s (2020) method is equivalent to $84.1\%^1$. In
47 addition to this difference, Aggius-Vella drew their thresholds from a psychometric function with
48 a relatively coarse resolution of 4.4° . These factors may explain the difference in the reported

49 MAAs. Overall, both these studies support the expected front-back symmetry. However, the third
50 study (Fischer et al., 2020) measured MAAs at 135°, 180° and 225° and found these locations to
51 produce larger MAAs, averaging 3.6°, than the equivalent locations in the frontal hemifield,
52 averaging 2.2°.

53 In his definitive study of the MAA, Mills (1958) only measured the precision of sound
54 localization for positions in front of and to the right of the listener. Regarding this decision, he
55 remarked that “it is probably safe to assume that azimuth discrimination in the other quadrants is
56 similar in all important respects,” but he immediately acknowledged that “Because of the
57 projection of the pinna and the asymmetry of the head, azimuth discrimination in the region behind
58 the subject may be somewhat different at high frequencies” (Mills, 1958, p246). Pinna cues are
59 most commonly thought of as monaural spectral cues because experiments that explore their role
60 have generally involved listening to sources on the median plane that differ only in elevation (e.g.
61 Hebrank and Wright, 1974) or listening with one ear blocked (e.g. Musicant and Butler, 1974). In
62 either case, there is no binaural information that would be relevant to solving the task. However,
63 the spectral changes introduced by the pinna could also be interpreted binaurally, effectively using
64 the contralateral ear as a reference spectrum. Since the experiments we present here involved
65 listening to sources away from the median plane and listening binaurally, we will consider the
66 different potential ways that the acoustic effects of the pinna might be accessed.

67 In Exp. 1, our measurements confirm Saberi et al.’s and Aggius-Vella et al.’s observation
68 of front/back equivalence at 0°/180° but find smaller MAAs in front compared to the rear at other
69 angles, a difference that becomes substantial for angles close to the interaural axis. In Exp. 2, the
70 possible influence of residual room acoustics is excluded by facing the listener in the opposite
71 direction within the room. In Exps. 3 and 4, the superior performance in the frontal hemifield is

72 shown to be dependent on high-frequency pinna cues. The pinna thus substantially enhances the
73 horizontal-plane MAA for oblique frontal sources during binaural listening.

74 **I GENERAL METHODS**

75 The laboratory for this experiment contains a circular array of 48 loudspeakers that was designed
76 for the presentation of moving sound sources without physical movement of the transducers.
77 Sound sources are positioned and moved by using a spatially weighted Gaussian function with a
78 specified center location and standard deviation in order to create ‘blobs’ of controllable size,
79 location and movement. Effectively, the source is subjected to Gaussian smoothing analogous to
80 that used in anti-aliasing for visual stimuli, rather than using cross-fading between adjacent
81 loudspeakers. Given that our methodology differs somewhat from that used by Mills (1958), and
82 many subsequent authors who generally used point sources, an experiment in Appendix 1
83 evaluated the adequacy and limits of this form of presentation for measurement of MAAs.

84 **A. Listeners**

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

87 **B. Stimuli**

88 Sounds were presented using a circular array of 48 Cambridge Minx satellite loudspeakers
89 (London, UK) of 1.2 m radius. Groups of six loudspeakers were driven by Auna CH-06 car
90 amplifiers (Berlin, Germany), and 2 groups of 24 loudspeakers were each controlled by a Motu
91 24-channel digital-to-analogue converter (Cambridge, Mass.). Each loudspeaker output was
92 individually calibrated using a sound level meter at a fixed distance. The array is housed in a sound
93 deadened listening room (3.2 m by 3.6 m) with acoustically absorbing panels on the walls and
94 ceiling and a carpeted floor. The reverberation time of this room is approximately 60 ms and the

95 direct-to-reverberant ratio at the listening position was measured from an impulse response at 13
96 dB using a hand-fitted 4-ms window to isolate the direct sound from the earliest reflections.

97 Independent Gaussian noises of 500-ms duration were generated digitally in MATLAB
98 (Natick, Mass.) for all 48 channels and shaped with 10-ms raised-cosine onset and offset ramps.
99 The noises had a sampling frequency of 44.1 kHz and were high-pass filtered at 200 Hz, using a
100 512-point linear-phase FIR filter. The 48 channels were then spatially weighted in power using a
101 Gaussian function. Power rather than amplitude scaling was chosen because the independently
102 excited channels were not in phase. The scale factors were thus drawn from a square-rooted
103 Gaussian function. The center location and standard deviation of the Gaussian function could be
104 arbitrarily specified in order to control the position and size of the source at a given moment.

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

116 **C. Procedure**

117 In each session, the listener was seated and leaning forward with their chin on a chinrest, such that

118 the head was at the center of the loudspeaker ring. In order to verify that the head was correctly
119 positioned, a cord connected to the loudspeaker at -90° was drawn across the top of the listener's
120 head to the opposite loudspeaker. The cord was then used as a sightline to ensure that the interaural
121 axis was aligned with the two loudspeakers. Finally, a Polhemus Liberty electromagnetic
122 headtracker (Colchester, Vermont) was placed on the listener's head to monitor any deviation from
123 this positioning.

124 MAAs were measured using 2-Interval/2-Alternative forced-choice trials controlled by two
125 interleaved 2-down, 1-up adaptive sequences for the same test direction. A trial consisted of two
126 stimuli, in a random order, separated by a 100-ms interstimulus interval. Listeners pressed buttons
127 on a gamepad to indicate the direction of displacement. Each adaptive track began at 10° difference
128 in center location and continued until ten reversals were completed on that track (i.e., the other
129 track may continue a while after one was completed). The adaptation used a log-2 step size of 0.25
130 (i.e., a factor of 1.189). The geometric mean of the last eight reversals from each staircase was
131 used to estimate the MAA for each staircase.

