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Review

Sound source localization

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ABSTRACT

Sound source localization is paramount for comfort of life, determining the position of a sound source in 3 dimensions: azimuth, height and distance. It is based on 3 types of cue: 2 binaural (interaural time difference and interaural level difference) and 1 monaural spectral cue (head-related transfer function). These are complementary and vary according to the acoustic characteristics of the incident sound. The objective of this report is to update the current state of knowledge on the physical basis of spatial sound localization.

1. Introduction

Sound source localization has long been indispensable in the animal kingdom: it enables offspring but equally prey or predators in a hostile environment to be rapidly located. In vertebrates, a middle ear able to receive airborne sounds developed in the Triassic era 210–230 million years ago, with separate evolution in amphibians, sauropsida and mammals [1]. This enabled binaural hearing to develop, contributing to sound source localization. In *Homo sapiens*, the present-day human being, sound source localization contributes greatly to comfort of life. Notably, it enhances speech comprehension by locating different sound sources (demasking of speech in noise).

The present report updates the current state of knowledge on the physical bases of sound source localization, analyzing the most recent or most relevant publications retrieved by the search-term "sound source localization" in the PubMed® data-base, while also including older studies that are references in the field.

2. Discussion

Sound source localization consists in determining the position of the source of a sound in 3 dimensions comprising 2 angles and 1 distance (Fig. 1):

- azimuth (azimuth angle α) in the horizontal (or azimuthal) plane: $0 \pm 180^\circ$;
- elevation (height or vertical angle θ) in the vertical plane: $0 \pm 90^\circ$;
- and distance (Δ) in depth: $0 \pm \infty$.

Three main physical parameters are used by the auditory system to locate a sound source: time, level (intensity) and spectral shape.

Horizontally, the azimuth is mainly determined by binaural factors, involving both ears: i.e., interaural time and level differentials.

Vertically, height is determined monaurally, involving just one ear: i.e., changes in incident spectral shape (reflection, diffraction and absorption) brought about by the pinna, head, shoulders and bust, known as the head-related transfer functions (HRTF).

Depth distance is mainly determined monaurally.

2.1. Horizontal localization

The duplex theory of directional hearing developed by Lord Rayleigh in 1907 was the first to analyze sound source localization in terms of interaural differences in cues [2].

In humans, the two ears are on either side of the head, separated by the width of the latter. Head radius is generally taken as 8.75 cm [3], corresponding to an average measured in several individuals by Hartley and Fry in 1921 [4]; in 2001, Algazi et al. reported a mean 8.7 cm radius in 25 subjects [5].

The two ears thus have different spatial coordinates.

As distance differs between the sound source and each of the ears, there is a time difference in reception between the two.

The head, coming between the two ears, exerts an acoustic shadow effect, and there is thus a difference in level between the signals received.

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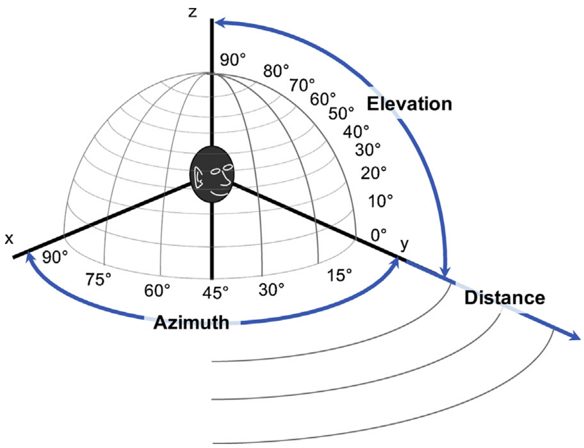

Fig. 1. Polar coordinates used to locate a sound source in an x-y-z perpendicular 3D space centered on the hearer: azimuth in horizontal plane, elevation or height in vertical plane, and distance as depth.

