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Angle-Dependent Distortions in the Perceptual Topology of Acoustic Space

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Abstract

By moving sounds around the head and asking listeners to report which ones moved more, it was found that 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. A relative expansion of space in the front and compression at the side has consequences for spatial perception of moving sounds by both static and moving listeners. An accompanying prediction that the apparent location of static sound sources ought to also be distorted agrees with previous work and suggests that this is a general perceptual phenomenon that is not limited to moving signals. A mathematical model that mimics the measured expansion of space can be used to successfully capture several previous findings in spatial auditory perception. The inverse of this function could be used alongside individualized head-related transfer functions and motion tracking to produce hyperstable virtual acoustic environments.

Keywords

spatial hearing, auditory motion, motion perception, spatial representation, coordinate transformation, virtual reality

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Introduction

Despite being among the best mammals at sound localization (Heffner, 1997), human listeners nonetheless make significant errors when asked to identify the direction of arrival of a sound or to make judgments about the movement of a sound source. These errors tend to increase as the sound source is moved away from the acoustic midline (Makous & Middlebrooks, 1990). Critically, however, the errors consist not only of scatter around a central point, but they also include systematic offsets or perceptual biases. These offsets form the basis of a perceptual topology of acoustic space, a term used by Oldfield and Parker (1984). It is known that this topology is warped by a number of factors, including eye position (Lewald & Ehrenstein, 1996) and head-to-trunk angle (Lewald & Ehrenstein, 1998b). One example of a systematic bias is that listeners routinely overestimate the direction of arrival of static signals (Dobreva, O'Neill, & Paige, 2011; Garcia, Jones, Rubin, & Nardini, 2017; Lewald & Ehrenstein, 1998a; Oldfield & Parker, 1984). That is, listeners tend to judge sound sources as being at a greater angle away from their acoustic midline than they truly are.

The study described here examined a potential consequence of this simple distortion of static auditory space: namely that if auditory motion perception is related to a change in apparent angle over time, then the overestimation of target angle with respect to the head would dictate that a sound rotating at a constant angular velocity around the head would not appear to do so but would instead appear to move faster at the front than at the side. Correspondingly, if we assume that the overestimation of target angle is in head-centric coordinate space, then listeners turning their heads at a constant velocity should experience an angle-dependent change in apparent source movement.

An angle-dependent distortion in the perception of stimulus velocity has been observed in the visual system (Campbell & Maffei, 1981; Johnston & Wright, 1983, 1986), but the literature on auditory motion is unclear on this subject: No studies have directly demonstrated a change in apparent sound source velocity or motion excursion as a function of angle relative to

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the head. It has been demonstrated that listeners make systematic errors in sound localization following an active head movement (Genzel, Firzlaff, Wiegrebe, & MacNeilage, 2016) and experience distortions in spatial auditory perception during both slow (Freeman, Culling, Akeroyd, & Brimijoin, 2017) and rapid head movements (Leung, Alais, & Carlile, 2008). Lewald and Ehrenstein (1998b) also described an incomplete coordinate transformation, demonstrating that a person's head-on-trunk angle may affect the direction from which they perceive a sound to emanate. But these are indirect demonstrations; this article tests the hypothesis that sounds should appear to move by different amounts depending on where the motion occurs with respect to the head.

The underlying hypotheses to be tested in this study can be more formally stated as follows: first, that relative extent-of-motion judgments should change as a function of azimuth, and second, that a quantitative description of these extent-of-motion judgments should capture both dynamic phenomena such as inconsistent self-motion subtraction (Freeman et al., 2017; Genzel et al., 2016) as well as static phenomena such as sound source eccentricity overestimation (Dobreva et al., 2011; Garcia et al., 2017; Lewald & Ehrenstein, 1998a; Oldfield & Parker, 1984).

Here, relative perceptual expansion/compression was quantified by measuring the dependence of judgments of relative motion on sound-source angle with respect to the head. The distortion measured is fitted with a simple mathematical function describing an angle-dependent change in apparent sound location. Successful quantitative comparisons are made between the predictions of this proposed mathematical framework and the results of a number of previously published studies. Finally, the perceptual consequences of such a nonlinear representation of space are discussed, as well as a proposal for hyperstable audio that could potentially increase the apparent stability of motion-tracked virtual acoustics.

Materials and Methods

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. Complete data sets were collected for the remaining 25 listeners, the result of two separate visits to the lab, with sessions of 60 min each. The average age of the listeners was 27 years (±7.3 STD) ranging from 22 to 58 years old. Written and verbal informed consent was received from all subjects, and the experiment was conducted in accordance with procedures approved by the West of Scotland Research Ethics Service (reference number 09/S0704/12).

