The equivalent arc ratio for auditory space

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1 Abstract

2 The minimum audible movement angle increases as a function of source azimuth. If listeners do not

3 perceptually compensate for this change in acuity, then sounds rotating around the head should

4 appear to move faster at the front than at the side. We examined whether judgments of relative

5 amounts of acoustic motion depend on signal center angle and found that the azimuth of two signals

6 strongly affects their point of subjective similarity for motion. Signal motion centered at 90° had to

7 be roughly twice as large as motion centered at 0° to be judged as equivalent. This distortion of

8 acoustic space around the listener suggests that the perceived velocity of moving sound sources

9 changes as a function of azimuth around the head. The "equivalent arc ratio," a mathematical

10 framework based on these results, is used to successfully provide quantitative explanations for

11 previously documented discrepancies in spatial localization, motion perception, and head-to-world

12 coordinate transformations.

1 Introduction

13

14   The binaural cues that are used to construct our internal representation auditory space are

15   interaural time difference (ITD) and interaural level difference (ILD). Both of these arise from the

16   physical structure of the head, as sounds arrive at the ear closest to the sound source both earlier

17   and at a higher level than at the further ear. Measurements of these binaural cues as a function of

18   sound source angle demonstrate that they change most rapidly at the front of a listener [1, 2]. If the

19   internal representation of space were based purely on these cues, then listeners would have

20   increased spatial resolution near the sagittal plane. Indeed this is well supported: both the threshold

21   measurements of minimum audible angle (MAA) and minimum audible movement angle (MAMA)

22   are known to change as a function of source azimuth [3, 4].

23   The study described here examined a potential consequence of this representation of auditory

24   space: namely that if listeners do not perceptually compensate for it, then the expansion of

25   resolution at the front and contraction at the side would dictate that a sound rotating at a constant

26   angular velocity around the head would not appear to do so, but would instead appear to move

27   faster at the front than at the side. Correspondingly, listeners turning their heads at a constant

28   velocity would experience an angle-dependent change in apparent source movement. The literature

29   on auditory motion is unclear on this subject and to our knowledge no studies have directly

30   examined the perceived difference in auditory motion at different angles and directions relative to

31   the head. That said, a number of curious discrepancies in spatial auditory perception have been

32   described over the years. Some of these have been classed as 'incomplete coordinate

33   transformations' [5], suggesting that a person's head angle may affect the direction from which they

34   perceive a sound to emanate. Similarly, studies have reported discrepancies in listeners' subtraction

35   of their own active head movements from the movement of the auditory scene [6, 7].

36   Although the latter two studies used Bayesian inference as a description of their observations, no

37   mathematical framework has been suggested to account for these findings. We propose instead that

38 these and a number of other discrepancies in spatial hearing could be explained via an angle-

39 dependent distortion in apparent sound location and motion. The underlying hypotheses to be

40 tested can be more formally stated as follows: first, that relative velocity judgements should change

41 as a function of azimuth, and second, that a quantitative model based on any observed expansion of

42 space should capture static phenomena such as sound source eccentricity overestimation [8-11] and

43 dynamic phenomena like inconsistent self-motion subtraction [6, 7]. We further argue that the

44 MAMA is not simply a measure of acuity, rather it underlies a constant perceptual unit, changing in

45 absolute magnitude across space. One could argue that as a threshold measurement, roughly 1-2

46 degrees at the front of a listener may be considered equivalent to roughly 4 degrees at the side of

47 the listener in that these are the minimal amounts of motion required for a listener to change their

48 judgement from no motion to 'some motion.' Whether a similar azimuth-dependent expansion in

49 the perception of auditory space exists at suprathreshold levels has never been directly

50 demonstrated.

51 We term the proposed relationship of equal perceptual units across angle the "equivalent arc ratio"

52 for auditory space, borrowing terminology from the equivalent rectangular bandwidth [12]. Here we

53 quantify perceptual expansion by measuring the dependence of judgements of relative sound-source

54 motion on the angles with respect to the head from which the signals arrive. The consequences of

55 such a nonlinear representation of space are discussed, as is the potential for 'hyper-stable' virtual

56 acoustics. Finally, successful quantitative comparisons are made between the predictions of a

57 proposed mathematical framework and the results of a number of previously published studies.


