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Spatial hearing and hearing aids

Michael A Akeroyd and **William M Whitmer**
MRC Institute of Hearing Research (Scottish Section), Glasgow Royal Infirmary Glasgow G31 2ER United Kingdom

Spatial hearing is a central part of everyday listening. The ability to determine the direction of a sound source is a natural and effortless skill that is only remarked on in rare or challenging circumstances, such as when a driver cannot determine the direction of the siren of a passing ambulance. But spatial hearing performance by hearing-impaired listeners is considerably degraded, and generally hearing aids do not offer any benefit.

In most circumstances — excepting only if a sound source is *exactly* directly ahead, above, or behind — the fine details of a sound's waveform at the left ear will differ in some way from those at the right ear. The auditory system is sensitive to these interaural ("between the ears") differences. Imagine that the source is to the right of someone's head. The left ear is further from the source than the right ear, by about 18-20 cm, so the sound will arrive there a fraction of a millisecond after it arrives at the right ear. The left ear is also in the acoustic shadow cast by the head, so the sound's level will be less there than at the right ear. Both interaural cues physically occur at all frequencies, but their importance varies with frequency. The interaural level differences (ILDs) can reach 20 or 30 dB at frequencies around 5-10 kHz, but are less than 5 dB below 500 Hz. ILDs are therefore generally regarded as being most useful at high frequencies. Conversely, the interaural time differences (ITDs) — at most, about 600-800 millionths of a second — are primarily a low-frequency cue, useful up to around 1500 Hz

Many laboratory experiments have demonstrated that normal-hearing listeners are remarkably sensitive to these two cues: at best, people can discriminate changes of about 0.5 dB of ILD or 10 millionths of a second of ITD. But in everyday listening people are never called onto discriminate pure changes in ILD or ITD in isolation: when the direction of a source changes, both cues vary. At best, the discrimination for changes in direction is about 1 degree of spatial angle. This is the "minimal audible angle": one can reliably distinguish the left *vs.* right direction of two sounds, presented in quiet, 1 degree apart. These measurements can be made directly using very closely-spaced loudspeakers or with robot arms to accurately move loudspeakers by very small amounts. An alternative approach is to use a fixed loudspeaker array with relatively large spacing between loudspeakers, such as 15 degrees, and then measure how inaccurate listeners are at reporting the direction of sounds presented from them.

One degree of angle is really not very much: it corresponds to the apparent width of the index fingernail held at arm's length. Comparative measurements in mammals have demonstrated that humans have amongst the best performance: of all species measured so far; only dolphins and elephants do as well or better (Heffner, 2004). It is curious why we should be so good at distinguishing sound direction in quiet. Perhaps it is a by-product — an evolutionary spandrel (Gould and Lewontin, 1979) — of something else, such as better directional resolution for sounds in noise, or dealing with moving sounds, or even helping to guide visual attention.

Corresponding experiments with hearing-impaired listeners have indicated that they show, on average, worse performance than normal-hearing listeners, coupled with a substantial

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variation from person to person (e.g. Hausler et al, 1983; Koehnke et al., 1995; Noble et al 1997; Lorenzi et al., 1999). For example, Hausler et al reported results for 54 listeners with various kinds of hearing impairment. Their median minimal audible angle was 4 degrees, but one-quarter of the listeners had a minimal audible angle of 9 degrees or more. In contrast, the entire range of values for 36 normal-hearing listeners was 1-4 degrees. Hearing aids do not offer any overall benefit in spatial hearing — indeed, many studies have shown that they can impair performance slightly. This is succinctly epitomized by the title of one study from Belgium: "Horizontal localization with bilateral hearing aids: Without is better than with" (van den Bogaert et al., 2006). Complex processing features are not guaranteed to help either: in one set of conditions for aided listeners van den Bogaert et al. found mean inaccuracies of 16 degrees for listening with the aids set to a omnidirectional configuration but 18 degrees when set to an adaptive-directional configuration — and 13 degrees without hearing aids.

There is more to auditory space than just left *vs.* right, however: sounds are also above or below, or in front or behind. If there were no pinnae, or if the ear canals were exactly in the middle of the two sides of the head, then distinguishing up *vs.* down (or front *vs.* back) ought to be impossible. There would be no auditory cues that could separate either from left *vs.* right: the sensation of auditory space would reduce to a one-dimensional line. But the pinnae are present, and affect sounds from up or behind more than they do for down or front (also, the ears are slightly back from the middle of the sides of the head). Much of the resulting information for three-dimensional space occurs at high frequencies as a result of complicated perturbations due to interference from reflections at the corrugations of the pinnae.

