



## The psychoacoustics of binaural hearing

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# The psychoacoustics of binaural hearing

## La psicoacústica de la audición binaural

### Abstract

This paper introduces the major phenomena of binaural hearing. The sounds arriving at the two ears are rarely the same: usually one ear will be partially shadowed from the sound source by the head, and the sound will also have to travel further to get to that ear. The resulting differences in interaural level and time can be detected by the auditory system and can be used to determine the direction of the source of sound. They also facilitate improvements in the detectability of a target sound masked by some other sound from some other direction. In many circumstances there is a special emphasis to the onset of a sound, which helps to perceptually suppress the complex patterns of reflections and reverberations that are present in most listening environments; yet, the auditory system is often insensitive to—and cannot take advantage of—fast dynamic changes within a sound.

### Sumario

Este trabajo presenta a los principales fenómenos de la audición binaural. Los sonidos que llegan a los dos oídos rara vez son iguales; generalmente un oído recibe el sonido parcialmente cubierto, en relación con la fuente sonora, por la sombra de la cabeza, por lo que el sonido tendrá que viajar más para llegar al oído. El sistema auditivo puede detectar las diferencias resultantes de intensidad y tiempo y las puede utilizar para determinar la dirección de la fuente sonora. También pueden facilitar el mejoramiento en la detectabilidad de un sonido objetivo enmascarado por algún otro sonido de alguna otra dirección. En muchas circunstancias hay un énfasis especial en el inicio de un sonido, que ayuda a suprimir perceptualmente los patrones complejos de las reflexiones y reverberaciones presentes en la mayoría de los ambientes sonoros; así, el sistema auditivo a menudo es insensible y no puede tomar ventaja de los rápidos cambios dinámicos de un sonido.

The term “binaural hearing” denotes our faculty for taking advantage from comparisons of the acoustic signals at the two ears. It enables us to find the direction of a source of sound, and, in many circumstances, it enables a sound to be detected in more-adverse conditions than if just one ear was available. Comparing the signal at one ear with the signal at the other ear is useful because the details of the sounds arriving at one ear will usually differ from those at the other ear. The causes of the differences can be illustrated by imagining a source of sound placed somewhere to the right of a listener. The left ear will be further from the source than the right ear, so the sound will arrive there just after it arrives at the right ear. This difference in arrival time across the ears is the *interaural time difference* (ITD). It varies with the angle of the sound source and is the primary cue for determining the direction of low-frequency sounds. The head also casts an “acoustic shadow”: the sound at the left ear is less intense than that at right ear. This difference in level across the ears is the *interaural level difference* (ILD). It too varies with the angle of the source and is particularly effective for determining direction at high frequencies. For example, if there is also a masking sound placed to the left of the listener, then the masker will itself be acoustically shadowed, giving less intensity at the right ear; thus, the signal-to-noise-ratio at the right ear will be better than that at the left ear. Furthermore, even with the shadowing, some of the noise will be present at both ears. A detailed comparison of its ITDs allows the auditory system to, in effect, partially “cancel” it, so giving a further advantage to the detectability of the signal.

The following précis introduces some of these topics. More details will be found in the general reviews by Green (1976), Moore (2003), Grantham (1995), and Hafter and Trahiotis (1997). Topic-specific reviews include the physics of sound around the head and ears (Kuhn, 1987; Shaw, 1997); ITD processing (Bernstein, 2001); interaural correlation (Trahiotis et al, 2005); the lateralization of sounds (Yost & Hafter, 1987); the localization of sounds (Middlebrooks & Green, 1991); HRTFs and virtual-auditory-space (Wightman & Kistler, 1993, 2005); distance perception (Zahorik et al, 2005); the “precedence effect” (Zurek, 1987, Litovsky et al, 1999); models of lateralization or the binaural-masking-level difference (Colburn & Durlach, 1978; Stern & Trahiotis, 1995, 1997; Colburn, 1996); binaural advantages to detection (Zurek, 1993); the “cocktail-party” effect (Bronkhorst, 2001); and binaural physiology (Palmer & Kuwada, 2005). The comprehensive publications of Durlach and Colburn (1978), Blauert (1997), and Gilkey and Anderson (1997) are especially recommended.