58 2 Results

59 2.1 Relative motion judgements

60 Listeners were asked to make a judgement about which of two signals, a reference and a test signal,

61 "moved more." The reference always moved 20° and the test moved less, the same, or more. Both

62 the test and reference signals could be centered at 0°, 45°, or 90°, and movement direction and the

63   order of presentation and condition were fully randomized. Across all conditions we found that the

64   center azimuth of both test and reference signals strongly affected subjects' comparison of relative

65   extents of motion, as expressed by a change in response as a function of test excursion. We found

66   main effects of test excursion, test azimuth, and reference azimuth ($F_{(1,6)} = 338.11$, $p < 0.05$, $F_{(1,2)} =$

67   71.34, $p < 0.05$, and $F_{(1,2)} = 97.74$, $p < 0.05$, respectively), an interaction between reference azimuth

68   and test excursion ($F_{(2,12)} = 3.99$, $p < 0.05$), an interaction between test azimuth and test excursion

69   ($F_{(2,12)} = 34.24$, $p < 0.05$), and a 3-way interaction between reference azimuth, test azimuth, and

70   test excursion ($F_{(2,24)} = 1.92$, $p < 0.05$). The only insignificant comparison in the test was found in

71   the interaction between test and reference azimuths ($F_{(2,4)} = 0.76$, $p = 0.55$).

72   Figure 1a illustrates this phenomenon for reference signals centered at 0°. Test signals centered at 0°

73   (orange line) were judged to move the same amount as the 20° reference motion when the test

FIGURE 1
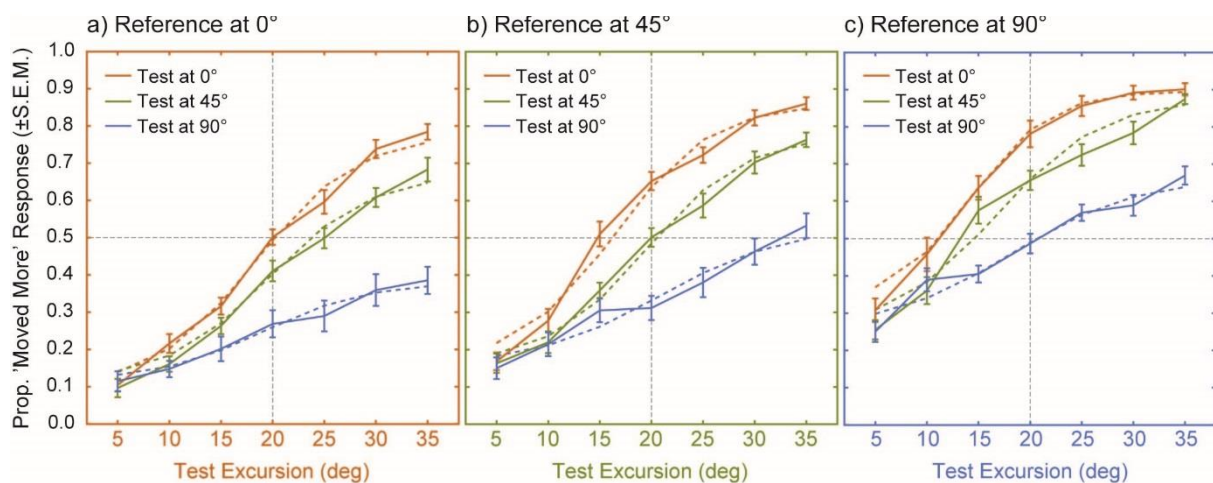
74   signals also moved by 20°. Thus the point of subjective equality (PSE) for this condition was roughly

75   20/20 = 1. The smooth psychometric function confirms that listeners were capable of making

76   judgements of relative motion, which is also reflected in the significant main effect of test excursion.

77   On the other hand, test signals centered at 45° (green line) had to move by about 25° to be judged as

78   moving the same amount as the 20° movement of the reference signal at the front. The range of

79   movement angles we used was not sufficient to estimate how much a 90° test signal (blue line) had

80   to be moved to reach the PSE with a reference at 0°, but the required excursion was likely much

81   greater than 35°. In Figure 1b it can be seen that when compared to reference signals at 45°, test

82   signals at 0° had to be moved significantly less to be perceived as moving the same amount, and test

83   signals at 90° had to be moved significantly more. Finally, reference signals at 90° (Figure 1c) showed

84   a pattern of expansion that was roughly inverted as compared to Figure 1a. Here it can be seen that

85   motion at 0° had to be roughly half as large to be judged as equivalent to motion at 90°.