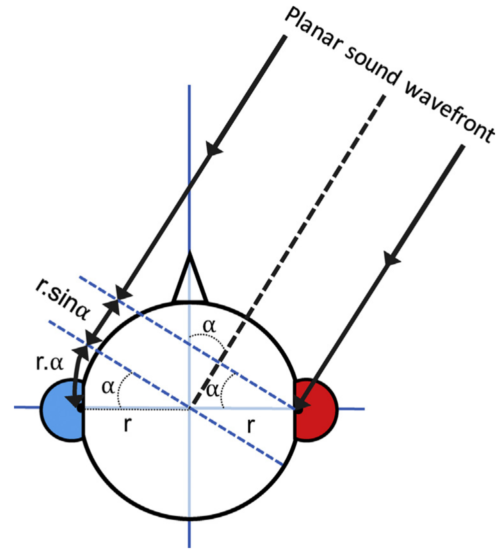

Fig. 2. Geometric representation of the difference in trajectory length between the two ears (left in blue, right in red) for a wavefront at angle α with head radius r. To reach the farther ear, the sound travels an extra distance r(α + sinα). (Based on [3,9,10]).

2.1.1. Binaural cues: interaural time difference (ITD) and interaural level difference (ILD)

2.1.1.1. Interaural time difference (ITD). Interaural time difference (ITD) is the sound propagation time between the two ears.

Sound propagation speed in air (ν, in m/s) depends on temperature (T, in °C) [6–8]:

$$\nu = 331 \cdot \sqrt{\frac{T + 273}{273}}$$

It is about 343 m/s at 20 °C. Thus each extra centimeter to be covered takes about an extra 29.2 μs. A sound coming from the right reaches the right ear before the left.

ITD is defined as [3,9,10]:

$$\Delta t = \frac{\Delta d}{\nu}$$

where Δt is the ITD (in sec), Δd the extra distance (in m) to be covered, and ν the velocity of the sound (in m/s).

Low-frequency sound waves, in which the wavelength exceeds the diameter of the head, will be diffracted by the head, giving rise to Woodworth's equation [11]:

$$\Delta t = \frac{r \cdot (\alpha + \sin \alpha)}{\nu}$$

with $-90°$ (or $-\pi/2$ rad) $\leq \alpha < 90°$ (or $\pi/2$ rad)where r is the head radius (in m) and α the azimuth angle (in°) of the sound's incidence (Fig. 2). Woodworth's formula is an approximation, assuming the sound to be a planar wave (source at infinite distance) and the ears to be 90° forward.

The auditory system assesses ITD by:

- low-frequency phase-shift for wavelengths exceeding head diameter;
- high-frequency envelope shift for wavelengths shorter than head diameter.

ITD is fundamental in locating sound sources at frequencies below 1500 Hz [12], but becomes ambiguous at higher frequencies [13]. This can be expressed mathematically. The basic relation is [8]:

$$\nu = \lambda \cdot f$$

where ν is the sound velocity (343 m/s), λ the wavelength (in m), and f the frequency (in Hz). Taken together with Woodworth's formula, the maximum extra distance the sound may have to cover, if it comes at 90° or π/2 rad, is 2.57r.

From this value, the maximum frequency at which ITD remains relevant can be calculated as the frequency corresponding to the minimum wavelength not exceeding an extra travel distance of 2.57r:

$$f_{max} = \frac{\nu}{\lambda_{\min}} = \frac{343}{2.57 \cdot 0.0875} \approx 1525 \quad Hz$$

This value is close to those found experimentally in the literature [12].

Thus, for pure tones higher than 1500 Hz, phase-shift ceases to be relevant, as several wavelengths may have followed one another between one ear and the other (Fig. 3).

In the case of complex sounds, on the other hand, ITD remains relevant beyond 1500 Hz thanks to the perceived difference in arrival time of the sound envelope between the two ears, sometimes known as the interaural envelope difference. However, envelope cues play little if any role in determining azimuthal localization in a free field [14].

In optimal conditions, humans can perceive ITD values down to 10 μs [12].

The precedence effect, also known as the law of the first wavefront [15–17], can locate the sound source on the side of the ear that first heard it. This is especially important in echogenic environments, with a lot of reverberating sounds.

2.1.1.2. Interaural level difference (ILD) (or interaural intensity difference). Interaural level difference (ILD) (or interaural intensity difference) is the intensity difference between the two ears for the same sound.

The head masks sounds: this shadow effect reduces intensity, especially at higher frequencies [10]. For wavelengths shorter than head diameter, the head partially decreases acoustic energy by reflection and absorption. Thus, the lowest frequency at which the shadow effect occurs is approximately:

$$f_{\min} = \frac{\nu}{\lambda_{\max}} = \frac{343}{0.175} \approx 1960 \quad Hz$$

where ν is sound velocity (343 m/s) and $\lambda_{\max}$ the maximal wavelength (for head width estimated as 0.175 m).

