

Diffraction around the head makes hearers mislocate sound sources

When light is obstructed by a small sphere, diffraction creates a bright spot at the center of the sphere's shadow. Psychoacousticians are studying the acoustic analogue of that bright spot.

For acoustic frequencies below 500 Hz, the wavelength of sound is more than four times the diameter of a human head. Therefore, at such low frequencies, diffraction of sound waves around the head renders the difference between sound levels in the hearer's two ears too small to be of use in localizing the source. Happily, however, the brain's extraordinary binaural timing acuity can discern interaural phase differences at 500 Hz corresponding to time differences of 10 μ s, and thus can localize a source near the forward direction to within a few degrees. (See the article by William Hartmann in *PHYSICS TODAY*, November 1999, page 24.)

At about 1 kHz, where binaural phase ambiguities can reverse the apparent direction of a source, interaural timing localization shuts down rather abruptly. "Nature seems to think it safer to have no timing cue at all," says Hartmann, "than to have one that points in the opposite direction." At frequencies well above 4 kHz, where diffraction becomes negligible and the head casts a proper sound shadow, the interaural level difference (ILD) provides reliable source localization.

In a new paper, Hartmann and Michigan State University colleagues Eric Macaulay and Brad Rakerd address what they call the twilight zone above 1 kHz, where phase information is gone, ILDs are already large, but a residual diffractive effect can render level differences strikingly misleading.¹ The deceptive diffractive effect is called the acoustical bright spot, by analogy to the Fresnel bright spot of optical diffraction: The optical bright spot appears at the center of the shadow cast by an opaque sphere whose size is comparable to the wavelength of the illuminating light. The effect is related to the forward diffraction peak in the differential cross section for high-energy protons scattering elastically off each other. And in acoustics, it manifests itself as an enhancement at the shaded ear relative to the overall acoustic shadow cast by the head when a sound wave is beamed directly at the other ear.

The twilight zone

For a range of frequencies of pure tones from a source in the horizontal plane, figure 1 plots the ILDs calculated from

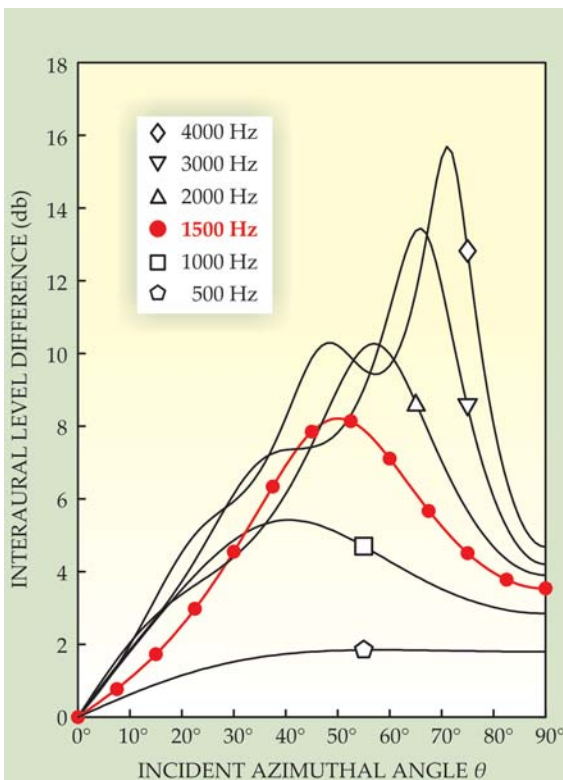


Figure 1. Interaural level difference is a logarithmic measure of the ratio of sound intensities from a single source at the hearer's two ears. Calculated from a model of sound-wave diffraction around a spherical head, ILD is plotted, for various pure-tone frequencies, against the angle θ between the source direction in the horizontal plane and the direction in which the hearer faces. At frequencies well above 4 kHz, where diffraction becomes negligible, the ILD grows almost monotonically with θ and yields reliable source location. But all the curves shown here exhibit non-monotonic effects of diffraction that can mislead the hearer. The 1500-Hz curve is particularly attractive for psychoacoustic tests of diffractive deception because its single prominent peak almost bisects the angular quadrant. (Adapted from ref. 1.)

a diffractive model against the source direction θ relative to the orientation of the listener's head (see figure 2a). The model assumes a nonabsorbing spherical head with antipodal ears. The team carried out the calculations using a formalism developed in the 1970s by theorist and hearing-aid designer George Kuhn, who gave the acoustical bright spot its name. But not until now have its psychoacoustic consequences been systematically investigated.