86 2.2 Points of subjective equality for motion

87   PSE ratios were drawn from the individual logistic fits to the data (the *mean* of said fits are plotted

88   with dotted lines in Figure 1). The point at which the logistic fit crossed 0.5 probability was taken for

89   each condition for each listener and divided by the reference motion PSE. PSE ratios were also

90   computed for inverted pairs (i.e., the test/reference ratio 0/90 is accompanied by 1/the

91   test/reference ratio 90/0). A scatter plot of these PSE ratios, plotted as a function of the absolute

92   difference between the test and reference angles, is shown in Figure 2. The use of 'comparison' in

FIGURE 2
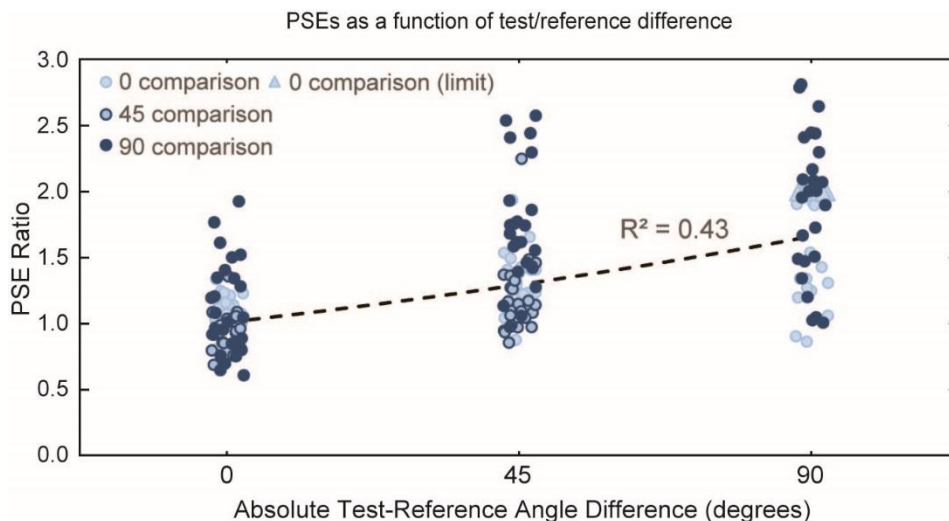
93   the legend is due to the mix of normal and inverted pairs (where reference and test are used

94   interchangeably). When the test and reference motions were identical the PSE ratios were clustered

95   around 1, albeit with a large degree of intersubject variability. PSE ratios for a difference of 45° were

96 on average larger than 1.0, and ratios for a 90° difference were still larger, reaching a value of

97 roughly 2. It should be noted that the triangle symbols in the plot represent measurements in which

98 the test signals at maximum excursion were still not judged to be moving by the same amount as the

99 20° reference motion. The true values for these data points cannot be reliably estimated as the

100 psychometric functions in question did not cross the PSE, but examining the individual data and

101 logistic fits makes it clear that the values are likely to be substantially larger than 2. The Pearson

102 correlation coefficient between the PSE ratio and the difference in test/reference angle is R^2 of 0.43.

3 Discussion

3.1 The non-uniformity of acoustic motion

105 The observed changes in the apparent amount of motion across azimuth are not subtle, making it

106 somewhat surprising that this effect has not been previously reported. Across all conditions we

107 found that the relative azimuth of two signals strongly affects their point of subjective similarity for

108 motion. Roughly speaking, 20° of motion at the front of the listeners is treated equivalently to 40° of

109 motion at the sides. This difference in PSE ratio over azimuth, which we will refer to as the

110 equivalent arc ratio from here onward, represents a perceptual expansion of space at the front and a

111 contraction at the sides. On one level, the equivalent arc ratio could be interpreted as a simple

112 relationship between acuity and perception, but this belies two perceptual consequences. One

113 consequence is that a sound rotating at a constant angular velocity around the head would appear to

114 accelerate towards the front of the listener, and decelerate towards the side. The second

115 consequence is that – from the perspective of a moving listener –the acoustic world not appear

116 stable as the head turns. Instead signals at the front should appear to counter-rotate as the listener

117 turns, and signals at the side should seem to be slightly dragged along with the listener's rotation.

3.2 Distortion in acoustic location

119 There are two possibilities for reconciling the observed change in perceived motion as a function of

120 angle with our current understanding of sound localization. The first requires a disassociation

121   between movement and location; in this case the apparent location of a signal at the end point of a

122   movement would have to be different from its apparent position(s) during the movement. There is

123   evidence in the visual system of just such disassociation [13]. It is conceivable that a similar process

124   occurs in the auditory system, but the disassociation in the visual system is thought to arise from

125   specialized motion-sensitive neurons in the middle temporal visual and medial superior temporal

126   areas [14], brain regions known for motion selectivity [15, 16]. Motion-specific processing has been

127   observed in posterior auditory cortex [17], however, there remains little physiological evidence for

128   auditory neurons that exhibit motion selectivity while being agnostic to spatial location.