132 **II EXPERIMENT 1: MAA AT ALL AZIMUTHS**

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

134 **A Stimuli**

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

137 **B. Procedure**

138 Because measurements were recorded in all four quadrants, the change in location from the first
139 to the second interval could be leftwards, rightwards, forwards, or backwards. In order to provide

140 listeners with an intuitive response interface that covered all these options, the ABXY buttons of
141 a gamepad, which are arranged in a diamond, were used: X for leftwards; B for rightwards; Y for
142 forwards and A for backwards. These buttons were active when the target stimulus fell within one
143 of four overlapping 120° zones centered on the cardinal directions. For instance, the leftwards and
144 rightwards buttons were active for stimuli between -60° and 60° , while the forwards and backwards
145 buttons were active if the stimuli were presented between 30° and 150° .

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

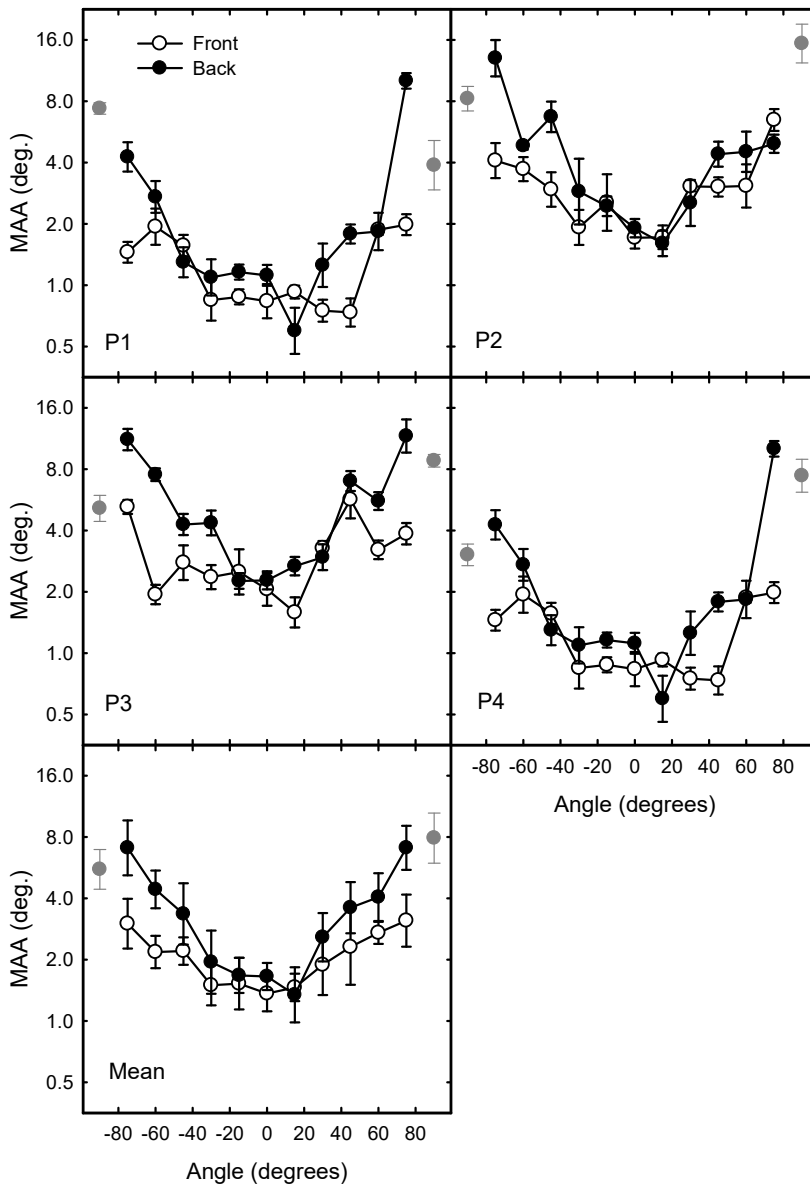
150 **C. Results**

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

160 The final panel shows the mean and variability across listeners. Consistent with previous
161 reports, mean MAAs directly in front and directly behind are both very small and very similar (the
162 mean across listeners was 1.5° and 1.7° , respectively). Away from the median plane, MAAs tend

163 to be substantially larger, particularly at the rear (black filled symbols).

164 A feature of the data is that the variability of thresholds tended to be higher the greater the
165 average threshold. Mauchly's test confirmed that the sphericity assumption for analysis of variance
166 was violated. This problem was resolved by applying a log transform to the threshold data. A
167 repeated-measures analysis of variance of the log-transformed data from the non-cardinal
168 directions was conducted with factors of direction (15° , 30° , 45° , 60° , 75° from the median plane),
169 left and right hemifield, and front and rear hemifield, and the two repeated measurements arising
170 from the use of interleaved staircases. Cardinal directions were excluded from the analysis because
171 they cannot be classified into both left/right and front/back categories. The analysis revealed
172 significant effects of direction [$F(4,12)=32.5, p<0.001$] and of front/rear hemifield [$F(1,3) = 744.0,$
173 $p < 0.005$], but no effect of left/right hemifield or repeat.



174

175 FIG.1. MAAs in degrees as a function of sound-source direction for each

176 individual listener and for their mean. Black symbols are in the rear hemifield.

177 Open symbols are in the frontal hemifield. Gray symbols are $\pm 90^\circ$. Error bars

178 are one standard error.

179 There was also one significant interaction between direction and hemifield [$F(4,12)=5.4$,

180 $p<0.01$], which reflected greater inflation of the MAA with direction in the rear hemifield. This
181 front/back difference in MAA increases progressively for directions away from the median plane
182 and closer to the interaural axis. Simple main effects tests revealed that the difference was
183 significant at $p<0.01$ for $30^\circ/150^\circ$, $60^\circ/120^\circ$ and $75^\circ/120^\circ$ and at $p<0.05$ for $45^\circ/135^\circ$. Note that
184 with Bonferroni correction for five comparisons, $\alpha=0.01$, leaving only the first three of these
185 comparisons as significant. For each of these differences, MAAs were at least 35% larger in the
186 rear hemifield than in front (38.5%, 56.7%, 76.7%, and 133% for each difference respectively from
187 $30^\circ/150^\circ$ to $75^\circ/105^\circ$).