At frequencies far above those in figure 1, the ILD becomes a good direction indicator because it increases almost monotonically as θ varies from 0° to 90° and the ear farther from the source sinks deeper into the head's acoustic shadow. But at the frequencies shown in the figure, the angular dependence is by no means monotonic. After it peaks at some intermediate angle, the calculated ILD falls as θ approaches 90°, indicating a brightening at the center of the shadow. Now at least two different directions in the azimuthal quadrant produce the same ILD, which would

seem to create a quandary for someone seeking the sound's source.

Coping with ambiguity

To investigate how real listeners cope with that quandary, the Michigan State team chose to test its subjects with tones at 1500 Hz, where a single prominent peak poses a clean ambiguity by almost bisecting the quadrant. Although a continuous pure tone provides no binaural phase-difference information at that frequency, the abrupt onset or end of a tone could give timing cues. To avoid such cues, the experimenters shaped the test tones to start and stop gradually.

Figure 2a shows the experimental arrangement. In an anechoic room, the subject sat facing the first of 13 identical speakers arrayed in an arc of 1-meter radius from in front of him to directly opposite his right ear. (All five test subjects were adult men younger than 57, with normal hearing.) One-second-long 1500-Hz tones were presented repeatedly in random speaker order. During

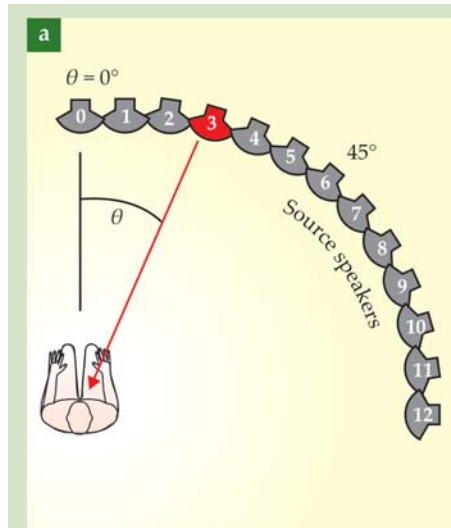
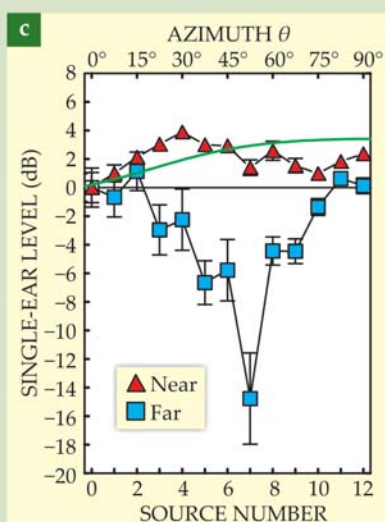
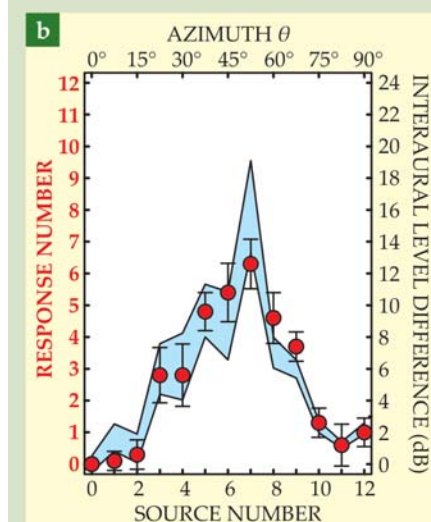


Figure 2. Psychoacoustic tests at Michigan State University. **(a)** Experimental arrangement, in which the subject is seated facing the first of 13 identical and equidistant speakers arrayed in a 90° arc. **(b)** Results for one typical test subject, averaged over multiple trials. Measured interaural level differences (blue band, right axis) and attempts to identify the source speaker (red dots, left axis) are plotted against true source location. **(c)** Separate sound levels measured in the same subject's near and far ears (relative to the level at $\theta = 0^\circ$). The green curve is the near-ear level calculated from the spherical-head model that yielded the level-difference predictions in figure 1. (Adapted from ref. 1.)



each tone, tiny, unobtrusive micro-phones in the subject's left and right ear canals measured the actual ILD. And that measurement was later correlated with his guess as to which speaker the tone had come from.