### A. Interaural time differences (“ITDs”)

A simple but useful model of ITDs assumes that the head is perfectly spherical and that the ears are single points at its surface (e.g., Woodworth, 1938; Duda & Martens, 1998). The source of sound is off to one side, so one ear is closer than the other. A geometrical construction gives the extra distance to the far ear as equal to  $r\theta + r\sin\theta$ , where  $r$  is the radius of the

head (usually taken as 8.75 cm) and  $\theta$  is the lateral angle (azimuth) of the sound source, in radians. The ITD is then found by dividing by the speed of sound,  $c$ , some 345 metres per second. This analysis gives an ITD of 0  $\mu\text{s}$  for a sound source that is straight ahead (or straight behind, above, or below) but which becomes progressively larger as its lateral angle is increased, reaching a maximum of about 650  $\mu\text{s}$  for an angle of  $+90^\circ$  (opposite the right ear) or  $-90^\circ$  (opposite the left), although there is some variation across individuals (Middlebrooks; 1999A) (the convention used throughout this paper is that positive values of lateral angles, ITDs, and ILDs correspond to sounds on the right side of the head, whilst negative values correspond to the left). Despite its simplicity, the geometry can give remarkably accurate predictions. Feddersen et al (1957) measured ITDs on five listeners, using microphones placed at the entrances to their ear canals and with the stimuli being brief clicks from loudspeakers placed at the same height as the ears, and found that the largest error of the model was just 30  $\mu\text{s}$ . Measurements with pure tones have demonstrated a dependence on frequency: although the geometry is accurate for frequencies higher than about 1500 Hz, for lower frequencies the ITD is larger than expected (e.g., the ITD for an angle of  $90^\circ$  is approximately 800  $\mu\text{s}$  for frequencies less than about 500 Hz). This variation matches the predictions of the physical theory of how sound diffracts around a rigid sphere (Kuhn, 1977, 1987).

ITDs can be easily created over headphones simply by delaying the signal at one ear relative to the other. Headphone-presented sounds are perceived typically inside the head (but see section C for exceptions). The perceived position (often termed the *lateralization*) of the sound is dependent upon its ITD (e.g., Sayers, 1964; Yost, 1981; Simon et al, 1994). A sound with an ITD of 0  $\mu\text{s}$  will be perceived at the center of the head. Sounds with larger positive ITDs will be heard progressively further to one side, whilst sounds with progressively larger negative ITDs will be heard on the other (but see below for an exception). The lateralization also depends on the frequency of the tone. Schiano et al's (1986) measurements showed that the position got slightly further out as frequency was increased from 300 to 1000 Hz, then progressively returned to the center of the head as frequency was further increased upto about 1500 Hz. Pure tones of yet higher frequency are perceived at the center of the head, no matter what the ITD.

Under optimal conditions—frequencies around 500–1000 Hz and for a reference value of 0  $\mu\text{s}$ —the *just-noticeable difference* (“jnd”) in the ITD of a pure tone can be remarkably small, being about 10  $\mu\text{s}$  or less (e.g., Klumpp & Eady, 1956; Zwislocki & Feldman, 1956; Domnitz, 1973). At frequencies above about 1500 Hz, however, the jnd cannot be measured; there is no ability to discriminate changes in ITD for high-frequency pure tones (Klump & Eady, 1956). This effect may be due to progressive losses in the accuracy with which the inner hair cells can “phase lock” to the fine structure of the pure tone and so faithfully reproduce it (e.g., Pickles, 1988). However, listeners are sensitive to ITDs carried by the *envelopes* of high-frequency sounds, such as sinusoidally-amplitude modulated signals (e.g., Leakey et al, 1958; Henning 1974, Nuetzel & Hafter, 1976; Bernstein & Trahiotis, 1994). Recent studies have demonstrated high-frequency ITD processing sometimes as good as that found for low-frequency tones for both jnds and in the perceived position

resulting from the ITD (Bernstein & Trahiotis, 2002, 2004). These experiments have used “transposed stimuli”, which are synthesized to have amplitude modulations which mimic the action of the inner hair cells to low-frequency tones (van der Par & Kohnrausch, 1997).