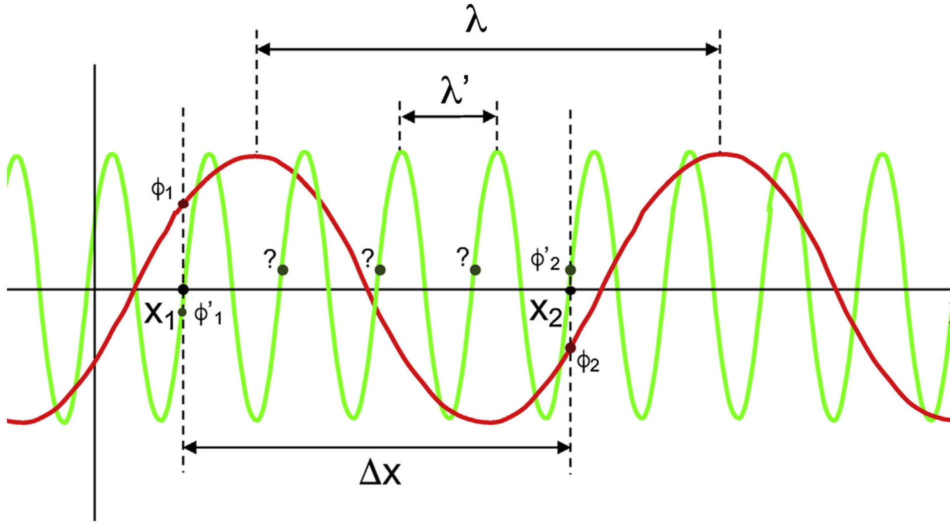

Fig. 3. Representation of phase difference between 2 points (x_1 and x_2) separated by distance Δx, for 2 sinusoidal pure tones, one of low-frequency (longer wavelength λ, in red) and one of high-frequency (shorter wavelength λ', in green). Wavelength λ is greater than distance Δx, and the phase difference between points ϕ_2 and ϕ_1 is unambiguous, whereas wavelength λ' is shorter than Δx, and the phase differential ϕ'_2-ϕ'_1 does not allow the time difference to be calculated, as there are several other waves ("?") with identical phase, leading to ambiguity.

This results in a level differential between the ear that is ipsilateral to the source (higher level) and the contralateral ear (lower level).

ILD is expressed as [10]:

$$ILD(\alpha, f) = 0.18 \cdot \sqrt{f \cdot \sin\alpha}$$

ILD is thus virtually zero below 1500 Hz, and becomes relevant for wavelengths shorter than head diameter (> 1500 Hz) [12].

The more lateral the incidence, the greater the ILD [17]. Under optimal conditions, the smallest perceptible ILD is 0.5 dB [12].

2.1.2. Cone of confusion: dynamic binaural and spectral monaural cues

ITD and ILD provide precise localization in the azimuthal plane, with the exception of what is known as the "cone of confusion" [18]. For sounds coming from the circumference of this cone, the axis of which is the interauricular line, there are no time or level differences, leading to confusing perceptual coordinates: the subject is unable to tell whether the sound is coming from in front or from behind, above or below, or from anywhere else along the circumference (Fig. 4). For any sound source with coordinates Δ, α, θ, there is a mirror-image position (Δ, 180 – α, $-\theta$) with similar ITD and ILD.

Dynamic, spectral and visual perceptual disambiguation strategies therefore developed.

There are dynamic cues that can reduce ambiguity. Moving the head (or, in animals, the ears) introduces extra binaural and spectral cues enhancing localization [19]. By leaning the head (and thus the vertical interaural axis) or turning it, the amplitude and phase of the sound waves reaching either ear are altered, providing dynamic binaural cues. Head movements also provide an accumulation of HRTFs, refining localization and shrinking the cone of confusion.

Moreover, even without altering the interaural axis angle (i.e., leaning or turning the head), the auditory system can take advantage of interference profiles induced by the pinna, head and trunk or by holding the hand to the ear. HRTFs thus allow two sources with identical ITD and ILD (in front of and behind the subject) to be distinguished. These spectral cues are, moreover, the only sort to be available for azimuthal localization in monaural hearing [20].

