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Review Paper

Sound Source Localisation in Digital Hearing Aids: A Review of Critical Factors

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Sound source localisation is a fundamental ability for a listener's functional interaction with the environment, yet it remains a significant challenge for hearing aid users. In general, they perform worse on spatial hearing tests than individuals with normal hearing. This narrative literature review examines the critical factors affecting sound source localisation when hearing aids are worn, with a focus on direction identification. We analysed peer-reviewed articles published over the past three decades to evaluate the impacts of the type of fitting, form factor, acoustic coupling, processing delay, bandwidth, directional microphones, and dynamic range compression on localisation ability. As a general conclusion, there is a consensus in the literature that binaural and open fittings, with microphones at the ear entrance and with extended bandwidth, significantly improve localisation performance. In addition, this review is intended to provide valuable information that can guide future innovations in hearing aid technology to improve users' hearing experiences and their integration into the environment.

Keywords: hearing aids; sound source localisation; binaural hearing; head-related transfer functions.

1. Introduction

Sound source localisation is an important auditory function that refers to the ability to infer both the direction and distance of a sound source. It enables us not only to localise sound sources but also to separate sounds based on their spatial locations, which is particularly important in situations where visual information is unavailable (Blauert, 1997). Spatial awareness comes into play in various scenarios, such as shifting attention between speakers during conversation or understanding speech in highly reverberant rooms (Minnaar *et al.*, 2010). Despite the higher spatial resolution of vision, the auditory modality allows us to monitor objects located anywhere around us. In addition to its role in survival, sound localisation significantly contributes to aesthetic experiences and spatial orientation (Killion, 1997).

It is known that the human hearing system is capable of estimating the position and distance of sound sources by exploiting so-called localisation cues. The human auditory system relies on input from both ears to assess the spatial properties of complex and reverberant environments, including the number, distance, direction, and orientation of sound sources, as well as the level of reverberation (Blauert, 1997; Derleth *et al.*, 2021). Normal-hearing listeners naturally master these spatial properties of sound and have a remarkable ability to localise sound sources. However, this is not the case for hearing-impaired individuals. In general, these people tend to perform worse in spatial hearing tests than people with normal hearing (Akeroyd, 2014). Such deficits in directional hearing can significantly diminish quality of life and may compromise rapid responses in potentially hazardous situations. Most of these people resort to hearing aids (HAs) to compensate for reduced hearing sensitivity, either in one or both ears.

Listeners with hearing loss (HL) tend to localise sounds more accurately without their HAs than with them (Akeroyd, 2014; Kumar *et al.*, 2024; Van den Bogaert *et al.*, 2006). However, some studies suggest that after an adaptation period, most listeners can recover their pre-amplification localisation abilities, particularly in the horizontal plane (Drennan *et al.*, 2005). Furthermore, individuals with hearing impairment often struggle to understand speech in complex acoustic environments, such as group conversations (Gatehouse, Noble, 2004), whereas normal-hearing individuals can do so effortlessly. Several studies suggest that sound source localisation plays a crucial role in the process of spatial separation between speech and competing signals, thereby enhancing intelligibility (Bregman, 1994; Cubick *et al.*, 2018; Freyman *et al.*, 1999; Hawley *et al.*, 1999; 2004; Wang, Brown, 2006).

A pioneering study by Byrne and Noble (1998) reviewed sound localisation with HAs and their characteristics: unilateral vs. bilateral, coupling, type of HA, frequency range, and potential effects of directional microphones and compression. Although this work dates from the early days of digital HAs – which began to be commercially available in 1996 (Bille *et al.*, 1999) – to the best of our knowledge, no updated review on this topic exists. There are other studies, with a more general focus, that address issues such as localisation and spatial hearing. Georganti *et al.* (2020) discussed intelligent hearing instruments, including HAs and cochlear implants, while Akeroyd and Whitmer (2016) investigated whether people with HL are also affected by a loss in sound source localisation ability and the potential benefits of HAs. They reviewed 29 studies published since 1983 that measured acuity in direction perception in the horizontal plane (left-right and front-back acuity). Derleth *et al.* (2021) briefly summarised the advantages of binaural over monaural hearing, followed by a detailed description of related technological advances in modern HAs. Zheng *et al.* (2022) reviewed contemporary studies on localisation ability across different populations in different listening environments, examining how this ability is affected by various hearing devices, including HAs, bone-anchored hearing instruments, and cochlear implants. Shiraishi (2021) discussed sound localisation and lateralisation with bilateral bone conduction devices, middle ear implants, and cartilage conduction hearing aids.