The close correlation between the guesses of a typical test subject and the ILDs actually measured in his ears is evident in figure 2b. Like all the other subjects, and indeed like an anatomically realistic manikin used by the team, this subject's ILDs peaked somewhat higher than those calculated for the oversimplified spherical-head model. But wherever the ILD posed an ambiguity between a small angle and a large one, this subject and his fellows overwhelmingly guessed the smaller angle, thus getting it seriously wrong almost half the time. "That's probably because the brain's auditory location system is trained with visual inputs," explains Hartmann. "And there's not much visual feedback in the peripheral field near 90°."

Might a bit of training and feedback help the test subjects? To find out, the team ran a second experiment in which the subjects were informed that before each randomized test sequence they would hear the tones in ascending angular order. And then after each guess during actual tests, one of two lights was promptly flashed to indicate whether the source had in fact been forward or sideward of 45°. Then the tests were repeated with new random sequences. "The training and feedback helped some subjects a bit," says Hartmann, "but none very much."

More auditory information

The ILD, given in decibels, is a logarithmic measure of the acoustical intensity in the near ear divided by the far-ear intensity. But that quotient is not the only information conceivably available to the hearer. Might not the separate, absolute levels in the two ears help resolve the ambiguity engendered by the bright

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spot at the far ear? One would think so, if the near-ear level is a strongly monotonic function of direction—and the hearer has already acquired some sense of the absolute loudness of the tones from the experiment's repeated trials.

The measured far- and near-ear levels are shown in figure 2c for the same listener as in 2b. Clearly, the shape of his ILD curve is determined mostly by his far-ear levels. The θ dependence of his near-ear level is weak and erratic. So it could do little to resolve the angular ambiguity in the far-ear levels.

The green curve in figure 2c shows the near-ear levels predicted by the spherical-head model. That calculated angular dependence is indeed monotonic, but it rises only a meager 3 dB from 0° to 90° . By contrast, two of the five subjects had strong monotonic near-ear rises of about 10 dB, and they consistently had the best test scores. But

like the others, they fell afoul of the ILD ambiguity more often than not, even when the separate single-ear levels could, in principle, have resolved it.

Finally, the team investigated the effects of timing cues added to the test tones. In one experiment, they imposed a 100-Hz amplitude modulation on the pure 1500-Hz tones. And in another experiment, they replaced the pure tones by spiky narrow-band noise centered on 1500 Hz. In both experiments, almost all the subjects did very well. With resolvable and unambiguous interaural timing differences now at their disposal, they seem to have largely ignored the misleading ILDs.

Interestingly, the one striking exception was one of the two subjects with the strongest near-ear monotonic level rises and the best scores in the earlier experiments. He gained nothing from the timing cues and continued to be

misled by the ILDs. It's as if his acoustic-level perception thought itself too good to be ignored, even in the presence of more reliable timing information.

That last result supports the idea, first suggested by experiments in the 1970s, that when conflicting localization cues arrive at a central processor in the nervous system, different hearers will weight them quite differently. "This idiosyncratic unconscious weighting is not necessarily hard-wired in early childhood," says Hartmann. "But failed attempts at retraining in those old experiments, as in our own, indicate that such things are very resistant to change."

Bertram Schwarzschild

Reference

1. E. J. Macaulay, W. M. Hartmann, B. Rakerd, *J. Acoust. Soc. Am.* (in press), available at <http://www.pa.msu.edu/acoustics/tmp/proof1.pdf>.