ITD processing at high frequencies can also be disrupted by the presence of low-frequency sounds. McFadden and Pasanen (1976) discovered that the jnd at 4000 Hz for a narrowband noise was substantially increased if a second band of noise, at 500 Hz, was presented simultaneously. This effect has been termed *binaural interference* (note that it is unrelated to another phenomenon also termed “binaural interference”: that in some people with asymmetric hearing losses, speech identification can be worse with two ears than with the better ear alone; e.g., Jerger et al, 1993; Allen et al, 2000). It is asymmetric across frequency—no change is observed in the jnd at 500 Hz—but it also depends upon the form of the second noise, being particularly large if that is gated simultaneously with the target (Trahiotis & Bernstein, 1990). Curiously, transposed stimuli are immune to binaural interference (Bernstein & Trahiotis, 2004), a result that cannot be predicted from current theory (Buell & Hafter, 1991; Heller & Trahiotis, 1996).

The perceived position of sounds with ITDs that exceed the head-size limit of about 600–800  $\mu\text{s}$  depends upon the bandwidth of the sound. A pure tone or narrowband stimulus shows a “cycling” behaviour due to the periodicity in the stimulus (Sayers, 1964). For example, consider a continuous pure tone at 500 Hz, whose period is 2000  $\mu\text{s}$ . With an ITD of +500  $\mu\text{s}$ , it will be perceived near the extreme right of the head. ITDs of +2500, +4500, +6500...  $\mu\text{s}$  will give the same lateralization, as these ITDs are, respectively, the sum of +500  $\mu\text{s}$  and 1, 2, 3... periods of 500 Hz. ITDs of +1500, +3500, +5500...  $\mu\text{s}$  will give a lateralization near the extreme *left* of the head, as these are the sum of –500  $\mu\text{s}$  and 1, 2, 3... periods. A broadband stimulus, however, does not show this cycling effect (e.g., Jeffress, 1972; Trahiotis & Stern, 1989; Hill & Darwin, 1996). An ITD of +500  $\mu\text{s}$  will, like the pure tone, give it a lateralization near the extreme right of the head, but an ITD of +1500  $\mu\text{s}$  will *also* give a lateralization on the right, unlike the pure tone. The perceived position will stay on the right side of the head until ITDs at least as large as +10000  $\mu\text{s}$  are reached (e.g., Blodgett et al, 1956; Mossop & Culling, 1998). Noises with much larger ITDs, greater than this “sidedness” limit, are perceived as having two positions, one at each ear. Such ITDs are too large for the binaural system to detect. It cannot discriminate them from a noise for which the correlation between its left and right waveforms is zero (this *interaural correlation* is often a useful summary statistic of a noise, and the lateralization and width of the perception depends upon it; e.g., Blauert & Lindemann, 1986).

The standard account of these effects is based on Jeffress' (1948) scheme for a neural “map” of ITD. For a sound with an ITD favouring the right ear, the neural spikes from that ear would occur before those from the other ear. But if the right-ear spikes are delayed along the way—by making them travel further, or by some form of neural inhibition—then both sets of spikes can be made to arrive at the same time at some central neuron. Given that the central neuron is sensitive to across-ear temporal coincidences, and that there are a set of such neurons, each fed by a differing delay, then the result is a

spatial code for ITD: whichever cell fires the most marks the ITD of the sound. It is likely that every frequency channel has its own independent set of delays. Simulations of the activity in each frequency-delay point in the map—the *correlogram*—have proved insightful in psychophysical models of lateralization (e.g., Lindemann 1986a,b; Stern et al, 1991; Shackleton et al, 1992; Akeroyd & Summerfield, 2000; see also the reviews by Stern & Trahiotis, 1995, 1997, and Trahiotis et al, 2005). Physiological data supports many aspects of Jeffress' hypothesis (reviewed by Palmer & Kuwada, 2005). There are indeed cells in the lower nuclei of the brain stem—the Medial Superior Olive and the Inferior Colliculus—that act as coincidence detectors; although there are also cells that respond least when the neural inputs are coincident, and there are other cells that are intermediate. However, current physiological results suggest that the range of internal delays available is somewhat limited and may not extend out as far as assumed in psychophysical models of the perceived positions resulting from large ITDs.