The aim of this work is to present a narrative literature review focusing on the critical factors that influence accurate sound source localisation in digital HAs. Particular emphasis will be given to direction identification rather than distance perception or externalisation. Estimating the distance of a sound source involves more complex variables, such as sound intensity, environmental acoustics, and reverberation. Instead, when a user determines the direction of a sound, they can quickly orient their head or eyes towards the source, allowing them to integrate visual cues and enhance overall localisation accuracy.

Based on the review by Byrne and Noble (1998), the present study attempts to provide an updated state-of-the-art overview of recent advances in the field, help to contextualise the problems, and identify potential solutions. The discussion focuses on factors influencing sound localisation, including fitting type and mode of operation, form factor, acoustic coupling, processing delay, bandwidth, and algorithms for directional microphone processing and wide dynamic range compression. Finally, a section on technological advancements with potential implications on sound localisation is included.

To ensure a thorough review, an initial core set of reference articles was selected and expanded through a comprehensive search of academic databases using various keyword combinations. Additional studies were identified via forward and backwards snowballing techniques. Finally, the authors' exclusion criteria were used to form the final corpus of relevant articles.

2. Background of sound localisation

Binaural hearing enables spatial localisation, noise filtering, and speech comprehension in noisy environments by extracting perceptual cues from sounds reaching both ears (Koenig, 1950; Werner *et al.*, 2012). This section outlines key aspects of auditory localisation, with additional details available in reviews by Yost (2017) and Carlini *et al.* (2024).

The localisation of sounds in the horizontal plane depends on two main cues: the interaural time difference (ITD) and the interaural level difference (ILD). The ITD is the difference in the amount of time it takes for a sound to reach both ears, resulting in interaural phase differences that vary with frequency, and depends on head size and the speed of sound (Blauert, 1997). ITDs are most effective at frequencies below 1500 Hz, corresponding to longer wavelengths, but become ambiguous at higher frequencies, where wavelengths are shorter than the distance between the ears (Byrne, Noble, 1998; Dillon, 2012). On the other hand, the ILD is the difference in intensity between the sounds reaching each ear due to the acoustic shadow on the ear farther from the source. ILDs become effective above 1000 Hz and are particularly robust above 4000 Hz (Shaw, 1974). There is an intermediate region (between 1500 Hz and 4000 Hz) where both cues contribute, but localisation is less precise since neither ITD nor ILD is fully effective (Mills, 1958; Risoud *et al.*, 2018). For broadband sounds, low-frequency components dominate because ITD cues prevail over ILDs (Wightman, Kistler, 1992). Furthermore, ITDs dominate in quiet environments, and ILDs in noisy ones (Lorenzi *et al.*, 1999).

The locus of all positions with equal ITD/ILD is known as the cone of confusion. These positions are located in a cone and share an emergent axis from the ear canal (Blauert, 1997; Shinn-Cunningham, 2000; Von Hornbostel, Wertheimer, 1920). To localise sound sources within the cone of confusion and in the vertical plane, listeners use spectral cues. These cues, that arise due to the transformations produced by the head and pinnae on incoming sounds, are embedded in the head-related transfer functions (HRTFs) (Blauert, 1997). Known as monaural cues, they provide the critical information needed for vertical localisation and for resolving front-back ambiguities.

The encoding of azimuth and elevation information is independent. Vertical localisation is disrupted when spectral cues are altered, whereas azimuthal performance remains unaffected (Oldfield, Parker, 1984). However, Hofman *et al.* (1998) demonstrated that humans can gradually adapt to spectral alterations and relearn elevation localisation without compromising their ability to localise sounds horizontally.

Furthermore, sound source localisation is significantly influenced by dynamics. Head movements while listening to a sound increase the accuracy in determining its location. This holds true for resolving front-back ambiguities (Macpherson, Kerr, 2008; McAnally, Martin, 2014; Wallach, 1940) and for determining elevation (Kato *et al.*, 2003; Perrett, Noble, 1997; Thurlow *et al.*, 1967).