Finally, like for other sensory stimuli, auditory perceptual disambiguation also involves integrating multiple other sensory input,

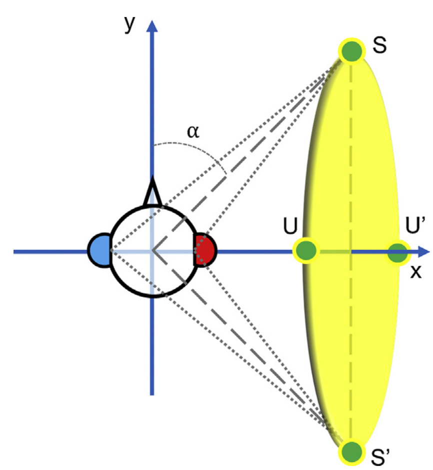

Fig. 4. Illustration of cone of confusion. When the subject holds his or her head still, sources S and S′ in the azimuthal plane show the same interaural time and level differences; likewise for sources U and U′ in the vertical plane. This front/back and high/low ambiguity applies to the entire surface of the cone of confusion. (Based on [10,19]).

notably visual. Once a sound has been located as coming from such-and-such an area and such-and-such a distance, visual data help fix the position. Moreover, prior knowledge concerning the location of the sound source helps determine its present location. It is noteworthy that images take precedence over sounds, in the "proximity-image effect" described by Gardner in 1968 [21]: if some visual clue is available, the sound source will be located accordingly, even if mistakenly. Indeed, the whole principle of the cinema depends on this.

2.1.3. Horizontal localization accuracy

The accuracy of localization depends on the azimuthal position of the sound source and the characteristics of the acoustic stimulus.

Accuracy varies firstly with azimuthal position. For example, for a 100 ms 70-phone white noise, localization uncertainty is 3–4° for frontal sources (azimuth 0°), 5–6° for sources behind the hearer (azimuth 180°), and around 10° for lateral sources (azimuth 90° or 270°) [15].

Acoustic characteristics further influence accuracy.

Table 1
Accuracy of azimuthal sound source localization by interaural time difference (ITD) and interaural level difference (ILD) according to frequency.

Binaural localization cue	Localization accuracy		
	< 1000 Hz	1000–3000 Hz	> 3000 Hz
ITD	Good	Mediocre	Impossible
ILD	Impossible	Mediocre	Good

Sound stimulus frequency greatly affects the accuracy of localization [12,22,23], which is best for low frequencies (< 1000 Hz), poorest between 1000 and 3000 Hz, and intermediate for high frequencies (> 3000 Hz) [9,12,22]. This finding was confirmed by Yost and Zhong in 2014 [23]: in young normal-hearing subjects with 60 dB stimuli centered around 250 Hz, 2000 Hz and 4000 Hz, whether as narrow-band (< 1 octave) or pure tone sounds, localization was optimal at the low-frequency (250 Hz), intermediate at the high-frequency (4000 Hz) and poorest at the intermediate frequency (2000 Hz). This poorer localization between 1000 and 3000 Hz is due to insufficient binaural cues (ITD and ILD) at these frequencies: ITD becomes a poor cue around 1500 Hz while ILD only becomes reliable at 2000 (depending on azimuth angle) [9], leaving a band between 1000 and 3000 Hz in which the binaural ITD and ILD cues are mediocre, impairing localization accuracy [12,13] (Table 1).

Spectrum width also affects accuracy [24], which is better for white than for broadband (> 1 octave) noise, for which in turn it is better than for narrow-band noise (< 1 octave), and even more than for a pure tone [23]. For broadband (> 1 octave) sounds, localization accuracy is independent of central frequency [23]. For broadband tone bursts (≥ 2 octaves: 125–500 Hz, 1500–6000 Hz and 125–6000 Hz), altering the upper and lower band-pass filter had little impact on localization accuracy in normal-hearing subjects [25]. This suggests that locating the source of a broadband sound does not depend on the binaural ITD and ILD cues in normal-hearing subjects [25].

Finally, a larger number of sources can be located in the case of speech stimuli: the maximum number of simultaneous spatially separate sources that can be distinguished is around 4 for speech stimuli and 3 for tonal stimuli [26].