## B. Interaural level differences (“ILDs”)

The head casts an acoustic shadow to any source of sound. Usually, one of the ears will be in it. The intensity of the sound at this shadowed ear will be less than that at the other, “illuminated”, ear. The resulting difference in level is the ILD. The amount of shadowing, and thus the ILD, depends upon angle, frequency, distance, and individual. To generalize considerably, the further the source of sound is from the midline, or the higher the frequency, the larger the ILD tends to be. Superimposed on these effects are substantial perturbations, especially at high frequencies and for directions above or behind the head.

Measurements of ILDs themselves—or the actual levels at each ear for which the ILD is the difference—have been reported many times, both for people (e.g., Wiener, 1947; Feddersen et al, 1957; Searle et al, 1975; Wightman & Kistler, 1989; Middlebrooks et al, 1989; Middlebrooks, 1999a) or a manikin (e.g. Burkhard & Sachs, 1975; Kuhn, 1987; Brungart & Rabinowitz, 1999). A meta-analysis of the levels at the ears pooled across 100 people was reported by Shaw (1974; Shaw & Vaillancourt, 1985). The maximum ILDs calculated from that data were 3, 10, 17, and 21 dB at frequencies of 0.2, 1, 5, and 10 kHz. The lateral angles that gave the maxima were, respectively, 90°, 60° and 135°, 60°, and 105°. These angles are all roughly opposite one ear, but, unlike the case with ITDs, are rarely *exactly* opposite. And the “double-peak” at 1000 Hz is one example of the perturbations: here, the ILD is actually less for a sound source directly opposite a ear than it is for angles slightly ahead or behind. The levels at the ears—and so the ILD—also depend upon the distance to the source (e.g., Brungart & Rabinowitz, 1999). The effects are only substantial for distances less than about 0.5 m, but, for those, even at 500 Hz the ILD can reach 20 dB (ITDs, though, are essentially independent of source distance).

The general effects can be understood from the physical theory of the interaction of sound with a sphere (e.g., Rayleigh, 1945; Kuhn, 1987; Duda & Martens, 1998; Brungart & Rabinowitz, 1999). The depth of the shadow is determined by how much the head blocks the sound, which, in turn, depends upon how the wavelength of the sound relates to the size of the

head. If the wavelength is much larger (e.g., at 500 Hz, the wavelength is about 70 cm), the shadowing is minimal as diffraction ensures that the head offers only a minor obstacle to the sound; if, instead, the wavelength is much smaller (e.g., at 5000 Hz it is about 7 cm) it is the diffraction which is minimal, and the acoustic shadow is correspondingly deeper. Minor deviations result from the interfering effects of sounds reflecting from the torso or shoulders, both generally at low frequencies. Substantial deviations occur at frequencies above about 2 kHz (e.g., Kuhn, 1987). They, too, result from interference from reflected sounds, but here the reflections are mostly from the folds and cavities of the outer ear. For instance, the concha and pinnae create resonances from 4 kHz up to at least 17 kHz (Shaw, 1997). As there are individual differences in the physical size of the head and ears—heads differ by about  $\pm 1$  cm, ear sizes by about  $\pm 0.5$  cm, ear orientations by about  $\pm 7^\circ$  (Algazi et al, 2001; see also Burkhard & Sachs, 1975, & Middlebrooks, 1999a)—there is substantial idiosyncracies in the ILDs, especially at high frequencies.

ILDs can be easily synthesized over headphones by attenuating the signal at one ear compared to the other. The resulting lateralization of the sound is approximately proportional to the amount of ILD, at least up to about 10 dB (e.g., Yost & Hafter, 1987). An ILD of about 15–20 dB will give a position about at the edge of the head. No matter what the bandwidth of the sound, still-larger ILDs hardly change the position (indeed, a monaurally-presented sound is just a sound with an infinite ILD). That both ILDs and ITDs affect independently the perceived position of a sound has proved valuable in experimental studies of lateralization: the position given to a sound by an ITD can be measured as the amount of ILD a listener uses to place a separate, “pointer” sound in the same place (e.g., Domnitz & Colburn, 1977; Bernstein & Trahiotis, 1985; Trahiotis & Stern, 1989). The duality also means that the amount of laterality resulting from an ITD can be “traded” against an ILD. Studies of this *time-intensity trading* have shown that ITD and ILD are often equivalent for purposes of lateralization but they are not identical; listeners can report perceiving two images (e.g., Whitworth & Jeffress, 1961; Hafter & Carrier, 1972).