3. Hearing aids and sound localisation

Sound localisation relies on the availability of precise timing and intensity cues throughout the frequency spectrum. As stated before, individuals with HL often exhibit diminished sound source localisation capabilities due to compromised hearing thresholds, limiting their access to both binaural and monaural localisation cues (Byrne, Noble, 1998). Certain HAs do not seem to significantly improve this ability in the hearing-impaired individuals. In fact, some studies suggest that they may even worsen it compared to unaided listening (Van den Bogaert *et al.*, 2006; 2009a). Akeroyd (2014) reviewed five studies from 2005 to 2014 and found that in all of them, normal-hearing listeners performed better than unaided listeners with HL, while aided listeners exhibited equal or greater localisation errors than unaided listeners. This negative impact appears to be due to alterations of localisation cues caused by HAs (Dillon, 2012; Mueller *et al.*, 2012). There are numerous ways in which HA processing can distort both monaural (Denk *et al.*, 2018b; Durin *et al.*, 2014; Pausch *et al.*, 2018) and binaural cues (Brown *et al.*, 2016; Dillon, 2012).

In terms of sound localisation in horizontal plane, studies indicate that people with normal hearing have a mean error ranging from 5.3° to 9° in free-field condition, and 6° to 7.5° in listening room. In contrast, bilateral HA users show significantly larger errors: 13°–16° in free-field and 12°–12.9° in listening rooms (Best *et al.*, 2010; Dorman *et al.*, 2016; Fernandez *et al.*, 2025). Furthermore, some studies report that individuals with HL may localise sounds more accurately without HAs than with them (e.g., from 13° without HA to 17.5° with adaptive HA for a noise-free signal) (Byrne, Noble, 1998; Keidser *et al.*, 2006; Van den Bogaert *et al.*, 2006). Possible explanations for such poor horizontal localisation with HAs result from alterations of ITD or ILD as a result of independent time delays and/or level compression in both HAs. However, Best *et al.* (2010) suggested that lateral error angles were not affected by the presence of HAs, likely due to preserved low-frequency thresholds in participants and the direct acoustic input provided through the HA vents. Additionally, there is evidence that people adapt to altered binaural cues for localisation, thus most people become accustomed to their HAs' effects (Dillon, 2012).

Vertical localisation and front-back disambiguation are greatly impaired in individuals with high-frequency HL (Byrne *et al.*, 1992; Byrne, Noble, 1998; Noble *et al.*, 1994) and are not significantly improved by the use of HAs (Dillon, 2012; Van den Bogaert *et al.*, 2009a). Best *et al.* (2010) showed that mean polar-angle errors ranged from 32° (without HA) to 37° (with HA) in people with HL, and were considerably lower in people with normal hearing (14°–18°). Furthermore, front-back localisation acuity is about 2.5 times worse than left-right acuity for aided users (Akeroyd, Whitmer, 2016).

Moreover, individuals with conductive or mixed HL exhibit inferior performance in sound source localisation compared to those with sensorineural hearing impairments. Noble *et al.* (1994) found that unaided listeners with sensorineural HL showed a localisation accuracy ranging from 18% (vertical) to 77% (horizontal) for frontal sounds, and from 10% (vertical) to 59% (horizontal) for lateral sounds. In contrast, a lower accuracy was observed in unaided individuals with conductive or mixed HL, with scores of 11% (vertical) and 45% (horizontal) for frontal sounds, and 13% (vertical) and 32% (horizontal) for lateral sources. This reduced performance is attributed to a greater proportion of sound being transmitted to the cochleae via bone conduction, as opposed to air conduction, which is more prevalent in individuals with normal hearing or sensorineural HL. Consequently, bone-conducted sound, which reaches both cochleae regardless of the stimulation site, reduces the normal interaural time and intensity difference information (Stenfelt, Goode, 2005). In essence, both cochleae receive identical rather than different information. The use of HAs leads to improvement in horizontal localisation in individuals with conductive or mixed HL by increasing the proportion of air-conducted sound relative to bone-conducted sound (Byrne, Noble, 1998; Byrne *et al.*, 1995). Studies reported significant improvements in localisation errors of 23° (for induced HL) and 30° (for acquired HL) (Agterberg *et al.*, 2012; Zavdy *et al.*, 2022).