129   If we assume, on the other hand, that auditory motion and spatial location are intrinsically linked

130   with each other, then the second possibility is that both the motion and the perceptual location of

131   *static* sound sources would be subtly distorted as a function of head angle. This framework prevents

132   any jump in perceived location after a movement (as would be found above), but requires that

133   listeners mislocalize sound sources. The function and its constants were chosen so that its slope at 0°

134   and its slope at 90° were related to each other in the same manner as the equivalent arc ratio

135   between these two angles. We used a hyperbolic tangent (Equation 1) because it is readily invertible,

136   although one could in principle also use a sine-expansion, or some other mathematical construct.

137   Equation 1:

138    $$\theta_p = \frac{\tanh(\theta_a \log(R\,t - c))}{\tanh\left(\log(R\,t - c)\right)}$$

139   where all angles are degrees / 90 (including θ_a), ln is the natural logarithm, t is a constant equal to

140   7.08, c is a constant equal to 5.97, R is the ratio between the PSE at 90° and at 0°, θ_a is the actual

141   position of a signal, and θ_p is the perceived position of that signal. The constants t and c were

142   empirically derived (using Matlab's fminsearch function) to ensure that the ratio between its 20°

143   slope (the amount of reference motion) at 0° and at 90° was closest to the ratio R between the PSE

144   at 0° and at 90° over a reasonable range of values of R.

145   For Θ_a angles larger than 0 and less than 90, the values of Θ_p generated by Equation 1 imply that

146   static acoustic targets would be perceived at larger eccentricities than they truly are. Precisely such a

147   phenomenon has been repeatedly demonstrated in the literature, as listeners have been shown to

148   regularly overestimate the angle of sound sources [11], particularly when fixating at the front and

149   using a laser pointer to indicate direction. Equation 1 provides a reasonable fit to the overestimation

150   of source angle measured in at least three separate laser-pointer studies [8-10] (laser pointing being

151   the most comparable task condition it does not involve a head movement). The data from the most

152   relevant portions of these studies are plotted in Figure 3 alongside predictions from the model. The
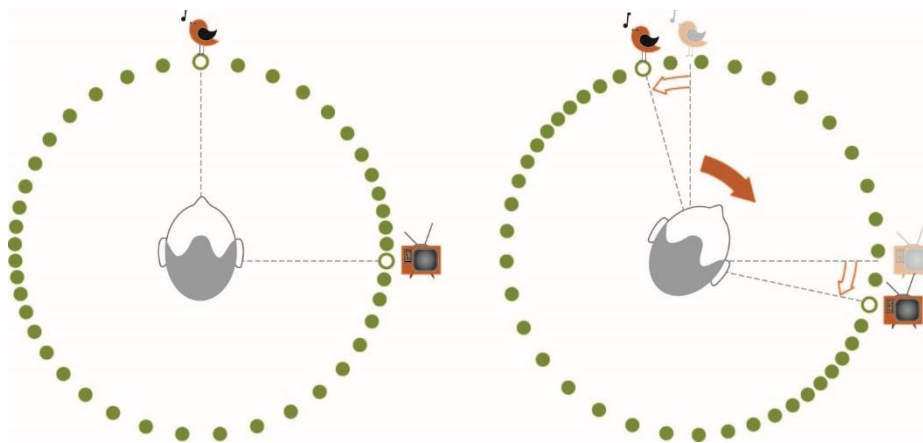
FIGURE 3
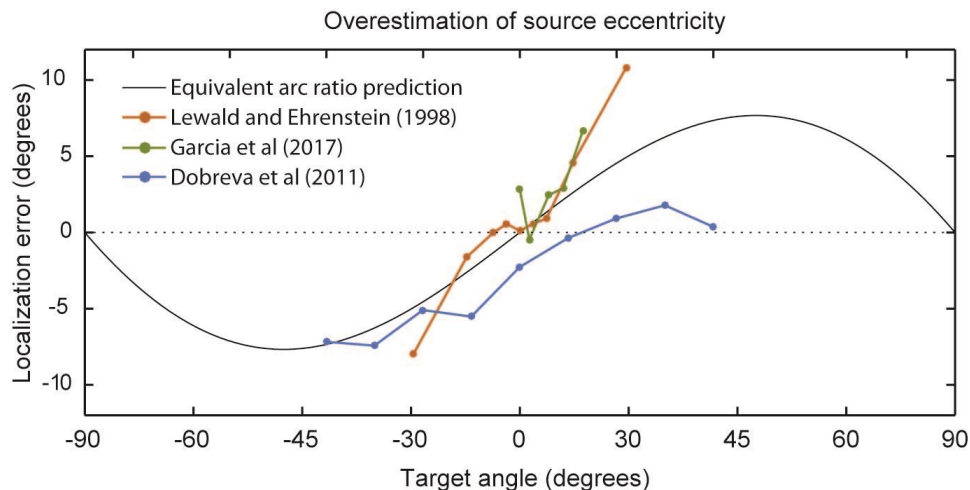
153   predictions are plotted as the difference between perceived and actual locations (Θ_p - Θ_a), and these

154   values fall well within the range of the data from the three studies. Physiological data on this subject

155   are somewhat limited, but predictions of a neural network trained on spike data from cat primary

156   auditory cortex also show a characteristic overestimation of target position that roughly follows the

157   predicted pattern [18]. The magnitude of this overestimation, however, is far larger than has been

158   observed behaviorally or predicted by the current mathematical framework.