Stimuli and Presentation

The experiment was conducted in a $4.8 \times 3.9 \times 2.75$ 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 (toward the 0° loudspeaker) offset in listener position could result in a geometric distortion in signal angle with respect to the head, the listener's chair was adjusted to ensure that the listener's head was visually aligned with the loudspeakers at 0, 180, and ±90°. This method, while subject to a few centimeters of error, prevented a misplacement that could explain the results observed (which would require the listener to be at least an order of magnitude closer to the front loudspeaker than the few centimeters of potential position error). The room was dimly lit, but the loudspeakers were visible, and listeners were trained to keep their head still and their eyes open and fixated on the loudspeaker ahead of them at 0°. No eye tracking was performed to verify fixation, but subjects were trained and asked to report afterward how consistently they fixated the front loudspeaker. Signal sources were moved around the ring using vector-based amplitude panning (sine interpolation) performed on a sample-by-sample basis in MATLAB 2015b (The Mathworks, Natick, MA, USA) and sent to a sound card via the open source dynamic link library playrec [www.playrec.co.uk]). The signals were played out using a MOTU 24 I/O (Mark of the Unicorn, Cambridge, MA, USA) over ART SLA-4 amplifiers (Applied Research & Technology ProAudio, Niagara Falls, NY, USA). The stimuli were unfrozen pink noise signals that were amplitude modulated with a 10-Hz sawtooth waveform at a depth of 50%. The sawtooth was reversed such that the signal level incremented rapidly and then tapered off slowly. These signals provided sufficient high-frequency energy to provide robust interaural level differences as well as frequent sharp onset transients to ensure that the signals were easily localizable. All signals were presented at a comfortable listener-determined listening level (this ended up being between sound pressure level of 70 and 75 dB).

Experimental Paradigm

We measured the point of subjective equality (PSE) for amount of acoustic motion between test and reference signals. Both the reference and the test signals could

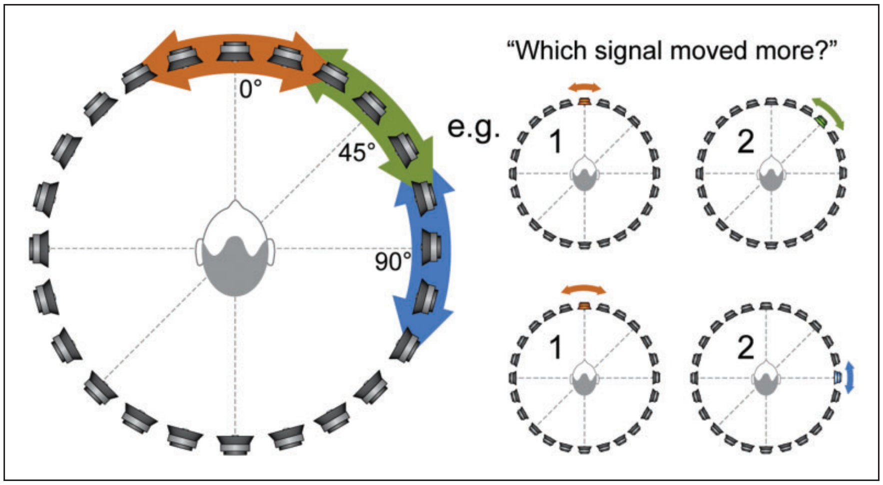

Figure 1. Experimental paradigm: Listeners were presented with moving reference (20°) and test signals (variable °) at three possible center angles (0°, 45°, and 90°), randomized in order, and asked to report which of the two signals moved more.

be centered at 0°, 45°, or 90° (see Figure 1) plus or minus a random value drawn from a uniform distribution between −7.5 and 7.5°. The reference signal always moved 20° in a random direction, and the test signal moved less, the same, or more (5, 10, 15, 20, 25, 30, or 35°), also in a random direction (see Figure 1). The order of the test and reference signals was also randomized. In a two-alternative forced choice paradigm, listeners were asked to report on a touch screen whether the first or second signal moved more. If the listeners requested clarification on these instructions, they were told that their task was to report whether the first or second noise moved over a larger distance in space, regardless of its duration or apparent speed. As auditory duration is a highly salient cue for listeners (stronger even than visual duration; Ortega, Guzman-Martinez, Grabowecky, & Suzuki, 2014), the durations of the test and reference signals were individually randomized on every trial to a value between 0.5 and 2 s. In this way, velocity and duration were mitigated as potential cues, leaving total angular excursion as the variable that listeners were asked to judge. Listeners were asked to complete 10 blocks of 126 trials, each of which contained 6 repeats of the 21 conditions (7 excursions × 3 center locations).

The resulting psychometric functions for each listener were individually fitted with a logistic function using MATLAB's fminsearch function. The resulting parameters were fed into an inverse logistic equation to compute the test excursion value at which the function crossed the PSE. The reader may roughly infer these values in Figure 2 as the point where the mean fit (dotted line) crosses 0.5 on the y axis. For logistic fits that did not cross the PSE before 40° (the next larger measurement point step), the value was fixed at 40°. This likely underestimates the true PSE for many listeners but avoids excessive extrapolation. The PSE was divided by the reference excursion of 20° to yield a ratio expressing the relative amount of expansion or contraction of auditory space.