4. Critical factors for sound source localisation in hearing aids

4.1. Types of fitting and operation

There are two main types of HA fittings: unilateral and bilateral. Unilateral fitting involves the use of an HA device in one ear, whereas bilateral fitting involves the use of HA devices in both ears. However, in bilateral fittings, the HAs may operate in different modes: bilateral unlinked, bilateral linked, or binaural. Figure 1 illustrates these configurations.

It is important to clearly distinguish between the terms 'bilateral' and 'binaural' to describe modes of operation in HAs, as these terms are often used interchangeably in the literature. An HA that has a bilateral mode of operation employs one device per ear, where each uses its microphone to produce the output for the corresponding ear, with no exchange of information between the two devices (unlinked) or with exchange of some control parameters such as volume, auditory scene, or directionality mode (linked). In the first case, the original acoustic scenario is not preserved, which affects the user's ability to localise, separate, and track sound sources (Jeub *et al.*, 2010). In contrast, binaural HAs, introduced in the 1990s, allow audio signals to be transmitted between the two devices (Blauert, Braasch, 2020; Kollmeier *et al.*, 1993; Wittkop *et al.*, 1996). In this configuration, both signals and control parameters received by the left and right devices are mutually shared, which better preserves acoustic cues and provides a more natural listening experience (Van den Bogaert *et al.*, 2009b).

Bilateral fitting offers advantages over unilateral fitting in many categories (detection, discrimination, speech intelligibility in quiet, speech intelligibility in noise, and localisation), as confirmed by questionnaires (Boymans *et al.*, 2008; 2009; Noble, Gatehouse, 2006) and by measuring speech perception in noise and localisation (Boymans *et al.*, 2008; Köbler, Rosenhall, 2002). In contrast, unilateral configurations tend to perform worse for horizontal localisation (Akeroyd, Whitmer, 2016; Boymans *et al.*, 2009; Noble, Gatehouse, 2006). In addition, Boymans *et al.* (2008) reported that people with HL preferred bilateral fittings over unilateral fittings because of the potential benefits of using two HAs. Nevertheless, Byrne *et al.* (1992) concluded that localisation performance in individuals with unilateral fittings was similar to that in bilateral fittings when HL was mild (<50 dB). However, these findings might not fully apply today. Given its publication date, the study likely used analogue HAs, which introduced negligible processing delays compared with modern digital HAs. This distinction is important because analogue devices have less impact on ITDs.

Although bilateral fitting and operation may support the activation of binaural hearing mechanisms, they do not ensure it (Derleth *et al.*, 2021). Georganti *et al.* (2020) indicated that bilateral HAs with parameter exchange (linked operation) can preserve binaural cues, therefore improving sound localisation performance compared with bilateral unlinked HAs.

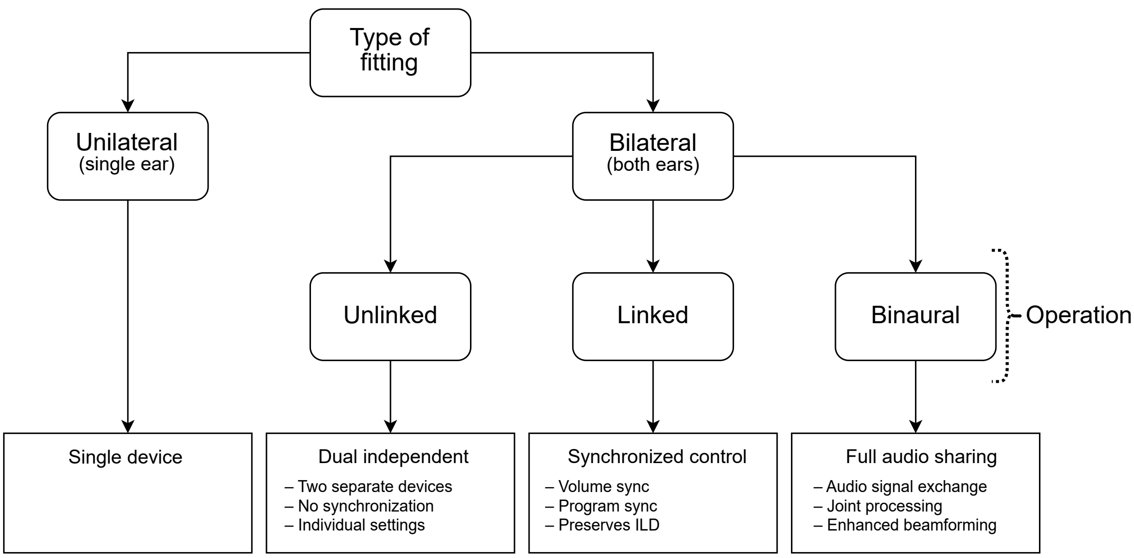

Fig. 1. HAs fitting configuration tree.