Level does not affect localization accuracy, as recently demonstrated by Yost [27]: in normal-hearing subjects, there were no significant differences in localization accuracy for various sounds between 25 and 85 dB SPL. Likewise, duration does not affect accuracy: there were no significant differences in localization accuracy for various sounds lasting 25, 150 or 450 ms, in agreement, as the author points out, with the other few published studies [27]. Finally, modifying the envelope (amplitude modulation) had little or no impact on the accuracy of locating an azimuthal source in free field [14].

The accuracy of sound source localization thus depends on:

- azimuthal position: better in front than to the side;
- type of stimulus:
  - band width: the wider the band, the better the accuracy,
  - frequency: poorer between 1000 and 3000 Hz,
  - and speech or tonal type of sound.

In contrast, it is unaffected by sound duration, level or envelope.

Head movements provide an accumulation of monaural and binaural dynamic cues, improving localization accuracy. It has, however, been shown that presenting a sound stimulus while the hearer is moving his or her head leads to poorer accuracy than if the head were not moving [28]. Likewise, detecting displacement of the source is poorer during head rotation [29].

Table 2
Accuracy of sound source localization in the vertical plane by head-related transfer function (HRTF) according to frequency.

Monaural localization cue	Localization accuracy	
	< 7000 Hz	> 7000 Hz
HRTF	Moderate	Good

2.2. Vertical sound source localization

It was in 1901 that Angell and Fite first described the contribution of monaural indices in sound source localization [30,31].

Vertical source localization depends on the spectral composition of the sound. The trunk, shoulders, head and especially pinna act as filters interfering with incident sound waves by reflection, diffraction and absorption. These interferences modify the sound spectrum according to its origin: reinforcement (spectral peaks) or degradation (spectral notches) in certain frequency bands, locating the source in the vertical plane. This is called pinna effect [32,33]. The first spectral dip, known as the pinna notch, seems to be the major cue for determining elevation localization [19].

These spectral cues generated by the filtering action of the pinna (and also trunk, head and shoulders) are the HRTFs [3,10,19], a set of spectral deformations exerted on the sound on its way to the tympanic membrane. They are calculated by Fourier transform between the spectrum at the tympanic membrane and at emission.

The pinna plays an important role in HRTFs, but so does the outer ear canal [34]. The morphology of the body and particularly of the pinna varies greatly between individuals, and HRTFs are correspondingly individual. They are memorized by the brain throughout life in a learning process recording a multitude of transfer functions corresponding to different sound source directions. In a study of subjects wearing pinna ear molds, learning new HRTFs began after a few days, achieving normal vertical localization in 3–6 weeks [35]; when the mold was removed, localization ability continued to be normal, indicating that the prior situation remained in memory [35]. Similar results were reported in studies of horizontal localization, testifying to the brain's capacity for new learning and reweighting of localization cues [36,37].

HRTFs are especially easy to harness with familiar sounds, the spectrum of which, filtered by equally familiar HRTFs, easily allows to the source to be located.

Human subjects were shown to be able to be able to determine monaurally the vertical localization of high but not low-frequency sounds, probably due to the small size of the pinna, which allows it to interact only with short-wavelength sounds [38]. Sounds can be accurately located vertically only if:

- they are complex;
- they include > 7000 Hz components;
- the hearer's pinna is present [39].

Likewise, in 1976 Gardner and Gardner showed that localization in the median vertical plane was pinna-dependent, and easier for high frequencies, in broad rather than narrow-band [40]. For high frequencies, they also showed that localization results were similar for broadband noise and for narrow-band noise centered on 8000 Hz or 10,000 Hz [40]. The accuracy provided by HRTFs in the vertical plane is thus highly dependent on frequency (Table 2).

2.3. Distance localization

Determining the distance of a sound source mainly depends on monaural cues, and is much easier for familiar sounds [41].

Generally speaking, close distances tend to be overestimated and long distances underestimated [42].