188 **D. Discussion**

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

196 **III EXPERIMENT 2: CONTROLLING FOR ROOM ACOUSTICS**

197 Experiment 1 found a marked difference in the MAA between the front and rear hemifields,
198 suggesting that listeners have a superior ability to discriminate locations at the front. However, the
199 listening room used for the experiment was not entirely anechoic and the location of the ring is
200 offset by 0.3 m from the center of the room on its longer axis. In consequence, the loudspeaker
201 directly in front of the listener was 0.3 m from the wall, while that directly behind was 0.9 m from
202 the wall. These factors raise the possibility that asymmetries in the room acoustics may have made

203 the task easier for sound sources at one end of the room than for sound sources at the other end. In
204 order to address this potential confound, a control experiment was conducted in which the listener
205 was seated in different orientations with respect to the room, so that any advantage of the room
206 acoustics would be conferred to different hemifields in different conditions.

207 **A. Stimuli**

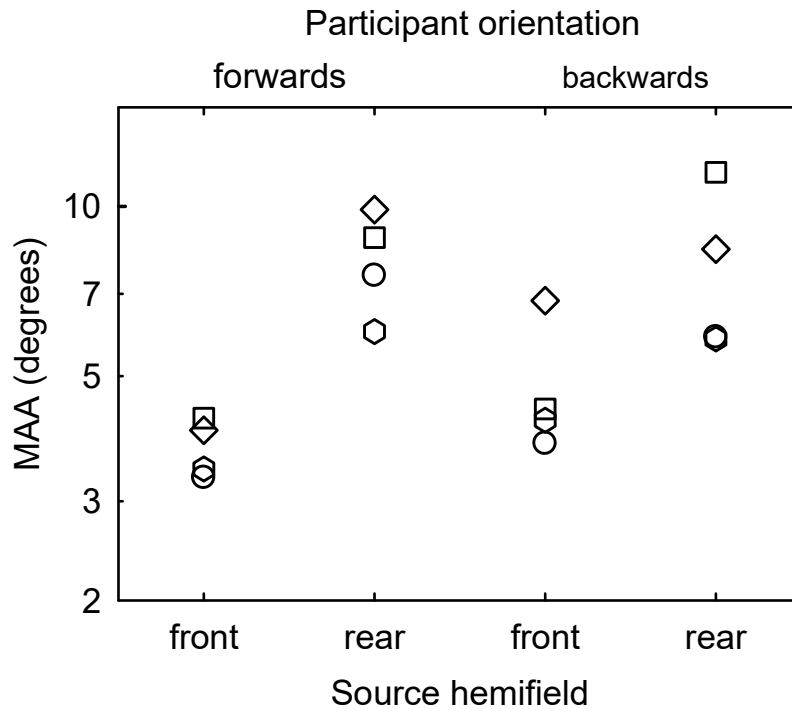
208 The stimuli were identical to those of Exp. 1, except that only sources at 45°, 135°, 225°, and 315°
209 were tested. These four directions were tested with each listener in two different orientations in
210 the room.

211 **B. Procedure**

212 Four naïve listeners attended a one-hour session to measure the 8 MAAs, each based on two
213 interleaved staircases per direction while seated in each orientation. The orientation of the listener
214 within the room was reversed after every second MAA, resulting in an AABBAABB orientation
215 sequence. Two listeners began facing in the same direction as in Exp. 1 and the other two began
216 facing in the reverse orientation.

217 **C. Results**

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



224

225 FIG. 2. Mean minimum audible angle for sources to the front (45° and 315°) and
 226 to the rear (135° and 225°) of each listener, while facing towards each end of the
 227 room. Each listener has a different symbol. Each point is the mean of four
 228 thresholds for a single listener.

229 D. Discussion

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

233 IV EXPERIMENT 3: EFFECT OF HIGH FREQUENCIES

234 Experiments 1 and 2 found a marked difference in the MAA in the front and rear hemifields. An
 235 obvious possibility is that the pinna has a greater influence on horizontal-plane localization during
 236 binaural listening than has previously been thought. Due to its physical dimensions, the pinna has

237 minimal influence at frequencies below about 4 kHz. Experiment 3 therefore tested whether the
238 front/back asymmetry was dependent upon frequencies above 4 kHz, which can be affected by the
239 pinna, or whether the effect was still present at low frequencies where ITDs have been shown to
240 dominate perception of laterality (Wightman and Kistler, 1992).

241 **A. Stimuli**

242 The stimuli were similar to those of Exp. 1 and 2, except that the spectrum of the noise was filtered
243 into different frequency bands using a 512-point FIR filter. The three conditions used were low-
244 pass filtered at 4 kHz (0.2-4 kHz), high-pass filtered at 4 kHz (4-20 kHz) and broadband (0.2-20
245 kHz). In order to test front/back asymmetry these stimuli were presented at around 45° or 135°,
246 subject to the same $\pm 7.5^\circ$ rove used in previous measurements.

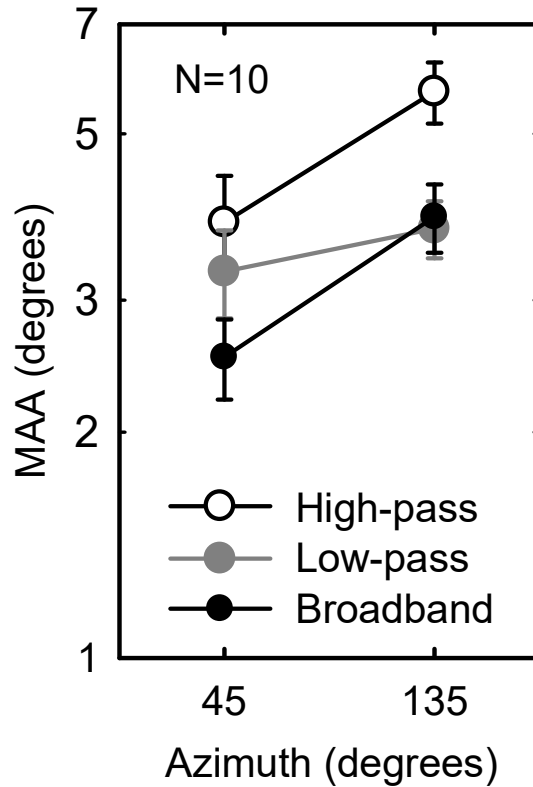
247 **B. Procedure**

248 The experimental procedure was identical to Exps. 1 and 2, but with 6 conditions. Ten naïve
249 listeners with no known hearing impairments attended a one-hour session to measure the 6 MAAs.
250 Each MAA was measured using two interleaved staircases.