Statistics

All statistics were performed with the Statistics Toolbox in MATLAB 2016a. The analyses consisted of a measurement of Pearson correlation coefficients as well as a three-way repeated measures analysis of variance with the dependent variable being the proportion of moved more responses (being less of a derivative measure than the PSE ratio) and the independent variables being reference angle, test angle, and test excursion. Alpha for all tests was set to .05.

Results

Relative Motion Judgments

Listeners were asked to make a judgment about which of two signals, a reference and a test signal, moved more. The reference always moved 20°, and the test moved less, the same, or more. Both the test and reference signals could be centered at 0°, 45°, or 90°, and movement direction and the order of presentation and condition were fully randomized. Across all conditions, it was found that the center azimuth of both test and reference signals strongly affected subjects' comparison of relative extents of motion, as expressed by a change in response as a function of test excursion (see Figure 2).

We found main effects of test excursion, test azimuth, and reference azimuth, $F(1, 6) = 338.11$, $p < .05$, $F(1, 2) = 71.34$, $p < .05$, and $F(1, 2) = 97.74$, $p < .05$,

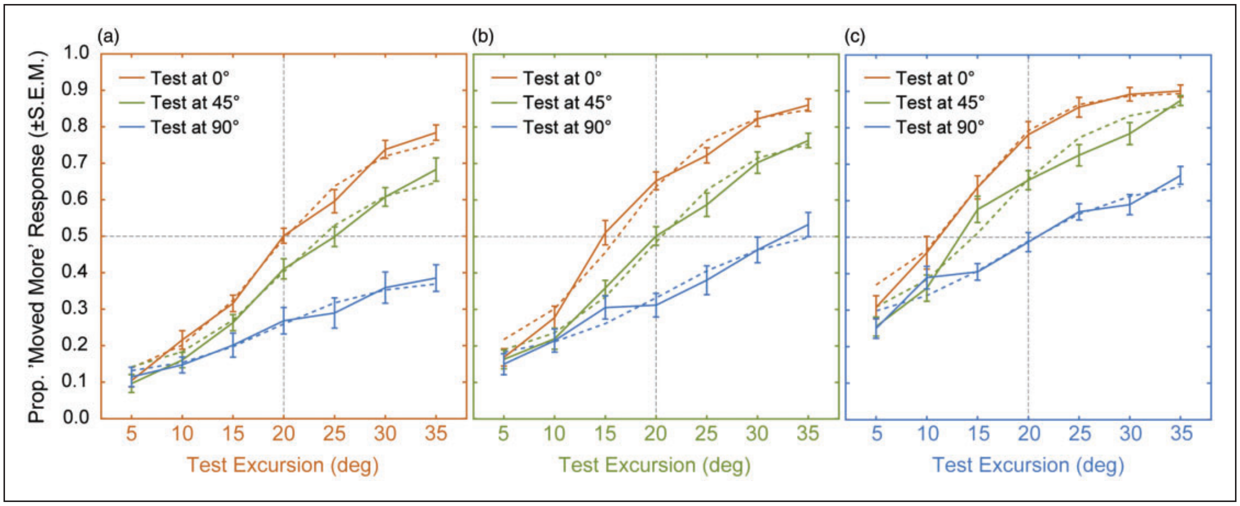

Figure 2. Psychometric functions for motion comparisons and points of subjective equality (PSEs) for motion for moving signals centered at 0°, 45°, and 90°. (a) For conditions with a reference signal at 0°, the psychometric function for test signals also at 0° crossed the PSE at 20° (orange line), whereas test signals at 45° and 90° (green and blue, respectively) had to move more to be judged as moving the same amount (rightward shift in the curves). (b) Compared with 45° reference signals, 0° test signals had to be moved less (orange) and 90° signals more (blue) to be judged as moving the same amount. (c). References of 90° required less motion to be judged the same as both the 0° (orange) and the 45° (green) test signals.

respectively; an interaction between reference azimuth and test excursion, $F(2, 12) = 3.99$, $p < .05$; an interaction between test azimuth and test excursion, $F(2, 12) = 34.24$, $p < .05$; and a three-way interaction between reference azimuth, test azimuth, and test excursion, $F(2, 24) = 1.92$, $p < .05$. The only insignificant comparison in the test was found in the interaction between test and reference azimuths, $F(2, 4) = 0.76$, $p = .55$.

Figure 2(a) illustrates how test angle influenced the PSE for reference signals centered at 0°. Test signals centered at 0° were judged to move the same amount as the 20° reference motion when the test signals also moved by 20° (orange line). Thus, the PSE ratio for this condition was roughly 20/20 = 1. The smooth psychometric function confirms that listeners were capable of making judgments of relative motion, which is also reflected in the significant main effect of test excursion. On the other hand, test signals centered at 45° (green line) had to move by about 25° to be judged as moving the same amount as the 20° movement of the reference signal at the front. The range of movement angles used was not sufficient to estimate how much a 90° test signal (blue line) had to be moved to reach the PSE with a reference at 0°, but the required excursion was likely much greater than 35°. In Figure 2(b), it can be seen that when compared with reference signals at 45°, test signals at 0° had to be moved significantly less to be perceived as moving the same amount, and test signals at 90° had to be moved significantly more. Finally, the reference signals at 90° (Figure 2(c)) showed a pattern of expansion/compression relative to test signals at 0° that was the same (albeit inverted) as can be seen in Figure 2(a): Test signals at 0° had to move roughly half as much to be judged as equivalent to the reference motion at 90°.