3.3 Distortion in acoustic motion

159

160   When Equation 1 is used to examine *motion* (by examining the differences in the distortion between

161   Θ_a and Θ_p at different head and source angles) it becomes clear that the overestimation of static

162   signal angle must move with the head. The consequence of this is that signals appear to move in

163   different ways depending on their subtended angle with respect to the head during a turn. Figure 4

164   displays the way in which the apparent location of two sound sources (here a bird and a television)

165   should shift as the listener turns to the right. A signal at 0° should shift to the left and a signal at 90°

FIGURE 4

166   should shift to the right. Supplemental Figure S1 is an animation of this phenomenon depicting the

167   perceived locations of 32 static signals arranged around the head as it turns. The angle of the

168   listener's nose is depicted as a line along the radius of the circle. The expansion/contraction in Figure

169   4 and in the animation is exaggerated by a factor of 2 for clarity.

170   There are established phenomena that suggest there are perceptual distortions of auditory space

171   that depend on some interaction between stimulus angle and head angle. Genzel and colleagues [7]

172   demonstrated that, after an active head movement, a second sound source had to be shifted in

173   azimuth to be perceived as being at the same azimuth as a sound before the movement. Within the

174   framework of the equivalent arc ratio, this may be explainable as a distortion in the perceived

175   location of a static midline signal. Using Equation 1 (with a 90°/0° PSE ratio of the mean 1.82), a 35.3°

176   active rightward movement (the average reported in the study) should result in a 0° signal appearing

177   to be at -6.5°, which not only sign-correct, it is also reasonably close to the value of -5.5° from Genzel

178   et al (2016). Other systematic errors in movement compensation have also been documented. For

179   example, Freeman et al [6] demonstrated that signals at the front of the listener must be moved

180   with the head with a gain of +0.17 to be judged as being static. Here gain refers to amount of motion

181   with respect to the head, so if a listener turns 10° to the right, signals that move by +1.7° to the right

182   would be most consistently judged to be static. The corresponding value predicted by Equation 1 is

183   +2.2°, which is at least sign-correct if not a perfect match.

184   Physiological data on the relationship between self motion and spatial receptive fields is virtually

185   non-existent, making comparisons with animal work problematic. Eye position has been shown to

186   clearly influence the apparent spatial location of auditory signals [19, 20], to modulate responses in

187   the inferior colliculus [21] and auditory cortex [22], and to actively shift spatial receptive fields in

188   superior colliculus [23], but little work has been done on head movements. Very recently, however,

189   experiments in ferret primary auditory cortex have revealed a subpopulation of neurons whose

190   spatial receptive fields appear to be specified in world-centric coordinates, rotated in opposition to

191   the animal's movement [24]. This finding represents a neural correlate of our percept of a stable

192   acoustic world. It is not currently possible, however to determine whether the shifts in receptive

193   field boundaries as a function of eccentricity match that predicted by the equivalent arc ratio

194   because the width and contralateral offset of cortical receptive fields make it difficult to assign

195   individual neurons to exact azimuths in space.

196   Returning to psychophysics work, results from the Freeman et al (2016) study are roughly in line with

197   what the equivalent arc ratio model would predict, with one notable exception. According to the

198   model, the gain at which signals must be moved to be judged as static should change as a function of

199   azimuth, reducing to 0 when 45° is reached, and even changing to a *counter*-rotation for larger

200   eccentricities. The Freeman et al study did not find this, although they did find a decrease in gain and

201   a substantial increase in variance as a function of stimulus angle. It should be noted that these

202   authors' own Bayesian explanation for the non-unity gain *also* predicts a change in gain as a function

203   of azimuth. But the subjects in that study were blindfolded, so the discrepancy may point to an as-

204   yet unresolved role of eye position in this and related phenomena. The previously mentioned

205   dependence of neural and behavioral responses on eye position certainly attest to this possibility. A

206   related phenomenon was previously described by Lewald and Ehrenstein [5]; the displacement of

207   the subjective auditory midline (as measured using ILD) towards the trunk as a listener turns to more

208   eccentric head angles. This displacement was argued as being the result of an 'incomplete

209   coordinate transformation,' a failure of listeners to fully compensate for their own movement. Taken

210   together with the results from Freeman et al [6] this suggests that head-to-trunk angle may

211   represent a second unresolved factor that results in a shift in target location into a different region of

212   expansion / contraction of acoustic space.