However, they do not enhance speech intelligibility (Ibrahim *et al.*, 2012; Smith *et al.*, 2008; Sockalingam *et al.*, 2009). In contrast, binaural HAs can significantly improve the performance of certain signal processing algorithms such as beamforming and noise cancellation, and thus provide better speech intelligibility. Chinnaraj *et al.* (2021) demonstrated that binaural operation can also improve horizontal localisation accuracy by about 5° compared with bilateral unlinked HAs.

4.2. Form factor

Figure 2 shows modern digital HA form factors (also called styles), which range from ultra-compact units that fit deep within the ear canal – invisible-in-the-canal (IIC) to devices that fill the outer ear to varying degrees, including completely-in-the-canal (CIC), in-the-canal (ITC), and in-the-ear (ITE), and finally to devices that are placed behind the pinna – behind-the-ear (BTE), or the receiver-in-the-canal (RIC) subtype, also called receiver-in-the-ear (RITE) (Durin *et al.*, 2014; Mondelli *et al.*, 2015). Note that these form factors also vary with respect to the placement of the microphone(s).

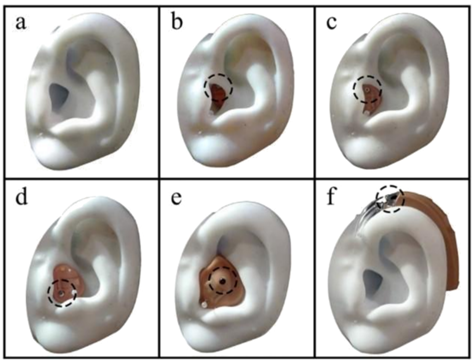

Fig. 2. HAs form factors: a) bare pinna; b) invisible-in-the-canal (IIC); c) completely-in-the-canal (CIC); d) in-the-canal (ITC); e) in-the-ear (ITE); f) behind-the-ear (BTE) HAs. Dashed circles indicate the microphone position. Adapted from Durin *et al.* (2014).[1]

HL itself does not affect a listener's HRTFs, as these are determined by individual anatomical features. When a person with HL wears HAs, HARTFs come into play (Pausch *et al.*, 2018). These HARTFs are strongly influenced by the location of the microphones (Derleth *et al.*, 2021; Diedesch, 2016; Durin *et al.*, 2014). For example, in the case of ITE HAs, the microphone is located at the entrance of the ear canal. In contrast, in BTE HAs, two microphones are typically located above the pinna and capture virtually no directional spectral cues (Best *et al.*, 2010; Denk *et al.*, 2018b; Diedesch, 2016). Given the similar microphone positions, there should be no major performance difference between BTE and RIC in terms of localisation (Kara *et al.*, 2024; Mondelli *et al.*, 2015). Denk *et al.* (2018a) demonstrated that direction-dependent errors can be observed at frequencies above 4000 Hz for microphones located on the concha and above 2000 Hz for microphones located behind the ear, with errors centred around the direction of frontal incidence. In the case of ITE, positioning the microphone closer to the canal does not produce better results in terms of directional cues compared with positioning it at the rear of the concha.

Regarding localisation in the frontal horizontal plane, no significant differences are observed between different HA form factors (Akeroyd, Whitmer, 2016; Van den Bogaert *et al.*, 2009a). For vertical localisation, Denk *et al.* (2019) conducted an experiment simulating different styles of HAs in individuals with normal hearing and found that BTE devices showed poorer accuracy and, in some conditions, approached chance levels. In this sense, devices positioned behind the pinna, such as BTE or its variant RIC, can also lead to increased front-back confusion (Byrne, Noble, 1998; Denk *et al.*, 2019). Other HA form factors, such as ITE, ITC or CIC, preserve most pinna-related directional cues naturally (Diedesch, 2016; Van den Bogaert *et al.*, 2009a) resulting in fewer reversals (e.g., 35 % for BTE and 26 % for CIC) (Best *et al.*, 2010). However, Best *et al.* (2010) found no differences in polar-angle error between CIC and BTE (~37°), probably due to the limited high-frequency audibility of their participants.