The just-noticeable-difference for changes in an ILD is approximately 0.5–1 dB (e.g., Mills, 1960; Domnitz & Colburn, 1977). Unlike ITD resolution, it is approximately independent of frequency between 200 and 10000 Hz, apart from a small, curious deterioration at 1000 Hz (e.g., Grantham, 1984). ILD resolution is slightly better than the corresponding resolution for monaural level differences (e.g., Jestead & Wier, 1977; Hartmann & Constan, 2002; Stellmack et al, 2004). The binaural value may reflect a sensitivity to the change in laterality caused by the change in ILD rather than to the monaural level change at either ear per se (Bernstein, 2004).

## C. ITDs and ILDs together: Spatial hearing

All real-world sounds generate both ITDs and ILDs, but that does not mean that the binaural system always uses both to determine the direction of a sound source. An influential theory of sound localization—the *duplex theory*—has that only ITDs are used at low frequencies and only ILDs at high (Rayleigh, 1907). It appears to hold for pure-tone signals presented in a free

field. For these, the best directional sensitivity is found at low or high frequencies (about 1° at 500 and 5000 Hz), but there is a deterioration—to about 3–4°—at frequencies around 1500 Hz (Mills, 1972). The dissociation can be accounted for by a combination of the ITD and ILD resolutions measured with headphones (Mills, 1960): ITDs are optimal at low frequencies, ILDs are optimal at high, but neither work well for mid frequencies. But what about for broadband sounds, which will generate both low-frequency ITDs and high-frequency ILDs? It appears that their direction is determined by their low-frequency ITDs, at least for sounds presented in silence (Banks & Green, 1973; Wightman & Kistler, 1992). With a background of noise, neither cue always dominates: listeners use whichever is best in each circumstance (Lorenzi et al, 1999). One study of amplitude-modulated noises did not show any benefit of having high-frequency envelope ITDs in addition to the usual ILDs (Eberle et al, 2000). It would be of interest to see if high-frequency transposed stimuli are equally dominated by low frequencies.

It has been assumed implicitly so far that *direction* has meant what is usually termed *azimuth*: the sound source is at the same level as the ears, so changes in angle change the horizontal direction only. As noted earlier, the scattering from the complex folds of the pinnae for high frequencies is dependent upon the orientation of the sound. Listeners can use the details of the spectral profiles created at each ear (and their differences across the ear) to determine the vertical direction (elevation) of a sound source. The resolution for changes in vertical direction is, at best, about 4° (Perrott & Saberi, 1990).

These intricate interactions between the direct sound and the numerous reflected, scattered, and resonant sounds occur for all directions. Their overall effect can be captured by placing a microphone at, or near, a listener's eardrums and then recording the response to an impulse, such as a click, presented from a loudspeaker at the required distance and direction. The resulting signals—the left and right *head-related-transfer functions* (“HRTFs”)—embody *all* the acoustic information to distance and direction (see reviews by Middlebrooks & Green, 1991; Wightman & Kistler, 1993, 2005). For instance, suppose that the Fourier Transform of the left and right HRTFs is calculated. The left-right differences in the phase spectra determine the ITD at each frequency; the differences in the magnitude spectra determine the ILD.