Points of Subjective Equality for Motion

PSE ratios were drawn from the individual logistic fits to the data for each listener (the *mean* of said fits are plotted with dotted lines in Figure 2). The point at which the logistic fit crossed 0.5 probability was taken for each condition for each listener and divided by 20. PSE ratios were also computed for flipped pairs (i.e., the test/reference ratio of 0/90 is included alongside the inverse of the test/reference ratio of 90/0). A scatter plot of these PSE ratios, plotted as a function of the absolute difference between the test and reference angles, is shown in Figure 3. The use of comparison in the legend is due to the mix of normal and inverted pairs (where reference and test are used interchangeably). When the azimuths of the test and reference motions were identical, the PSE ratios were clustered around 1, albeit with a large degree of intersubject variability. PSE ratios for a difference of 45° were on average larger than 1, and ratios for a 90° difference were still larger, reaching a mean value of 1.8. It should be noted that the triangle symbols in the plot represent measurements in which the test signals at maximum excursion were still not judged to be moving by the same amount as the 20° reference motion. The true values for these data points cannot be reliably estimated as the psychometric functions in question did not cross the PSE, but examining the individual data and logistic

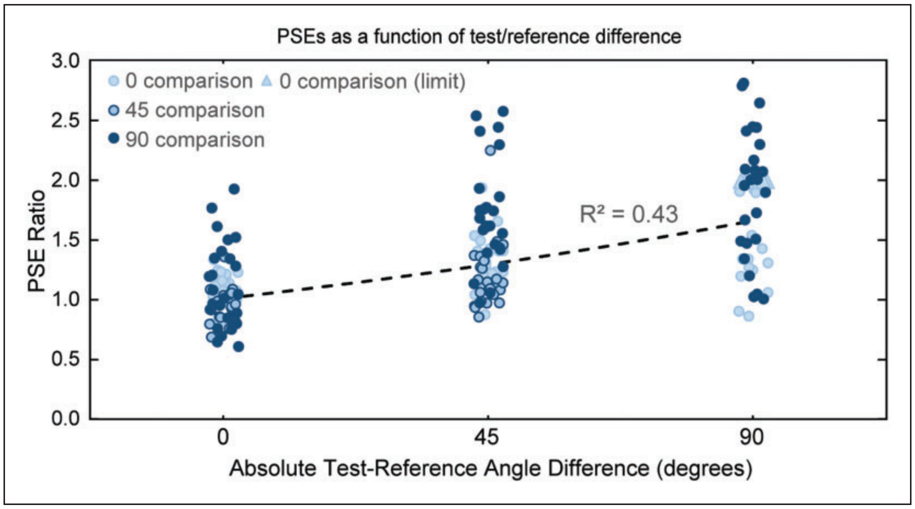

Figure 3. Scatter plot of PSE ratios showing an expansion of auditory space. All x values are jittered for visibility. PSE ratio increases as a function of the absolute difference between test and reference angles. The different symbols represent actual angle comparisons, some values for which were inverted from test/reference to reference/test. Triangle symbols represent measurements in which the test signals at maximum excursion were still not judged to be moving by the same amount as the 20° reference motion.
PSE = point of subjective equality.

fits makes it clear that the values are likely to be substantially larger than 2. It should be noted that there are unequal numbers of comparisons in each data cluster, with three combinations of angles giving 0° of difference, four giving 45, and two giving 90. The correlation for a linear fit between the PSE ratio and the difference in test/reference angle yields an R^2 of .43.

Discussion

The Nonuniformity of Acoustic Motion

Across all conditions, there was evidence that the relative azimuth of two signals strongly affects their point of subjective similarity for motion. Roughly speaking, 20° of motion at the front of the listeners is treated equivalently to 40° of motion at the sides. This difference in PSE ratio over azimuth suggests a relative perceptual expansion of space at the front and a contraction at the sides. Precisely, such an expansion has been repeatedly described in the visual system, typically referred to as the cortical magnification factor (Johnston & Wright, 1983), but has not been described for auditory motion. On one level, the auditory PSE ratio described in this study could be interpreted as a simple relationship between acuity and perception, but this belies two perceptual consequences. One consequence is that a sound rotating at a constant angular velocity around the head would appear to accelerate as it approaches the front of the listener and decelerate toward the side. The second consequence is that—from the perspective of a moving listener—the acoustic world should not appear perfectly stable as the head turns. Instead, signals at the front should appear to counter-rotate as the listener turns (see Freeman et al., 2017), and signals at the side should seem to be slightly dragged along with the listener's rotation.