251 **C. Results**

252 The log-transformed data were subjected to a repeated-measures analysis of variance with factors
253 frequency band (high-pass, low-pass and broadband) and azimuth (45° and 135°). Figure 3 shows
254 that MAAs were much larger when low-frequencies were removed (open symbols), resulting in a
255 significant main effect of frequency band [$F(2,18)=29.3, p<0.001$]. Consistent with Exp. 1 MAAs
256 were also lower at 45° than at 135° [$F(1,9)=9.6, p<0.05$]. This front/back asymmetry was largely
257 abolished when high frequencies were removed (gray symbols), but this interaction was non-
258 significant [$F(2,18)=3.3, p=0.06$]. The MAAs for broadband and low-pass-filtered stimuli were
259 almost identical at 135°, suggesting no benefit from high frequencies at the rear. Bonferroni-

260 corrected, two-tailed t -tests on the log-transformed data showed that the high-pass condition
 261 differed from both the low-pass [$t(9) = 4.2, p < 0.005$] and broadband [$t(9) = 6.7, p < 0.01$]
 262 conditions.



263

264 FIG. 3. Mean minimum audible angle for band-limited stimuli at 45° and 135°.

265 High- and low-pass stimuli were filtered with a 4 kHz cut-off. Error bars are one

266 standard error of the mean.

267 D. Discussion

268 The larger MAAs for high-pass-filtered stimuli support previous observations that low-

269 frequencies provide stronger sound-localization cues than high-frequencies, consistent with the

270 dominance of low-frequency ITDs in sound localization (Wightman and Kistler, 1992).

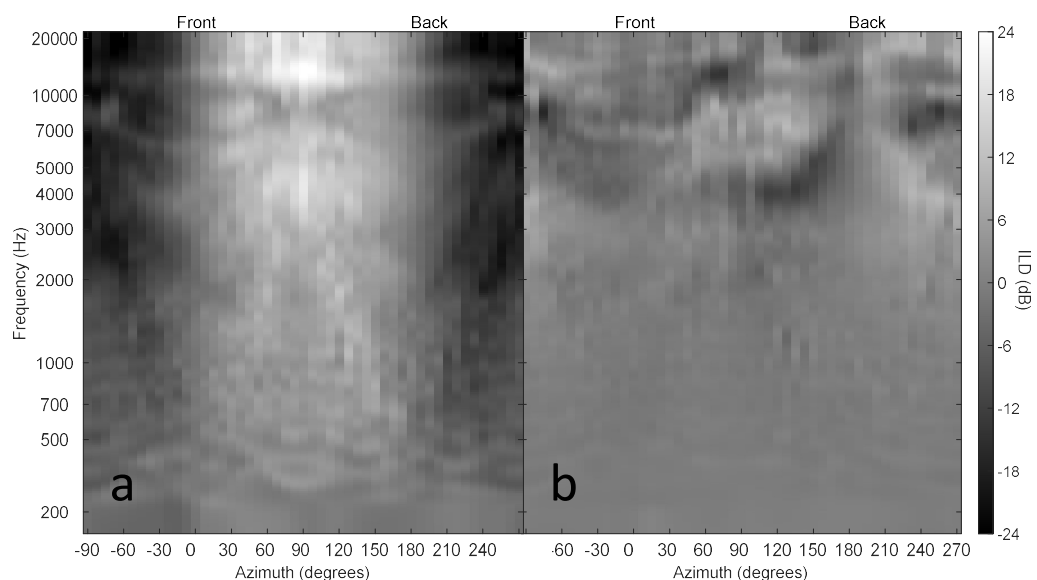
271 However, high frequencies (above 4 kHz) were found to make a substantial contribution to

272 precision in the frontal hemifield, because MAAs for full spectrum stimuli were significantly
273 lower than for those that only have frequencies below 4 kHz. Moreover, the removal of high
274 frequencies was found to have no effect at the rear (gray and black symbols overlap for 135° in
275 Fig. 4). This pattern of results is consistent with the existence of a high-frequency cue that
276 enhances sound localization, but only in the frontal hemifield.

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

285 High-frequency cues may come from the acoustic influences of both the pinnae and the
286 head, either of which might display a front/back asymmetry at these high frequencies. Moreover,
287 the effect of the pinnae will be different at the ipsilateral and contralateral ears producing a
288 modification of the ILDs, which may thus be considered an additive combination of pinna and
289 headshadow effects. Carlile and Pralong (1994, p3453) observed that the pattern of ILDs from
290 head-related-transfer functions (HRTFs) “was basically symmetrical about the interaural axis,”
291 suggesting that they are a less likely source for the front/back asymmetry in MAAs. Carlile and
292 Pralong’s HRTFs were collected from human listeners with intact pinnae. In order to more
293 directly test the front/back symmetry of ILDs produced by headshadow and any contribution to
294 them from asymmetric pinna influences, we used the ring of loudspeakers to measure HRTFs