An important practical application of HRTFs is to convolve them with another sound, such as an anechoic recording of a person talking, and then to play the result over headphones to a listener. If done carefully (with suitable equalization for the effects of the microphones and the headphones, and assuming the listener is the same as the person used for measuring the HRTFs), then the listener will perceive the talker to be at the distance and direction of the HRTF recording. This *virtual auditory space* percept will be externalized: the sound will appear to be outside the listener. The effect stands in contrast to the “within-the-head”, lateralized percept that is otherwise typical with headphone-presented sounds. The illusion can be compelling: Hartmann and Wittenberg (1996) showed that the virtual source could be indistinguishable from a real one. Unfortunately, as noted above in relation to ILDs, the details of the HRTFs differ considerably from one listener to another because of individual differences in their head and outer ears (e.g., Wight-

man & Kistler, 1989; Møller et al, 1995; Middlebrooks, 1999a). Front/back and elevation errors are more common if the HRTF is not from the actual listener (e.g., Wenzel et al, 1993; Møller et al, 1996). Externalization is often reduced too, although it is rarely completely removed (the amount of externalization also depends upon reverberation and on head movements; Durlach et al, 1992). Some of the idiosyncracies of individual HRTFs can be reduced by a simple scaling in frequency (Middlebrooks, 1999a,b).

The wide availability of generic sets of HRTFs recorded on a manikin (Gardner & Martin, 1995) or on people (e.g., the “AUDIS” database, Blauert et al, 1998, and the “CIPIC” database, Algazi et al, 2001), together with the decreasing cost of ever-more-powerful desktop computers needed to process the signals, has led to a near-revolution in binaural experimentation. The virtual-auditory-space method is being used increasingly often in a wide range of domains. One example is the study of questions about the relative importance of the ITDs and ILDs for spatial perception (e.g., Wightman & Kistler, 1992) or for binaural advantages to detection (e.g., Bronkhorst & Plomp, 1988; Hawley et al 2004, Culling et al 2004), as computer manipulation of the HRTF allows ITD and ILD to be varied independently. A second example is studies of the various cues to distance perception, as percepts of distance can be simulated without the expense of complicated loudspeaker arrangements (e.g., Bronkhorst & Houtgast, 1999; Zahorik, 2002; for distance perception itself, see the review by Zahorik et al, 2005).

#### D. Binaural advantages to detection

Licklider (1948) and Hirsh (1948) discovered that the detection thresholds of speech or pure tones masked by noise could be lowered substantially by giving the target a different ITD to the masker. This gain in detectability, the *binaural masking level difference* (“BMLD”), has become a mainstay of binaural experimental and theoretical work. Green and Yost (1975) and Durlach and Colburn (1978) reviewed many of the results in detail. For pure-tone signals presented over headphones in a wideband masking noise—a particularly common experimental design—three general effects are of particular importance. First, the BMLD is largest at low frequencies, being about 15 dB at 500 Hz, and reducing to about 3 dB for frequencies above about 1500 Hz (although high-frequency “transposed” stimuli give enhanced BMLDs; van de Par & Kohlrausch, 1997). Second, the BMLD depends upon the interaural configurations of the target and the masker, being largest when the noise is in-phase across the ears (i.e., its ITD is 0  $\mu$ s) and the tone is out-of-phase across the ears (i.e., its ITD is equal to one-half of the tone's period), but is non-existent (0 dB) when *both* are in-phase or out-of-phase. Third, the BMLD depends on the level of the noise; at absolute threshold, the gain from having an out-of-phase signal is just 1 dB (250 Hz; Diercks & Jeffress, 1962; see also Yost, 1988). Other classes of stimuli also give BMLDs, but the values may differ. For instance, the gain in the detectability of speech is about 13 dB, although the gain in *intelligibility* is only 6 dB (Levitt & Rabiner, 1967). The BMLD has been exploited experimentally to study other aspects of binaural hearing. Examples include the existence of long internal delays (van der Heijden & Trahiotis, 1999), the width of the binaural auditory

filter (e.g., Kohlrausch, 1988), and the temporal resolution to dynamic changes (see next section).

Many of the effects of frequency and of the interaural configuration can be accurately described by Durlach's influential "Equalization-Cancellation" model (1972). According to that model, there is an equalization in level and internal delay of the signals at the two ears, so that a subsequent subtraction of one from the other will cancel as much of the masking noise as possible. There is a resulting gain in target-to-masker ratio over that found at either ear; hence, there is a gain in detectability of the target. But as the gain in detectability is not infinite, but only, at most, about 15 dB, the cancellation must be imperfect. Durlach developed a mathematically-simple form of imperfection which was sufficient to predict much of the experimental data. This analytic, "black box" approach is still used (e.g. van der Heijden & Trahiotis, 1999; Akeroyd, 2004), although the E-C principle has also been incorporated into a successful physiologically-inspired computational model (Breebart et al, 2001).