Distortion in Acoustic Location

There are two possibilities for reconciling the observed change in perceived motion as a function of angle with our current understanding of sound localization. The first requires a disassociation between movement and location; in this case, if we integrate changes in position over time, then the apparent location of a signal at the end point of a movement would have to be different from its apparent position(s) during the movement. There is evidence in the visual system of just such disassociation (Kwon, Tadin, & Knill, 2015; Smeets & Brenner, 1995). It is conceivable that a similar process occurs in the auditory system, but the disassociation in the visual system is thought to arise from specialized motion-sensitive neurons in the middle temporal visual and medial superior temporal areas (Whitney & Cavanagh, 2000), brain regions known for motion selectivity (Tanaka & Saito, 1989; Tootell et al., 1995). Motion-specific auditory processing has been observed in posterior auditory cortex (Poirier et al., 2017); however, there remains little physiological evidence for auditory neurons that exhibit motion selectivity while being agnostic to spatial location.

If we assume, on the other hand, that auditory motion and spatial location are intrinsically linked with each other, then the second possibility is that both the motion and the perceptual location of static sound sources would be subtly distorted as a function of head angle. Such an interpretation prevents any jump in perceived location after a movement (as would be found earlier) but requires that listeners mislocalize sound sources. Here, I include a mathematical function that captures this mislocalization, quantifying the relationship between physical (Θ_a) and perceived azimuth (Θ_p). The function and its constants were based on the results of the current motion study and chosen so that its slope at 0° and its slope at 90° (i.e., the change—or movement—across angles) were related to each other in the same manner as the motion PSE ratio between these two angles. A hyperbolic tangent (Equation 1) was used because it is readily invertible, although one could in principle also use a sine expansion, or some other mathematical construct.

$$\theta_p = \frac{90 \times \tanh(\theta_a \log(Rt - c)/90)}{\tanh(\log(Rt - c))} \tag{1}$$

where all angles are degrees, tanh is computed for radians, log is the common (base 10) logarithm, t is a constant equal to 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 position of a signal, and Θ_p is the perceived position of that signal. Note that this function does not apply to angles with absolute values greater than 90. The constants t and c were empirically derived (using MATLAB's fminsearch function) to ensure that the ratio between its slope over 20° (the amount of reference motion) at 0° and at 90° was closest to the ratio R between the PSE at 0° and at 90°. No constants exist that would permit this relationship for very large values of R, so the values were optimized to work well over a reasonable range of values of R (between 0.5 and 4.0).

For Θ_a angles larger than 0 and less than 90, the values of Θ_p generated by Equation 1 imply that static acoustic targets would be perceived at larger eccentricities than they truly are. Precisely, such a phenomenon has been repeatedly demonstrated in the literature, as listeners have been shown to regularly overestimate the angle of sound sources (Oldfield & Parker, 1984), particularly when fixating at the front and using a laser pointer to indicate direction. Equation 1 provides a reasonable fit to the overestimation of source angle measured in at least four laser-pointer studies (Dobreva et al., 2011; Garcia et al., 2017; Lewald & Ehrenstein, 1998a; Oldfield & Parker, 1984). The data from these studies are plotted in Figure 4 alongside predictions from the model. The predictions are plotted as the difference between perceived and actual locations ($\Theta_p - \Theta_a$), and these values fall well within the range of the data from the four studies. Physiological data on this subject are somewhat limited, but predictions of a neural network trained on spike data from cat primary auditory cortex also show a characteristic overestimation of target position that roughly follows the predicted pattern (Middlebrooks, Xu, Eddins, & Green, 1998). Single unit and ensemble data from Furukawa, Xu, and Middlebrooks (2000) also show the same overestimation of target position. The magnitude of the overestimation in both physiological studies, however, is far larger than has been observed behaviorally or predicted by the current mathematical framework. It should be noted that some or all the azimuth overestimation observed in these two studies could have been a consequence of training limited degree-of-freedom neural networks to minimize

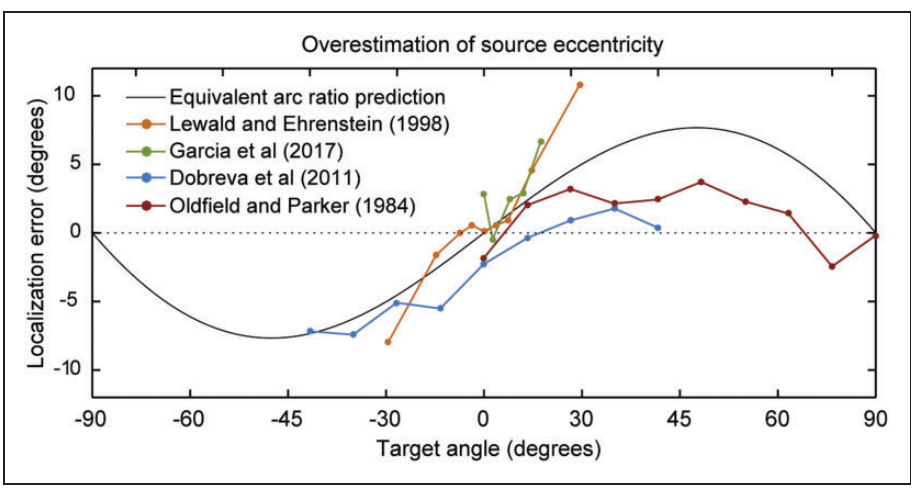

Figure 4. Predictions of overestimation of source eccentricity as a function of target angle. Data demonstrating that listeners overestimate target angles are displayed from three separate previous studies (colored dot symbols) alongside predictions of angle overestimation from Equation 1 (black line).