295 from KEMAR (Burkhard and Sachs, 1975) with the pinnae in place or removed (Fig. 4). With
 296 the effect of the pinnae removed, some front/back asymmetry might be caused by KEMARs
 297 facial features, or by eccentricity of the ear-canal openings on either side of the head. Despite
 298 these possibilities, Fig. 4(a) shows that the pattern of ILDs produced by the head and shoulders
 299 alone is strikingly front/back symmetric. Moreover, there is no discernible structure to the
 300 front/back differences that exist. Figure 4(b) shows the additional ILDs introduced by the pinnae,
 301 which were derived by subtracting the pattern with pinnae in place from the pattern without
 302 them. This figure confirms that the effects of the pinnae are limited to frequencies higher than 4
 303 kHz (Musicant and Butler, 1984) and also shows some differences in the pattern of ILDs in the
 304 frontal and rear hemifields. However, it is not clear that the pattern in the front is in any way
 305 stronger or more easily interpreted, indeed it seems to be less azimuth dependent in front than it
 306 is at the rear.
 307



308

309 FIG. 4a) Headshadow-generated Interaural level differences (ILDs) as a function

310 of frequency and azimuth, measured from a KEMAR manikin without pinnae;
311 b) pinna-generated ILDs as a function of frequency and azimuth, measured from
312 a KEMAR manikin by subtracting ILDs with pinnae in place from ILDs with
313 pinnae removed. Frequency smoothing is produced by calculation of cochlear
314 excitation patterns (Glasberg and Moore, 1983).

315 **V EXPERIMENT 4: EFFECT OF PINNAE**

316 The results of Exp. 3 confirm that the removal of high frequencies can substantially reduce the
317 front/back asymmetry, but it is at the front rather than at the rear where the effect is evident.

318 Experiment 4 tested more directly whether the pinna was responsible for the enhanced MAAs in
319 the frontal hemifield by using extension tubes inserted into the ears to bypass the acoustic effect
320 of the pinnae.

321 **A. Stimuli**

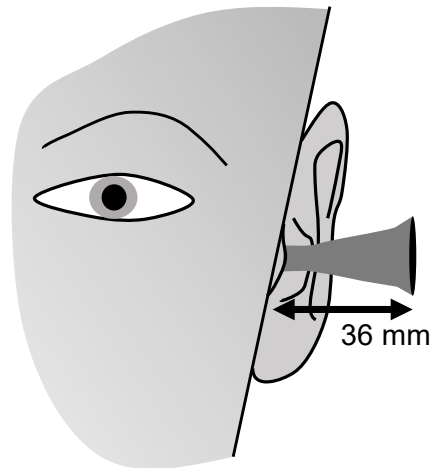
322 The stimuli were identical to those of the broadband conditions of Exp. 3, with source directions
323 of 45° and 135°.

324 **B. Procedure**

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

332 conditions in all.

333

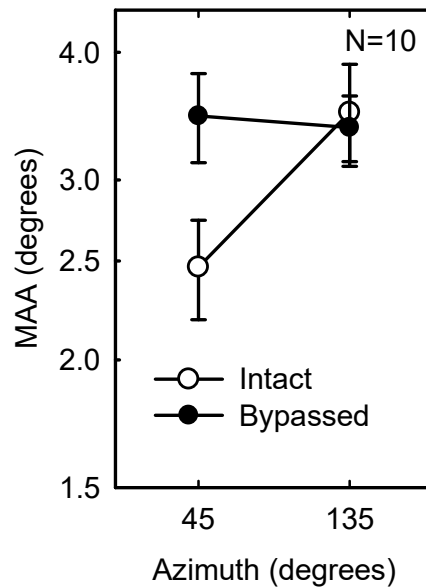


334

335 FIG. 5. Illustration of an audiological speculum inserted to bypass the pinna
336 acoustics.

337 C. Results

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



346

347

FIG 6. Mean minimum audible angle at 45° and 135° with and without extension

348

tubes that acoustically bypassed the pinna. Error bars are one standard error of

349

the mean.

350 **D. Discussion**

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The effect of bypassing pinna acoustics in Exp. 4 was very similar to that of removing high

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frequencies in Exp. 3, suggesting that the two manipulations were both influencing the same

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phenomenon. In Exp. 4, bypassing pinna acoustics completely removed the front/back asymmetry,

354

directly implicating their role. This outcome also reinforces the conclusion of Exp. 2. If room

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acoustics had been responsible for the front/back asymmetry, then one would have expected the

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effect to at least partially survive the use of acoustic bypass tubes.

357

The experiment was foreshadowed by Musicant and Butler (1984) who found in their

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sound-localization study that the advantage of the frontal hemifield was partially removed when

359

the pinna folds were occluded with ear mold material.

360 VI GENERAL DISCUSSION

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

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

383 hemifield.

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

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

390 First, localization studies usually report only accuracy (a measure that includes bias) rather
391 than precision data (i.e., response variability around the mean response, which excludes bias).
392 Where precision metrics have been extracted, they are almost always calculated in manner that is
393 contaminated by bias because the experiment is focused on angular error, that is the differences
394 between the actual location and the response, rather than response variability (Stevens and
395 Newmann, 1936; Oldfield and Parker, 1984; Musicant and Butler, 1984; Gilkey et al. 1995; Carlile
396 et al. 1997). As others have noted, this confounds accuracy and precision (Kolarik et al., 2021).