Culling et al (1998a,b) showed that an elaboration of the E-C model could also offer an account of many of the "dichotic pitches". These are sensations of pitch that are created by the binaural interaction of specially-crafted noise stimuli. They can *only* be heard binaurally: the noise stimulus at each ear, when presented (using headphones) monaurally in isolation, gives no pitch, but, when presented binaurally, there is a clear, definite pitch, which results from uncanceled ITD disparities in localized bands of the noise. The first, and still the clearest and perceptually most obvious, was discovered by Cramer and Huggins (1958). Simple melodies constructed with it can be heard with almost no training (Akeroyd et al, 2001). Curiously, in some situations the perceived position of this *Huggins pitch* stays the same if the left and right channels of the headphones are swapped around, unlike almost every other sound (e.g., Akeroyd & Summerfield, 2000; Hartmann et al, 2004), suggesting that it may arise from some inherent left/right asymmetry in binaural processing.

A process known as the *better-ear effect* (or *head-shadow effect*) can also lead to an improvement in the detectability of a target sound. Suppose that a target source of sound, such as speech, is directly ahead, but the noise masker is opposite one ear. The level of the speech will be the same at both ears—as its ILD is zero—but the acoustic shadowing of the head will make the level of the target somewhat less at the far ear than the near ear. There is a resulting improvement in the target-to-masker ratio at the far ear (for instance, Bronkhorst & Plomp, 1988, measured a gain of 8 dB in intelligibility for the spatial configurations described). The different spatial directions of the target and noise will also give rise to a difference in ITDs, so leading to a BMLD that can further improve detectability.

The better-ear effect will probably occur in almost all listening situations (it can only not occur if there are no left/right differences in *any* of the sounds), but its size is not necessarily impressively large. On average—across all directions for the noise and for a target directly ahead—the better-ear effect offers an average advantage of 3 dB and the BMLD an additional advantage of 2 dB (Zurek, 1993). To make use of the better-ear effect requires the auditory system to decide which ear is the better one. Accordingly, it is facilitated by having two ears. The full gain in target-to-masker ratio occurs when one ear is in the

deepest part of the acoustic shadow for the masker. Twice as many orientations will suffice if there are two ears to choose from.

## E. The dynamics of binaural hearing

The binaural system has famously been characterized as "sluggish" (a term first used by Grantham & Wightman, 1978): in many situations, it is unable to follow fast dynamic fluctuations in ITD. One illustration is the *binaural beat*, for which the stimulus is a pure tone presented to one ear with a second, different frequency pure tone presented simultaneously to the other (e.g., Licklider et al, 1950, Perrott & Nelson, 1969). The frequency difference induces a time-varying ITD. For differences less than about 2 Hz, the percept is of a lateralized position that cycles across the head. For larger frequency differences, however, the change in position cannot be followed, and instead the percept is dominated by loudness modulations or, at still higher frequency differences, roughness. The inability to follow the motion at anything other than the very slowest modulation rates reflects binaural sluggishness.

Many studies of binaural sluggishness have used the size of the BMLD as the experimental measure. One example is Grantham and Wightman (1979), who measured the binaural detectability of a short signal masked by a noise whose interaural correlation was modulated. When the modulation rate was 0.5 Hz, the BMLD was about 10–12 dB, but when the modulation rate was 4 Hz, the BMLD was about 0–3 dB. A modulation rate of 4 Hz is quite slow in comparison to "monaural" hearing: there is no substantial loss in the ability to detect *amplitude* modulation until the modulation rate is faster than about 100 Hz (e.g., Viemeister, 1979; Bacon & Viemeister, 1985). Yet, it was sufficient to effectively abolish the BMLD. The effect has often been modelled by a device which acts like a filter, smoothing fast changes in interaural configuration. The precise details of the shape and duration of this "binaural temporal window" remain elusive (e.g., Kollmeier & Gilkey, 1990; Culling & Summerfield, 1998; Holube et al, 1998; Akeroyd & Summerfield, 1999; Boehnke et al, 2002), but it is clear that it is far longer than an equivalent monaural window smoothing amplitude modulations (e.g., Moore et al, 1988; Plack & Moore, 1990).