prediction error over 360° of true azimuthal space, rather than an actual cortical overestimation of target angle. Whether or not the physiological data show strong evidence of overestimation, the behavioral data are clear and are captured well by Equation 1. Notably, this function was fitted to data describing how sounds appear to move, not the angle from which they appear to emanate, so the success of its quantitative predictions of the perceptual location of static signals suggests a processing framework that may be common to the perception of both acoustic motion and direction of arrival.

Distortion in Acoustic Motion

The overestimation of static signal angle is specified relative to the head, so when Equation 1 is used to examine *motion* (by examining the differences in the distortion between Θ_a and Θ_p at different head and source angles), it becomes clear that this distortion must move with the head when the head turns. The consequence of this is that signals appear to move in different ways depending on their subtended angle with respect to the head during a turn. Head and eye position has been shown to clearly influence the apparent world-centric spatial location of auditory signals (Lewald, 1998; Lewald & Ehrenstein, 1996; Razavi, O'Neill, & Paige, 2007); here, Figure 5 displays the way in which the apparent source angle of static sound sources (two specific ones shown here are a bird and a television) should shift as the listener turns to the right. Because the locations of both static sources are pushed away from the nose, in world-centric coordinates, a signal at 0° should shift to the left and a signal at 90° should shift to the right. Supporting Figure S1 is an animation of this phenomenon depicting the perceived locations of 32 evenly spaced static signals arranged around the head as it turns. The angle of the listener's nose is depicted as a line along the radius of the circle. The expansion/contraction in Figure 5 and in the animation is exaggerated by a factor of 2 for clarity.

There are established phenomena demonstrating perceptual distortions of auditory space that depend on some interaction between stimulus angle and head angle. Genzel et al. (2016) demonstrated that, after an active head movement, a second sound source had to be shifted in azimuth to be perceived as being at the same azimuth as a sound before the movement. This could be the result of an incomplete updating of position (which is how the authors account for it), but it could also be explainable as a distortion in the perceived location of a static midline signal. Using Equation 1 (with a 90°/0° PSE ratio of the mean 1.82), a 35.3° active rightward movement (the average reported in the study) should result in a 0° signal appearing to be at −6.4° (the apparent head angle of a target at −35.3 would be −41.7), which is not only sign-correct, it is also reasonably close to the value of −5.5° from Genzel et al. (2016). Other systematic errors in movement compensation have also been documented. For example, Freeman et al. (2017) demonstrated that signals at the front of the listener must be moved with the head with a gain of +0.17 to be judged as being static. Here, gain refers to amount

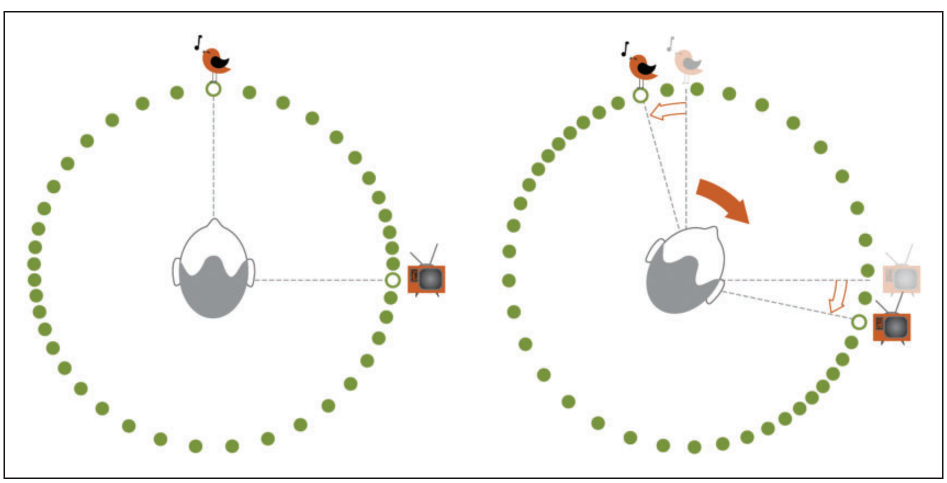

Figure 5. Illustration of the spatial distortion introduced by the PSE ratio. The dots represent the perceived locations of 32 evenly spaced static signals arranged around the head as it turns to the right. The apparent location of a signal at the front moves leftward, whereas a signal at the right should appear to move further to the right. The expansion represented here is exaggerated by a factor of 2 for the purpose of more clearly illustrating the phenomenon.
PSE = point of subjective equality.

of motion with respect to the head, so if a listener turns 10° to the right, signals that move by +1.7° to the right would be most consistently judged to be static. The corresponding value predicted by Equation 1 is +2.2°, which is at least sign-correct if not a perfect match.