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

405 Oldfield and Parker (1984) noted the problem of motor noise and attempted to factor out

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

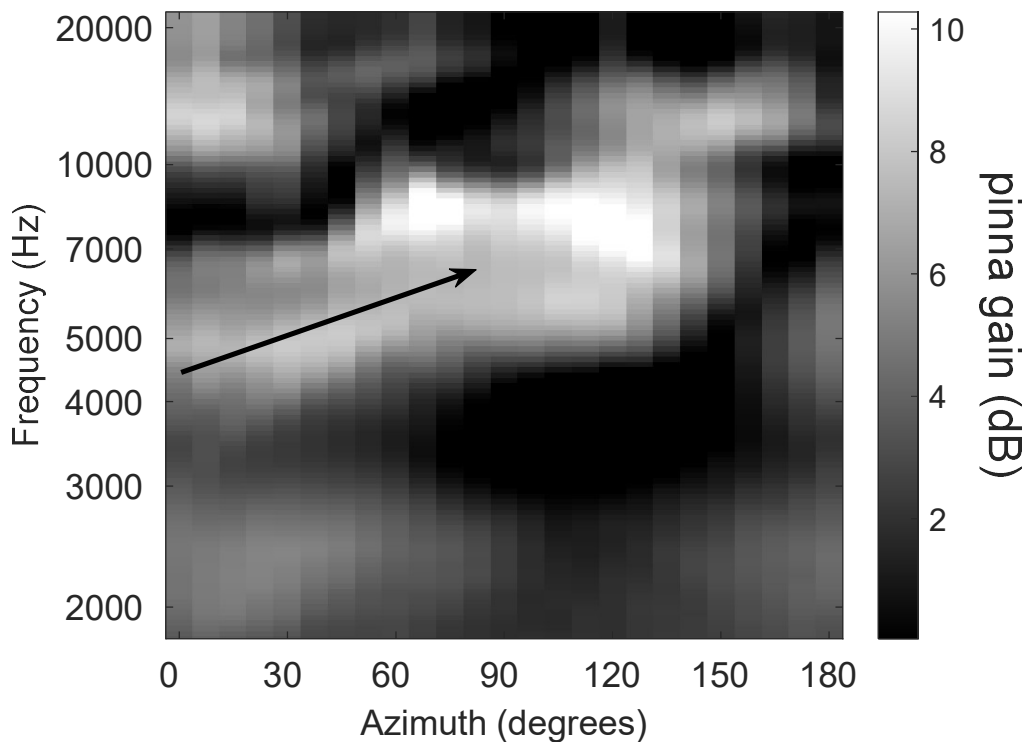
412 The problems with the mode of response are well illustrated by the fact that such studies
413 also report large response variability for sources at 180°. In contrast, when measured more directly
414 using the MAA (Saberri et al. 1990; Aggius-Vella et al. 2020; Exp. 1 of the present study), precision
415 at 180° can rival that at 0°, indicating that these non-psychoacoustic sources of error in a sound
416 localization task can substantially inflate the measured precision in the rear hemifield.

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

423 **B. The role of the pinna**

424 The pinna is thought to provide monaural spectral cues to sound source elevation in the
425 form of spectral notches (Hebrank and Wright, 1974; Watkins, 1978) or the overall spectral shape
426 (Baumgartner et al. 2014; van Opstal et al, 2017; Balachandar and Carlile, 2019). What cues might
427 it provide in the horizontal plane? A clue comes from Butler and Flannery (1980) who found that
428 listeners experienced changes in the perceived lateral position of a 1-kHz-wide band of noise as a

429 function of its center frequency between 4 and 8 kHz. A virtual simulation of such a stimulus
430 (MM1.wav) is included in the supplementary materials for this paper¹. The experiment was
431 concerned with monaural listening, so listeners had one ear plugged and the stimuli were presented
432 from a loudspeaker at 45° on the unoccluded side. The fact that this effect occurs at frequencies
433 above 4 kHz is consistent with the possibility that the stimuli may be mimicking aspects of the
434 pinna response. Supporting that suggestion, Carlile and Pralong (1994) and Shub et al. (2008)
435 described a peak in the HRTF for the ear ipsilateral to the source that varied systematically as a
436 function of horizontal location in the frontal hemifield. In order to illustrate the specific role of the
437 pinna in this effect, we measured HRTFs from KEMAR with and without its pinnae.



438

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

442 Figure 7 shows the gain introduced by the pinna as a function of source azimuth. Pinna
443 gain is the difference between excitation patterns (Moore and Glasberg, 1983) with and without
444 pinnae. Pinna gain is predominantly positive, consistent with a sound-gathering role for the
445 pinna. Particularly high gain (~10 dB) is seen in exactly the region described by Carlile and
446 Pralong (1994) and by Shub et al. (2008) showing explicitly that the effect is produced by the
447 pinna rather than by the head. It thus seems likely that Butler and Flannery's (1968) noise band
448 was mimicking an effect of pinna acoustics, and that this cue provides the listener with
449 supplementary lateral-position information in the frontal hemifield. In the rear hemifield, less
450 systematic changes are observed, and this contrast may explain the observed front/back
451 difference.

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

462 Our experiments show substantially improved precision when pinna cues are available in
463 combination with congruent binaural cues. In contrast, pinna cues appeared rather ineffective in
464 the horizontal plane when Shub et al. (2014) measured monaural MAAs. In particular, they found

465 that MAAs were relatively poor when pinna cues alone were available because they produced
466 psychometric functions that were highly idiosyncratic to individual listeners and often non-
467 monotonic.

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

481 **VII CONCLUSION**

482 The MAA is smaller in the frontal hemifield than the rear. The difference is negligible at
483 0° but increases monotonically and substantially with increasing azimuth up to 90°. The benefit to
484 the frontal field is produced by spectral changes introduced by the pinna.

485 **VIII Acknowledgments**

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489

490 **APPENDIX I: BLOB-SIZE AND LOUDSPEAKER SPACING**

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

502 **A. Stimuli**

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

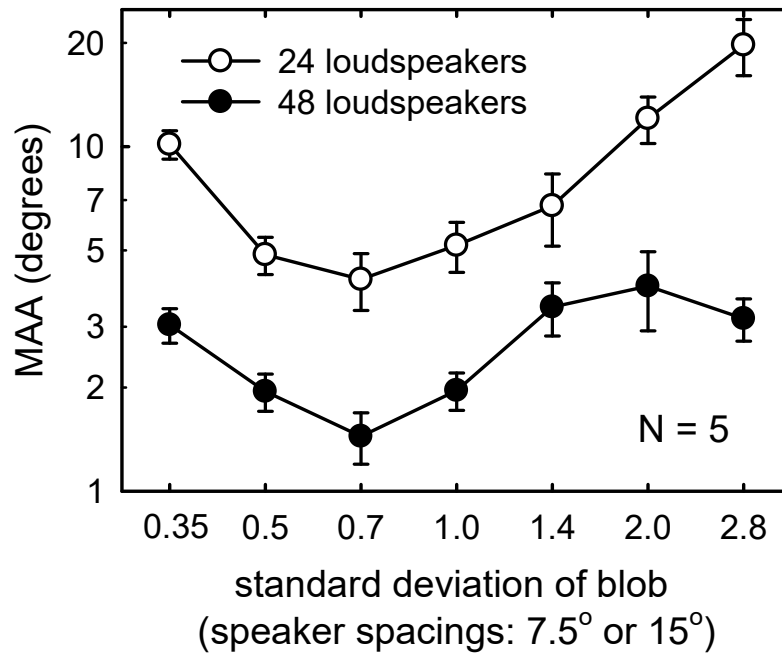
507 **B. Procedure**

508 Five listeners with self-reported normal hearing each attended two one-hour experimental sessions
509 on different days.