How well the information for three-dimensional space is preserved by hearing aids would therefore be expected to depend on the location of the hearing-aid microphones: the closer to the eardrum, the better. Accordingly, completely-in-the-canal (CIC) aids should be better than behind-the-ear (BTE) hearing aids. One test of this prediction was recently reported by Best et al (2010). They found no difference between these two types of aids for up *vs.* down, nor for left *vs.* right, but they did for front *vs.* back. In their experiment, it was marked as an error to report a sound that was physically behind to be in front, or vice-versa. They found such errors on around 25% of trials for CIC aids but around 35% for BTE aids (after 4-6 weeks accommodation to the hearing aids; the errors were even higher immediately after fitting). Though the CIC aids were the better of the two types of aid, the number of front/back errors was no different to when the listeners were tested unaided, and was still far higher than normal hearing listeners, who gave an error rate of 5%. Other studies have also found remarkably poor abilities at distinguishing front from back with hearing aids (Keidser et al, 2006; van den Bogaert et al, 2011).

It can be argued that hearing aids do not necessarily have to give someone a left *vs.* right minimal audible angle of 1 degree, as 1 degree is, as noted, a very small angle. But it is hard to argue that a hearing aid should unnecessarily induce front *vs.* back errors: if a sound really is in front, then it is likely that a person will want to hear it from in front, even if it is not in exactly the right direction. Hearing aids should be capable of recreating a "realistic" three-dimensional world. That is, are distant sounds perceived as being distant? Are in-front sounds perceived as in front? Are moving sounds perceived as moving? Are the apparent directions of sounds consistent with vision? Are external sounds perceived as being outside? Perhaps a future success of bilateral hearing aids will be in giving someone a full auditory space, even if they do not give the same level of left *vs.* right discrimination as that of normal-hearing listeners. Recent research by Alan Boyd, a PhD student in our group, has demonstrated that hearing-impaired listeners report external sounds to be less "outside" than normal-hearing listeners, even with all the normal acoustic and visual cues to depth being

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present. It is therefore not certain that the sensation of auditory space of normal-hearing listeners is the same as that of hearing-impaired listeners. Indeed, this is what one would predict from consideration of the fundamental phenomena of spatial hearing: the best auditory cues for three-dimensional space occur at high frequencies, but high frequencies are those mostly lost first in hearing-impaired listeners and are those least well handled by modern hearing aids. It is possible that hearing-impaired people have learnt to listen to their environment in different ways from those with normal hearing. There is still much research to be done in how aided listeners perceive auditory space.

But there is a caveat that is sometimes under-appreciated: the apparent direction of a sound is *not* determined by its acoustics alone. One demonstration is that moving your head helps to resolve front from back (Perrett and Noble, 1997). If a sound is really in front of you, then it will appear to move leftwards if you rotate your head to the right, but if it is really behind you then it will move rightwards. This effect can be reversed to make an illusion. Dr Owen Brimijoin (a post-doctoral scientist in our group) has modernized an effect first reported in the 1940s, in which a sound is physically presented in front of a listener. When the listener moves his or her head, computer synthesis is used to ensure that the sound moves in exactly the same way had it been behind the listener. The listener perceives the sound as behind – even though it is *always* in front. The illusion also holds if the sound is presented from behind but made to move as though it was in front.

A second example highlights the importance of vision: the ventriloquist effect. This is the classic demonstration that the apparent direction of a sound source can be captured by corresponding visual events. It would be valuable to know how much of a hearing-impaired listener's sensation of auditory space is based on the combined effects of head movements and vision. Even in the simplest situations they may be influential. Imagine talking to another person who is standing in front. Any front *vs.* back ambiguity in the acoustics could, at least in principle, be resolved y randomly rotating one's head slightly – and it is a commonplace observation that people rarely keep still. A hearing aid would then only need sufficient directional capability to place the voice close enough to the correct direction for the ventriloquist effect to then "capture" the sound to the real direction of the person talking. It may not be necessary for the hearing aid itself to be so good that the auditory direction is itself exactly correct. As far as we know, however, the ventriloquist effect has not been explored in hearing-impaired listeners, with or without hearing aids.

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