Holograms tie optical vortices in knots

Using techniques from mathematics and optical wavefront engineering, researchers demonstrate that lines of zero intensity in a light beam can be shaped into links and loops of arbitrary topology.

What's the physical significance of a knot? William Thomson (who later became Lord Kelvin) must have asked himself that question in 1867 when he proposed his "vortex atom" hypothesis—the idea that different knotted configurations of swirling vortex lines in the ether are manifest in nature as different atoms. Earlier that year he'd witnessed Peter Guthrie Tait's intriguing experiments on smoke rings. And

based on earlier work by Hermann von Helmholtz, he knew that lines of vorticity are topologically conserved quantities. The closed loop and knotted configurations Thomson envisioned would thus be discrete and immutable—ideal traits for a theory of atoms.

Although initially skeptical, Tait came to believe that one could account for the rich variety of atoms in the periodic table by systematically building a

classification system for all types of knots. For the catalog he produced, Tait is now viewed as the father of knot theory. Thomson, for his part, had to abandon the vortex atom hypothesis. Ironically, though, it wasn't due to the nonexistence of the luminiferous ether—the 19th century's perfect fluid—but to an inability to analytically prove the temporal stability of a vortex knot.

Still, the subsequent history of

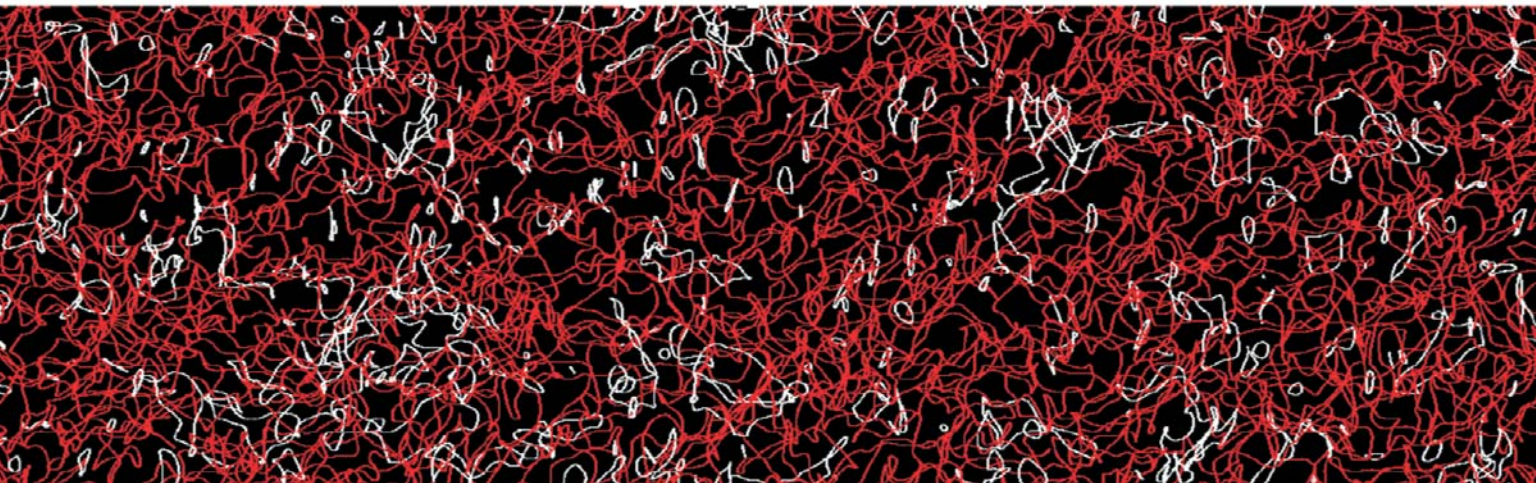


Figure 1. Speckleghetti. When coherent light from a laser scatters off a rough surface, it evinces a mottled speckle pattern of light and dark spots on that surface. The interference pattern is not restricted to a two-dimensional plane, though. In this numerical simulation of 625 randomly superposed plane waves propagating from left to right, points of perfectly destructive interference in the 2D plane transverse to the beam extend into tangled lines (red) and loops (white), known as optical vortices, in the 3D volume of a light beam. (Adapted from ref. 2.)