510 **C. Results**

511 The results are shown in Fig. 8 as a function of the angular size of the blobs for both the 24-
512 loudspeaker and the 48-loudspeaker conditions. For each number of loudspeakers, the MAA as a

513 function of blob size is U-shaped, with a minimum at 0.7 times the angular spacing of the
 514 loudspeakers (5.3° for 48 loudspeakers: 10.5° for 24 loudspeakers). Since the set of blob sizes for
 515 each number of loudspeakers is the same when scaled by speaker separation, the analysis of
 516 variance uses this scaling as a factor.



517

518 FIG. 8. Minimum audible angle as a function of Gaussian blob size (standard
 519 deviation in multiples of the speaker spacings) for loudspeaker rings with 24 or
 520 48 loudspeakers. Error bars are one standard error of the mean.

521 An analysis of variance of the log-transformed MAAs confirmed that 48 loudspeakers
 522 produced significantly smaller MAAs than 24 loudspeakers [$F(1,9)=12.5$, $p<0.01$]. It also
 523 confirmed the significant main effect of blob size [$F(6,54)=129.5$, $p<0.001$]. Finally, there was
 524 also a significant interaction between the two [$F(6,54)=13.5$, $p<0.001$]. The variation in MAA with
 525 blob size appears similar for both speaker separations, but there is a marked increase in MAAs for
 526 the two largest blob sizes when using 24 loudspeakers, which is presumably responsible for this

527 interaction. Holm-corrected post-hoc comparisons showed that the MAAs for a blob size of 0.7
528 times the speaker separation differed significantly at 0.35, 1.4, 2 and 2.8 times the speaker
529 separation.

530 **D. Discussion**

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

¹ The virtual simulation of Butler and Flannery's stimulus 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.

547

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549 **REFERENCES**

- 550
- 551 Aggius-Vella, E., Kolarik, A. J., Gori, M., Cirstea, S., Campus, C., Moore, B. C. J., and Pardhan,
552 S. (2020). “Comparison of auditory spatial bisection and minimum audible angle in front,
553 lateral, and back space.” *Scientific reports*, 10, 1-9.
- 554 Alais, D., and Burr, D. (2004). “The ventriloquist effect results from near-optimal bimodal
555 integration.” *Current Biology*, 14, 257–262. <https://doi.org/10.1016/j.cub.2004.01.029>
- 556 Balachandar, K., and Carlile, S. (2019). “The monaural spectral cues identified by a reverse
557 correlation analysis of free-field auditory localization data.” *J. Acoust. Soc. Am.*, 146(1),
558 29–40. <https://doi.org/10.1121/1.5113577>
- 559 Baumgartner, R., Majdak, P., and Laback, B. (2014). "Modeling sound-source localization in
560 sagittal planes for human listeners," *J. Acoust. Soc. Am.*, 136, 791-802, doi:
561 10.1121/1.4887447.
- 562 Brimijoin, W. O. (2018). “Angle-Dependent Distortions in the Perceptual Topology of Acoustic
563 Space.” *Trends in Hearing*, 22, 1–11. <https://doi.org/10.1177/2331216518775568>
- 564 Burkhard, M. D., and Sachs, R. M. (1975). Anthropometric manikin for acoustic research. *J.*
565 *Acoust. Soc. Am.*, 58, 214–222. <http://link.aip.org/link/?JAS/58/214/1>
- 566 Butler, R. A., and Flannery, R. (1980). “The spatial attributes of stimulus frequency and their
567 role in monaural localization of sound in the horizontal plane.” *Perception &*
568 *Psychophysics*, 28(5), 449–457. <https://doi.org/10.3758/BF03204889>

- 569 Carlile, S., Delaney, S., and Corderoy, A. (1999). "The localisation of spectrally restricted
570 sounds by human listeners." *Hear. Res.*, 128(1–2), 175–189. [https://doi.org/10.1016/S0378-](https://doi.org/10.1016/S0378-5955(98)00205-6)
571 5955(98)00205-6
- 572 Carlile, S., Leong, P., and Hyams, S. (1997). "The nature and distribution of errors in sound
573 localization by human listeners." *Hear. Res.* 114, 179-196.
- 574 Carlile, S., and Pralong, D. (1994). "The location-dependent nature of perceptually salient
575 features of the human head-related transfer functions." *J. Acoust. Soc. Am.*, 95(6), 3445–
576 3459. <https://doi.org/10.1121/1.409965>
- 577 Ernst, M. O. and Banks, M. S. (2002). "Humans integrate visual and haptic information in a
578 statistically optimal fashion." *Nature* **415**, 429-433.
- 579 Fischer, T., Kompis, M., Mantokoudis G., Caversaccio M. and Wimmer W. (2021). "Dynamic
580 sound field audiometry: Static and dynamic spatial hearing tests in the full horizontal plane"
581 *Applied Acoustics*, **166**, 107363.
- 582 Fisher, H. G., and Freedman, S. J. (1968). "The role of the pinna in auditory localization."
583 *Journal of Auditory Research*, 8, 15–26.
- 584 Gilkey, R. H., Good, M. D., Ericson, M. A., Brinkman, J., and Stewart, J. M. (1995). "A pointing
585 technique for rapidly collecting localization responses in auditory research." *Behavior*
586 *Research Methods, Instruments, & Computers*, 27, 1–11.
587 <https://doi.org/10.3758/BF03203614>