Physiological data on the relationship between self-motion and spatial receptive fields are virtually nonexistent, making comparisons with animal work problematic. Eye position has been shown to modulate responses in the inferior colliculus (Groh, Trause, Underhill, Clark, & Inati, 2001) and auditory cortex (Werner-Reiss, Kelly, Trause, Underhill, & Groh, 2003) and to actively shift spatial receptive fields in superior colliculus (Jay & Sparks, 1984), but little work has been done on head movements. Very recently, however, experiments in ferret primary auditory cortex have revealed a subpopulation of neurons whose spatial receptive fields appear to be specified in world-centric coordinates, rotated in opposition to the animal's movement (Town, Brimijoin, & Bizley, 2017). This finding represents a neural correlate of our percept of a stable acoustic world. It is not currently possible, however, to determine whether the shifts in receptive field boundaries as a function of eccentricity match that predicted by the PSE ratio because the width and contralateral offset of cortical spatial receptive fields make it difficult to assign individual neurons to exact azimuths in space.

Returning to psychophysics work, results from the Freeman et al. (2017) study are roughly in line with what Equation 1 would predict, with one notable exception. According to the model, the gain at which signals must be moved to be judged as static should change as a function of azimuth, reducing to 0 when 45° is reached (where the slope of Equation 1 is 1), and even changing to a counter-rotation for larger eccentricities. The Freeman et al. study did not find this, although they did find a decrease in gain and a substantial increase in variance as a function of stimulus angle. It should be noted that these authors' own Bayesian explanation for the nonunity gain *also* predicts a change in gain as a function of azimuth. But the subjects in that study were blindfolded, so the discrepancy may point to an as-yet unresolved role of eye position in this and related phenomena. The previously mentioned dependence of neural and behavioral responses on eye position certainly attests to this possibility. A related phenomenon was previously described by Lewald and Ehrenstein (1998b): The subjective auditory midline (as measured using interaural level difference) rotates toward 0° in trunk-centric space as a listener turns to more eccentric head angles. This displacement was argued as being the result of an incomplete coordinate transformation, a failure of listeners to fully compensate for their own movement. Taken together with the results from Freeman et al. (2017), this suggests that both eye-in-head and head-to-trunk angle may represent unresolved factors that result in a shift in target location into a different region of expansion/contraction of acoustic space.

Studies examining representational momentum have argued that the faster a signal is rotating around the head, the further the perceived end point will be displaced in space (e.g., Carlile & Best, 2002; Getzmann, Lewald, & Guski, 2004). This is argued to be a consequence of a mental extrapolation of the signal's trajectory (Getzmann & Lewald, 2007). According to the expansion model, signals moving toward the midline would appear to accelerate, suggesting their end points could seem more displaced than those of signals receding from the midline. The apparent magnitude of this acceleration could be reduced by the inherent overestimation of target angle (the perceptual displacement away from the midline of the end point of the motion could potentially counteract a change in apparent velocity). The outcome of such a study could speak to the snapshot versus smooth motion processing debate, so it may be worth reexamining these data sets in light of the current results. An advantage in direction discrimination has been demonstrated for signals approaching the median plane (Hirnstein, Hausmann, & Lewald, 2007), congruent with the expansion model, but in the case of the first representational motion study (Carlile & Best, 2002), all the motion trajectories used were across the midline. The analysis in the second study (Getzmann et al., 2004)—while it did examine left versus right movements—collapsed the data across different center azimuths, an averaging method that would prevent us from observing any asymmetry predicted by the expansion model.

The Relationship Between the PSE Ratio and Spatial Acuity

The binaural cues of interaural time difference and interaural level difference both arise from the physical structure of the head, and both change more rapidly at the front of a listener than at the sides (Blauert, 1983; Howard & Angus, 2009; Kuhn, 1977). Arguably, as a consequence, listeners have increased spatial resolution near the sagittal plane (Mills, 1958): The threshold measurements of both minimum audible angle (MAA) and minimum audible movement angle (MAMA) are known to increase as a function of source azimuth (Perrott & Saberi, 1990; Strybel, Manllgas, & Perrott, 1992). Considering the current results, one might conjecture that the MAA and the MAMA are not simply threshold measurements of acuity, but they also represent basic perceptual units upon which our suprathreshold organization of acoustic space is based, and while they get larger as a function of angle, these units are nonetheless treated equivalently across azimuth. In other words, the one-to-two-degree MAMA at the front of the listener is perceived as being the same amount of motion as the roughly four-degree MAMA at the sides. Similarly, the roughly one-degree MAA at the front is treated as the same separation as larger MAA values to the side. At suprathreshold amounts of separation or motion, we could potentially expect similar equivalence between, for example, 20° of arc at the front and 40° of arc at the side.