Despite microphone position having a strong impact on monaural cues, all HA form factors – except BTE – preserve directional information that can be partially relearned. Previous pinna-occlusion experiments have shown that by continuously wearing an earmould over a period of several days (10–60 days), allows subjects to adapt, to a greater or lesser extent, to distorted HRTFs for spatial localisation both within (Hofman *et al.*, 1998) and outside the visual field (Carlile *et al.*, 2007; 2014; Carlile, Blackman, 2014).

Durin *et al.* (2014) qualitatively described the spectral distortions of each HA form factor compared with the bare ear. Figure 3, adapted from that study, illustrates the directional transfer functions (DTFs) of HARTFs for the left ear on a logarithmic scale, highlighting how different HA form factors impact sound localisation. DTFs eliminate any directionally independent components of HARTFs to focus only on location-dependent variations (Middlebrooks, Green, 1990). Four cones of confusion are observed

[1]Adapted from [Durin V., Carlile S., Guillon P., Best V., Kalluri S. (2014), Acoustic analysis of the directional information captured by five different hearing aid styles, *The Journal of the Acoustical Society of America*, **136**(2): 818–828, https://doi.org/10.1121/1.4883372] with permission of Acoustical Society of America. Copyright [2014], Acoustical Society of America.

for: a) α = 20°, i.e., the contralateral hemisphere, b) α = 0°, the median plane, c) α = −30°, and d) α = −45°, the ipsilateral hemisphere. The red line represents the bandwidth limit of conventional HAs (~8 kHz) (see bandwidth Subsec. 4.5).

In the DTFs of the reference condition (without an HA), the first notch (N1) is clearly evident across all cones of confusion, with its centre frequency varying monotonically with polar angle, providing a strong elevation-dependent cue. It is important to note that the N1 in the IIC style most closely resembles the reference condition. The CIC and ITC styles also show good similarity to the reference in terms of spectral shape and N1 characteristics. However, the ITE and BTE styles significantly deviate, with the N1 being unclear in the ITE and completely absent in the BTE. Other differences among HA styles are observed in peaks around 13 kHz for the frontal region and 8 kHz for the superior region. While the IIC style closely mirrors the reference, CIC and ITC styles show slight deviations from it. The BTE style shows a different pattern of peaks across the whole frequency range.

Despite their poorer performance with regards to sound source localisation, Strom (2020) reported that people in the United States prefer BTE-type (BTE and RIC) HAs, which account for ~88 % of all devices sold. The reasons for this could be that such devices are comfortable to wear and virtually invisible on most ears and often provide better noise management algorithms and connectivity features compared with other HA styles.

4.3. Acoustic coupling

The occlusion effect is an increase in ear canal sound pressure level that results when bone-conducted sounds, such as the user's own voice, are prevented from escaping. In the case of HAs, the ear-mould or shell creates this effect by blocking the ear canal (Groth, Birkmose, 2004). This effect is most pronounced at