However, it is not the case that the binaural auditory system is insensitive to *all* changes that happen quickly or abruptly. There is an emphasis to the onset of a sound mirrored by an insensitivity a moment later. This is the *precedence effect* (see reviews by Gardner, 1968; Zurek, 1987; Blauert, 1997; Litovsky et al 1999; the term was first used by Wallach et al, 1949). Suppose that the stimulus is two clicks presented over headphones. The first click is given a positive ITD so, if presented alone, would be lateralized on the right side of the head, whilst the other click is given a negative ITD, giving a lateralization on the left. But when played as a pair, about 2 ms apart, the two clicks are perceived as one, with a lateralization on the right side (listeners do not report perceiving two separate clicks unless their time gap is longer than about 8–10 ms). The ITD information in the second click is almost completely ignored, but this does not necessarily mean that the suppression is a result of special processing, such as a dedicated inhibitory mechanism: Hartung and Trahiotis (2001) showed that the results of some of

the influential click experiments (e.g., Wallach et al, 1949) could be accounted for using a modern computational model of the auditory periphery and a Jeffress-style model of lateralization. Other effects, however, almost certainly reflect higher processing. Two instances are the *build-up effect* (in which a repeated presentation of pairs of clicks leads to a decrease in the threshold time gap for the perception of two separate clicks) and the associated *Clifton effect* (in which a switch in location resets the build-up effect).

The emphasis to the onset can also be measured in other tasks. For example, the jnd for ITD measured just after the beginning of a sound is much greater than when measured at the beginning or end (e.g., Zurek, 1980; Akeroyd & Bernstein, 2001). In a second example, the jnd for ITD is like most discrimination jnds or detection thresholds: lower for longer sounds than for shorter sounds (at least up to a duration of about one-third of a second; e.g., Tobias & Zerlin, 1959). But the rate of improvement is less than would be predicted from the assumption that all parts of the sound are equally important. Instead, the results are consistent with the idea that, perhaps as a result of some form of adaptation or actual weighting, the onset is more important than the rest (e.g., Houtgast & Plomp, 1968; Hafer & Dye, 1983; Yost & Hafer, 1987).

Without the precedence effect, listening in rooms would be somewhat tiresome. Most rooms are reverberant to at least some extent, so the direct sound to a listener will be quickly followed by a vast number of subsequent reflections of the various surfaces and objects in a room. Each of these will come from differ directions and at many levels, but they all have one thing in common: they arrive at the listener *after* the direct sound. Yet only in exceptional cases—large spaces with long reverberation times, such as a hall or railway station—are the additional sounds noticed as separate echoes. More usually they colour the main, direct sound. Their suppression is one facet of the emphasis to the first-arriving sound that is characteristic of the precedence effect.

## Conclusion

The ability of the binaural system is remarkable. It can detect a change in ITD of as little as 10  $\mu$ s. It can give a gain in detectability for a pure tone in noise of 15 dB. It can emphasize the onset of a sound whilst effectively ignoring information only a few milliseconds later. There are models or hypotheses for the general aspects of most of the effects, but the theoretical approaches vary from the truly explanatory, such as the physical theories of ITD and ILD, to the more descriptive, such as the binaural temporal window. A succinct summary by Green holds true today:

“... certain cues and modes of processing are able to explain certain facts and data, but single mechanisms or theories are unable to encompass all binaural phenomena. A multiplicity of systems and cues are probably used in localization, lateralization, or MLD experiments”. (Green, 1976, p. 232)

Although written in the context of the effects of high-frequency ITDs, this comment is just as applicable to phenomena only studied in detail in more-recent years, such as binaural interference, straightness, binaural sluggishness, or transposed stimuli. The search for simple, wide-ranging explanatory principles will

continue, even if it is likely that the processing done by binaural system is more complex than anyone presently can imagine.

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