213   Studies examining representational momentum have argued that the faster a signal is rotating

214   around the head, the further the perceived endpoint will be displaced in space [e.g., 25, 26]. This is

215   argued to be a consequence of a mental extrapolation of the signal's trajectory [27]. According to

216   the equivalent arc model, signals moving towards the midline would appear to accelerate, suggesting

217   their endpoints could seem more displaced than those of signals receding from the midline. An

218   advantage in direction discrimination has been demonstrated for signals approaching the median

219   plane [28], congruent with the equivalent arc model, but in the case of the first representational

220   motion study [25] all the motion trajectories used were across the midline. The analysis in the

221   second study [26] – while it did examine left versus right movements – collapsed the data across

222   different center azimuths, an averaging method that would prevent us from observing any

223   asymmetry predicted by the equivalent arc ratio model. Examination of the latter data set could

224   either lend support to or require a re-evaluation of the equivalent arc framework.

3.5 The relationship between the equivalent arc ratio and the MAMA

The equivalent arc ratio expansion observed appears to be related to – but not entirely dependent on – the change in MAMA as a function of angle (the MAMA being roughly 1° in front of the listener and increasing to about 4° at the side [4]). If the equivalent arc ratio were a simply the result of the change in MAMA as a function of angle, then we might expect slightly larger equivalent arc ratios between 0° and 90° than we observed. However, the two measurements may be linked with each other on some level, as acoustic movement, whether a consequence of source or self motion, may rely on similar underlying processing mechanisms [c.f. 29]. We did not test the MAMA at 0°, 45°, and 90° in our listeners, so we cannot at this point describe the correlation between the two measures.

3.6 Creating hyper-stable virtual acoustics

Because listeners may perceive signals to move at different velocities at different points in the arc around the head, the equivalent arc ratio could be utilized alongside individualized head related transfer functions and motion tracking to produce head-stabilized acoustic environments that appear to be more stable than the real world. As seen from the scatter in Figure 2, the PSE ratio can vary greatly from listener to listener. As such this must be measured or approximated through other means to match a given listener's spatial distortion. Given the close relationship between the equivalent arc predictions and previously described overestimations of target angle, it may be sufficient simply to have a listener point to a few sound sources with a laser. Regardless of how this is measured, an inverse of Equation 1 that is solved for θ_a would be necessary. This is included here as Equation 2.

Equation 2:

$$\theta_a = \frac{\ln(10) \times \tanh^{-1}\left(\theta_p \tanh\left(\frac{\ln(R\,t - c)}{\ln(10)}\right)\right)}{\ln(R\,t - c)}$$

where the constants and definitions in the formula are the same as in Equation 1.

248   This formula allows one to determine the angles at a signal must be presented to be perceived at a

249   particular azimuth with respect to the head.

3.7 Caveats

251   The range of movement excursions in this study was not sufficient to compare references at 0° and

252   test signals at 90° for all listeners. We did not anticipate the magnitude of the spatial expansion that

253   we observed and so were not able to fully bracket the motion values and measure PSE ratios for all

254   movement pairs. We were able to measure PSE ratios for the inverse of these particular

255   reference/test pairs, but direct comparison between these makes the tacit assumption that the

256   amount of spatial expansion/contraction is a simply a multiple of the reference motion.

257   It should be also noted that Equation 1, while it may be reasonably applicable to perceptual

258   distortion of signal location in the listener's front hemifield they may not accurately reflect any

259   expansion or contraction of auditory space in the *rear* hemifield (and indeed Equation 1 is not

260   constructed to compute the perceived location of angles beyond ±90°). We have no data that speaks

261   to this, so the expansion and contraction in the rear hemifield is depicted in Figure 4 and

262   Supplemental Figure S1 as a mirror reflection of the front, despite there being no reason to believe

263   this is necessarily the case. It remains for future studies to map out spatial distortions for 360°

264   around the head.

265   More generally speaking, since expansion estimates were only measured at three angles, it is unclear

266   whether a hyperbolic tangent expansion or some other function may be the most appropriate

267   mathematical descriptor of the change in equivalent arc ratio over all azimuths. Future work will be

268   required to determine what function best captures the observed phenomena but – provided the

269   function is readily invertible – such a technique could potentially increase the experience of

270   immersion for virtual reality systems.