- 588 Hebrank, J., and Wright, D. (1974). "Spectral cues used in the localization of sound sources on
589 the median plane." *J. Acoust. Soc. Am.*, 56(6), 1829–1834.
590 <https://doi.org/10.1121/1.1903520>
- 591 Kolarik, A. J. Pardhan, S. and Moore, B. C. J. (2021). "A framework to account for the effects of
592 visual loss on human auditory abilities." *Psych. Rev.* 128, 913–935
- 593 Kuhn, G. F. (1977). "Model for the interaural time differences in the azimuthal plane." *J. Acoust.*
594 *Soc. Am.*, 62, 157–167. <https://doi.org/10.1121/1.381498>
- 595 Landy, M. S., Maloney, L. T., Johnston, E. B. and Young, M. (1995). "Measurement and
596 modelling of depth cue combination: in defense of weak fusion." *Vision Research*, 35, 389-
597 412.
- 598 Majdak, P., Goupell, M. J., and Laback, B. (2010). "3-D localization of virtual sound sources:
599 Effects of visual environment, pointing method, and training," *Atten. Percept. Psychophys.*,
600 72, 454-469, doi: 10.3758/APP.72.2.454
- 601 Makous, J. C. and Middlebrooks, J. C. (1990). "Two-dimensional sound localization by human
602 listeners." *J. Acoust. Soc. Am.*, 87, 2188-2200.
- 603 Macaulay, E. J., Hartmann, W. M., and Rakerd, B. (2010). "The acoustical bright spot and
604 mislocalization of tones by human listeners." *J. Acoust. Soc. Am.*, 127, 1440–1449.
605 <https://doi.org/10.1121/1.3294654>
- 606 Macpherson, E. A., and Middlebrooks, J. C. (2002). "Listener weighting of cues for lateral angle:
607 The duplex theory of sound localization revisited." *J. Acoust. Soc. Am.*, 111, 2219–2236.
608 <https://doi.org/10.1121/1.1471898>

- 609 Mills, A. W. (1958). "On the Minimum Audible Angle." *J. Acoust. Soc. Am.*, 30(4), 237.
610 <https://doi.org/10.1121/1.1909553>
- 611 Moore, B. C. J., and Glasberg, B. R. (1983). "Suggested formulae for calculating auditory-filter
612 bandwidths and excitation patterns." *J. Acoust. Soc. Am.*, 74, 750–753.
- 613 Mossop, J. E., and Culling, J. F. (1998). "Lateralization of large interaural delays." *J. Acoust.
614 Soc. Am.*, 104, 1574–1579.
- 615 Musicant, A. D., and Butler, R. A. (1984). "The influence of pinnae-based spectral cues on
616 sound localization." *J. Acoust. Soc. Am.*, 75, 1195–1200. <https://doi.org/10.1121/1.390770>
- 617 Oldfield, S. R., and Parker, S. P. (1984). "Acuity of sound localisation: a topography of auditory
618 space. I. normal hearing conditions". *Perception*, 15, 67–81.
- 619 Oldfield, S. R., and Parker, S. P. (1986). "Acuity of sound localisation: a topography of auditory
620 space. III. Monaural hearing conditions." *Perception*, 15, 67–81.
621 <https://doi.org/10.1068/p150067>
- 622 Perrett, S., and Noble, W. (1997). "The effect of head rotations on vertical plane sound
623 localization." *J. Acoust. Soc. Am.*, 102, 2325–2332. <https://doi.org/10.1121/1.419642>
- 624 Saberi, K., Dostal, L., Sadralodabai, T., and Perrott, D. R. (1991). "Minimum audible angles for
625 horizontal, vertical, and oblique orientations: lateral and dorsal planes." *Acta Acustica
626 United with Acustica*, 75, 57–61.
- 627 Shub, D. E., Carr, S. P., Kong, Y., and Colburn, H. S. (2008). "Discrimination and identification
628 of azimuth using spectral shape," *J. Acoust. Soc. Am.*, 124, 3132-3141, doi:
629 10.1121/1.2981634.
- 630 Stevens, S. S., and Newman, E. B. (1934). "The localization of pure tones." *Proc. Nat Acad. Sci.*
631 20, 593–596.

- 632 Van Opstal, A. J., Vliegen, J., and Esch, T. V. (2017). "Reconstructing spectral cues for sound
633 localization from responses to rippled noise stimuli," PLOS ONE, 12, e0174185, doi:
634 10.1371/journal.pone.0174185.
- 635 Van Wanrooij, M. M., and Van Opstal, A. J. (2004). "Contribution of head Shadow and Pinna
636 Cues to Chronic Monaural Sound Localization" *J. Neurosci.*, 24, 4163–4171.
637 <https://doi.org/10.1523/JNEUROSCI.0048-04.2004>
- 638 Watkins, A. J. (1978). "Psychoacoustical aspects of synthesized vertical locale cues." *J. Acoust.*
639 *Soc. Am.* 63(4), 1152–1165. <https://doi.org/10.1121/1.381823>
- 640 Wichmann, F. A., and Hill, N. J. (2001). "The psychometric function: I. Fitting, sampling, and
641 goodness of fit". *Perception and Psychophysics*, **63**, 1293–1313.
642 <https://doi.org/10.3758/BF03194544>
- 643 Wightman, F. L., and Kistler, D. J. (1992). "The dominant role of low-frequency interaural time
644 differences in sound localization." *J. Acoust. Soc. Am.*, 91(3), 1648–1661.
645 <https://doi.org/10.1121/1.402445>
- 646 Yost, W. A., and Dye, R. H., Jr. (1988). "Discrimination of interaural differences of level as a
647 function of frequency," *J. Acoust. Soc. Am.* 83, 1846-1851
648
649
650