The PSE ratio expansion observed does appear to be related to the change in MAMA as a function of angle. But if the PSE ratios were simply the result of the change in MAMA as a function of angle, then one might expect slightly larger PSE ratios between 0° and 90° than was observed. Because self- and source motion may be processed by similar underlying central auditory mechanisms, the two measurements could be linked with each other on some level (cf. Brimijoin & Akeroyd, 2014), but this remains for future exploration. The MAMA was not tested at 0°, 45°, and 90° in our listeners, so it is not possible at this point describe any correlation between the two measures.

Creating More Stable Virtual Acoustics

Because listeners may perceive signals to move at different velocities at different points in the arc around the head due either to source or head motion, the PSE ratio could be used 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 3, 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 PSE 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.

$$\theta_a = \frac{90 \times \ln(10) \times \tanh^{-1}\left(\theta_p \tanh\left(\frac{\ln(Rt-c)}{\ln(10)}\right)/90\right)}{\ln(Rt-c)} \tag{2}$$

where the constants and definitions in the formula are the same as in Equation 1, but ln is the natural logarithm.

This formula allows one to determine the actual angle, Θ_a, at which a signal must be presented to be perceived at a particular azimuth with respect to the head, Θ_p. Use of this correction in motion-tracked virtual acoustics could result in sounds being perceived as being more stable. Informal listening tests have demonstrated that without applying this perceptual correction, virtual sources rendered with KEMAR binaural impulse responses can exhibit apparent instability (moving too much relative to the head), especially near 0°, so this technique may have immediate applications in virtual acoustics.

Caveats

The range of movement excursions in this study was not sufficient to compare references at 0° and test signals at 90° for all listeners. The magnitude of the spatial expansion that was observed was unexpected, and so the experiment did not fully bracket the motion values and measure PSE ratios for all movement pairs. The PSE ratios for the inverse of these particular reference/test pairs were similar to one another, but not identical (see, e.g., the outlined vs. solid circles at the 45° comparison in Figure 3). This suggests that the PSE ratio may change as a function of the absolute magnitude of the reference motion, which makes direct comparison between these different ratios someone problematic, because the described framework makes the tacit assumption that the amount of spatial expansion/contraction is a simply a multiple of the reference motion. The current data cannot address this, as only one reference excursion was used, so further work will be needed to examine the source of this discrepancy.

It should be also noted that Equation 1, while it may be reasonably applicable to perceptual distortion of signal location in the listener's front hemifield, they may not accurately reflect any expansion or contraction of auditory space in the *rear* hemifield (and indeed Equation 1 is not constructed to compute the perceived location of angles beyond ±90°). We have no data that speak to this, so the expansion and contraction in the rear hemifield is depicted in Figure 5 and Supporting Figure S1 as a mirror reflection of the front. If the phenomenon being measuring here is in fact related to the MAA, this may be a reasonable starting assumption, as the MAA in the rear hemifield is roughly similar to matching angles in the front (Saberi, Dostal, Sadralodabai, & Perrot, 1991). Data from Oldfield and Parker (1984), however, suggest that overestimation of target angle in the rear hemifield is more pronounced than in the front hemifield. These conflicting results suggest that future studies are necessary if we are to accurately map the perceptual spatial topology around the head.

More generally speaking, because expansion estimates were measured only at three angles, it is unclear whether a hyperbolic tangent expansion or some other function may be the most appropriate mathematical descriptor of the change in PSE ratio over all azimuths. Future work will be required to determine what function best captures the observed phenomena but—provided the function is readily invertible—such a technique could potentially increase the experience of immersion for virtual reality systems.

The room in which the study was performed was not an anechoic chamber but used 10-cm wedge foam on the walls and the ceiling. This resulted in a low reverberation time for high-frequency signals, but some reflections at low frequency. This combined with our method of using vector-based amplitude panning over 15° loudspeaker intervals could potentially result in some mislocalization of our virtual sources. In the case of the panning technique, however, any small mislocalizations would likely be toward the front of the listener (Pulkki, 2002), resulting in an *underestimation* of the reported effects, rather than being the cause of what was observed.

Conclusions

We examined whether judgments of relative amounts of acoustic motion depend on signal center angle and found that the head-centric azimuth of two signals strongly affects their point of subjective similarity for motion. Signal motion centered at 90° had to be roughly twice as large as motion centered at 0° to be judged as equivalent. This distortion of acoustic space around the listener suggests that the perceived velocity of moving sound sources changes as a function of azimuth around the head. A mathematical function based on these results was used to successfully provide quantitative explanations for previously described phenomena in spatial localization, motion perception, and head-to-world coordinate transformations. An inverse of this function could potentially increase the apparent stability of motion-tracked virtual acoustics.

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Supplemental Material

Supplementary material for this article is available online.

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