3.8 Conclusions

Sound sources at the side of a listener must move at least twice as much as ones in front to be

judged as moving the same amount. This expansion of space in the front and compression at the side

that moves with the listener we term the equivalent arc ratio, and likely has real consequences for

spatial perception in dynamic listening situations. The prediction that the apparent location of static

sound sources may also be distorted suggests that this phenomenon is not limited to moving signals.

A mathematical model that mimics the equivalent arc ratio can be used to successfully predict

several previously unexplained phenomena in spatial auditory perception. We further suggest that

the inverse of this function could be utilized alongside individualized head related transfer functions

and motion tracking to produce head-stabilized virtual acoustic environments that appear to be

more stable than the real world.

4 Materials and Methods

4.1 Participants

We recruited 30 normal-hearing listeners, with normal hearing being defined as a four-frequency

average pure tone hearing threshold of less than 20 dB HL. Five listeners were excluded from the

analysis because they did not complete the full set of trials. We collected complete data sets for the

remaining 25 listeners, the result of two separate visits to the lab, with sessions of 60 minutes each.

The average age of the listeners was 27 (±7.3 STD) years, ranging from 22 to 58 years old. We

received written and verbal informed consent from all subjects and the experiment was conducted

in accordance with procedures approved by the West of Scotland Research Ethics Service.

4.2 Stimuli and Presentation

The experiment was conducted in a 4.8 x 3.9 x 2.75 m double walled, sound-attenuated chamber

that had 10 cm acoustic wedge foam lining the walls and ceiling, but not the floor, which was

carpeted. The listeners were seated in this chamber in the center of a 3.5 m diameter circular ring of

24 Tannoy VX-6 loudspeakers (Tannoy, Coatbridge, UK) placed at intervals of 15°. Because a forward

(towards the 0° loudspeaker) offset in listener position could yield an apparent expansion in space,

297   the listener's head was aligned with a spot on the ceiling and the floor. This method, while subject to

298   a few centimeters of error, prevented a misplacement that could explain the results observed (which

299   would require the listener to be at least an order of magnitude closer to the front loudspeaker). The

300   room was dimly lit, but the loudspeakers were visible, and listeners were asked to keep their head

301   still and their eyes open and fixated on the loudspeaker ahead of them at 0°. Signal sources were

302   moved around the ring using vector-based amplitude panning (performed on a sample-by-sample

303   basis in Matlab 2015b (The Mathworks, Natick, MA, USA) using the open source dynamic link library

304   "playrec" (www.playrec.co.uk)). The signals were played out using a MOTU 24 I/O (Mark of the

305   Unicorn, Cambridge, MA, USA) over ART SLA-4 amplifiers (Applied Research & Technology ProAudio,

306   Niagara Falls, NY, USA). The stimuli were unfrozen pink noise signals that were amplitude modulated

307   with a 10 Hz reverse sawtooth waveform at a depth of 50%. These signals provided sufficient high

308   frequency energy to provide robust interaural level differences as well as frequent sharp onset

309   transients to ensure that the signals were easily localizable. All signals were presented at a

310   comfortable listener-determined listening level (this ended up being between 70 and 75 dB SPL).

4.3 Experimental Paradigm

311

312   We measured the point of subjective equality (PSE) for amount of acoustic motion between "test"

313   and "reference" signals. The reference signal always moved 20° in a random direction and the test

FIGURE 5
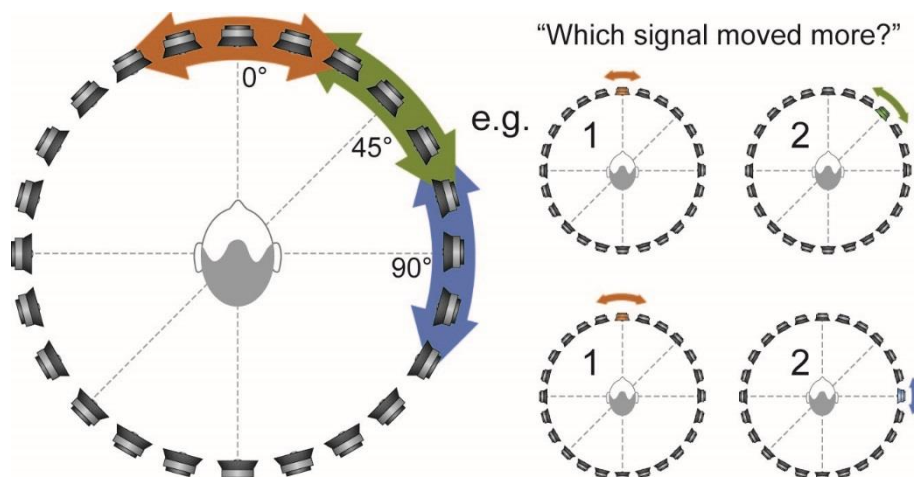
314   signal moved either less, the same, or more (5, 10, 15, 20, 25, 30, or 35°), also in a random direction