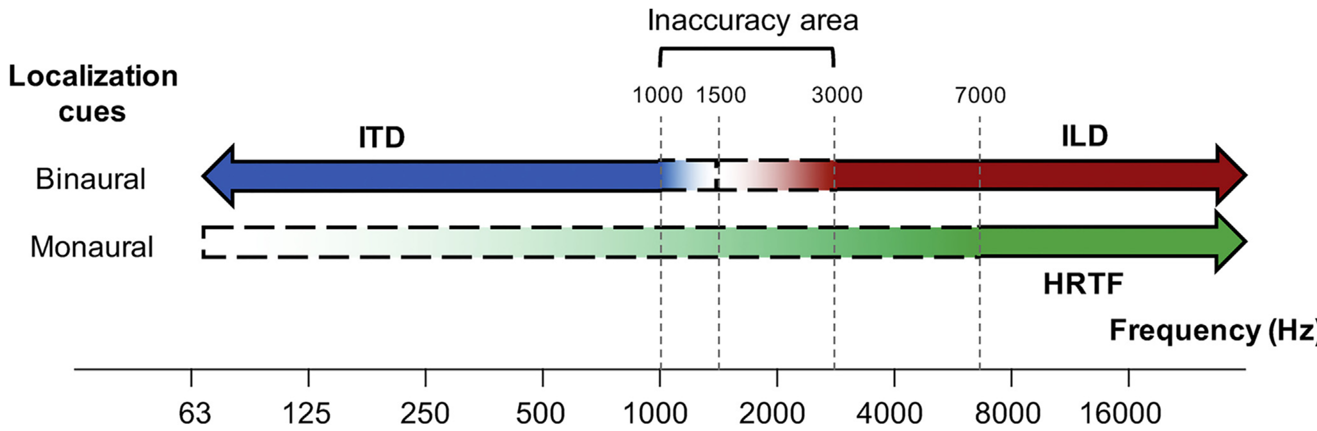

Fig. 5. Representation of sound source localization cues according to stimulus frequency. ITD: interaural time difference; ILD: interaural level difference; HRTF: head-related transfer function.

The direct-to-reverberant energy ratio [19] is the first distance cue. Two types of sound reach the ear, especially in closed echogenic spaces: direct and reverberant. The former arrive without being reflected by a wall, while the latter have been reflected at least once. The ratio between the two gives an indication of source distance [43], which is indeed easier to determine in a reverberant than in an anechoic environment [44]. For nearby sources, it is the direct sound that predominates (e.g., a speaker close to the listener), while for more distant sources the reverberant sound predominates (e.g., gunshot in the countryside). The reverberant sound includes multiple reflections and is thus homogenous throughout the space of a room, whereas the direct sound varies with proximity. It is also the direct sound, which, arriving first, is taken into account for localization: this is the above-mentioned precedence effect, or law of the first wavefront [15–17]. Localization thus remains feasible in echoing conditions, even if the reverberant sound is louder than the direct sound [45].

Initial time delay gap (ITDG) is the time gap between the arrival of the direct sound wave and the first strong reflection. Nearby sources entail relatively large ITDGs, as the first reflections have further to travel, whereas direct and reflected waves from distant sources travel comparable distances and show short ITDGs.

Level is also a distance cue, distant sources giving rise to lower perceived level. This can most easily be assessed for familiar sources. The intensity loss (I, in dB) is expressed as [46]:

$$I = 20 \cdot log_{10}\left(\frac{d_1}{d_0}\right)$$

where d_0 is the initial distance of the source and d_1 the new distance. Thus, level is reduced by 6 dB per doubling of distance.

Spectrum is another distance cue, high frequencies being more quickly muffled by the air: air absorption coefficient is higher the higher the sound frequency [46]. Thus, distant sources sound more muffled, as their high-frequency components are attenuated. For sounds of known spectral shape (such as speech), distance can be roughly judged from the perceived spectrum.

Movement also affects acoustic perception: for a moving hearer, neighboring sound sources pass by more quickly, in a parallax effect.

Binaural cues, and especially ILD, also help locate nearby (< 1.5 m) sources [47], due to considerable level differential between the ears (e.g., whispering in one ear).

3. Conclusion

Sound source localization depends on 3 types of cue: 2 binaural (ITD and ILD) and 1 monaural (HRTF).

Interestingly, due to the physical properties of the head, preponderant cues depend on sound stimulus characteristics. There is thus a change in cuing around 1500 Hz, with ITD used below and ILD above [9,12]. This leaves a “gray area”, roughly between 1000 and 3000 Hz, where the binaural cues are inefficient (Fig. 5).

Good understanding of the physics of sound source localization is a prerequisite for good stereo-audiometric assessment of patients.

Disclosure of interest

The authors declare that they have no competing interest.

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