315   (see Figure 5). The order of the test and reference signals was also randomized. In a two-alternative

316   forced choice paradigm, listeners were asked to report on a touchscreen whether the first or second

317   signal 'moved more.' If the listeners requested clarification on these instructions, they were told that

318   their task was to report whether the first or second noise moved over a larger distance in space,

319   regardless of its duration or apparent speed. Both the reference and the test signals could be

320   centred at either 0°, 45°, or 90° (See Figure 5) plus or minus a random value drawn from a uniform

321   distribution between -7.5 and 7.5°. The duration of the test and reference signals were individually

322   randomized on every trial to a value between 0.5 and 2 seconds. In this way, we mitigated velocity

323   and duration as potential cues, leaving total angular excursion as the variable that listeners were

324   asked to judge. Listeners were asked to complete a total of 10 blocks of 126 trials, each of which

325   contained 6 repeats of the 21 conditions.

326   The resulting psychometric functions for each listener were individually fitted with a logistic function

327   using Matlab's fminsearch function. The resulting parameters were fed into an inverse logistic

328   equation to compute the test excursion value at which the function crossed the PSE (the reader may

329   roughly infer these values in Figure 1 as the point where the mean fit (dotted line) crosses 0.5 on the

330   y-axis). For logistic fits that did not cross the PSE before 40° (the next larger measurement point

331   step) we fixed the value at 40°. This likely underestimates the true PSE for many listeners, but avoids

332   excessive extrapolation. This value was divided by the reference excursion of 20° to yield a ratio

333   expressing the amount of expansion or contraction of auditory space.

4.4 Statistics

335   All statistics were performed with the Statistics Toolbox in Matlab 2016a. The analysis consisted of a

336   three-way repeated measures ANOVA with the dependent variable being the proportion of 'moved

337   more' responses, and the independent variables being reference angle, test angle, and test

338   excursion. Alpha was set to 0.05.

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Acknowledgements

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416

Figure Legends

417

418   Figure 1. Psychometric functions for motion comparisons and points of subjective similarity (PSE)

419   for motion for moving signals centered at 0°, 45°, and 90°. A) For conditions with a reference signal

420   at 0°, the psychometric function for test signals also at 0° crossed the PSE at 20 degrees (orange line),

421   whereas test signals at 45° and 90° (green and blue, respectively) had to move more to be judged as

422   moving the same amount (rightward shift in the curves). B) Compared to 45° reference signals, 0°

423   test signals had to be moved less (orange) and 90° signals more (blue) to be judged as moving the

424   same amount. C). References of 90° required less motion to be judged the same as both the 0°

425   (orange) or the 45° (green) test signals.

426   Figure 2. Scatter plot of PSE ratios showing an expansion of auditory space. All x values are jittered

427   for visibility. PSE ratio increases as a function of the absolute difference between test and reference

428   angles. The different symbols represent actual angle comparisons, some values for which were

429   inverted from test/reference to reference/test. Triangle symbols represent measurements in which

430   the test signals at maximum excursion were still not judged to be moving by the same amount as the

431   20° reference motion.

432   Figure 3. Predictions of overestimation of source eccentricity as a function of target angle. Data

433   demonstrating that listeners overestimate target angles are displayed from three separate previous

434   studies (colored dot symbols) alongside predictions of angle overestimation from Equation 1 (black

435   line).

436   Figure 4. Illustration of the spatial distortion introduced by the equivalent arc ratio. The

437   dots represent the perceived locations of 32 static signals arranged around the head as it

438   turns to the right. The apparent location of a signal at the front moves leftward, whereas a

439   signal at the right should appear move further to the right. The expansion represented here is

440   exaggerated by a factor of 2 for the purpose of more clearly illustrating the phenomenon.

441   Figure 5. Experimental Paradigm: Listeners were presented with moving reference (20°) and test

442   signals (variable °) at three possible center angles (0°, 45°, and 90°), randomized in order, and asked

443   to report which of the two signals moved more.

444   Supplemental Figure S1. Animation of the spatial distortion introduced by the equivalent arc

445   ratio. The dots represent the perceived locations of 32 static signals arranged around the head

446   as it turns. The angle of the head is represented by the line along the radius of the circle. The

447   expansion represented here is exaggerated by a factor of 2 for the purpose of more clearly

448   illustrating the phenomenon.

SUPPLEMENTAL FIGURE S1