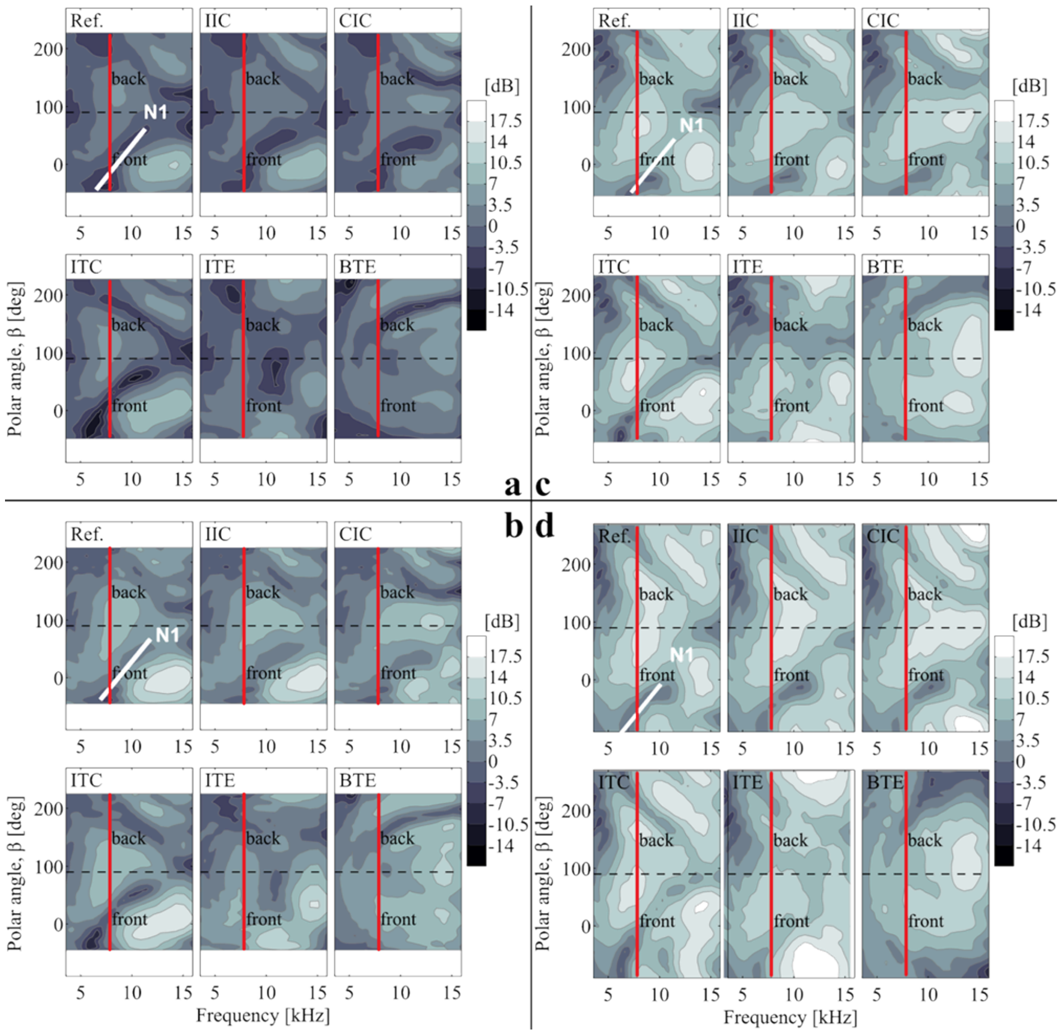

Fig. 3. Left-ear DTF log-magnitude as a function of frequency and polar angle in the planes: a) α = 20°; b) α = 0°; c) α = −30°; d) α = −45°, for five HA form factors and a reference. N1 is the first prominent notch in the DTF magnitude spectrum. The red vertical line represents ~8 kHz. Adapted from Durin *et al.* (2014).[1]

frequencies below 500 Hz and can cause the user to perceive the sound of their own voice as loud or 'boomy' (Dillon, 2012). Self-perceived occlusion decreases as the opening size of the earmould increases (Conrad, Rout, 2013). An open-fit HA reduces or even eliminates the occlusion effect, which results in better sound quality of the user's own voice and potential improvement of the user's localisation ability (Taylor, 2006; Winkler *et al.*, 2016). This improvement is due to the fact that it allows direct and undistorted access to low-frequency content and ITD cues, which are diminished or practically eliminated when closed or semi-open earmoulds (with openings up to 2 mm) are used (Byrne *et al.*, 1996; Mueller *et al.*, 2012; Noble *et al.*, 1998).

Diedesch (2016) showed that people with normal hearing and mild HL achieved the best localisation performance in a room without HAs (~7° error), followed by open earmould fittings (~8°), with the poorest performance observed in the occluded condition with closed earmoulds (~13°). For individuals with conductive and mixed HL, Byrne *et al.* (1996) found equivalent mean localisation performance across different earmoulds. It should be noted, however, that this study likely employed analogue HAs, given its publication date.

However, open-fit earmoulds also present certain disadvantages, such as reduced audibility at low frequencies due to lower maximum gain, diminished control over gain, reduced benefits of directional microphones, compression and noise reduction, as well as impaired sound quality due to the interaction between delayed amplified sound and the non-delayed opening, and, finally, less gain available before feedback occurs (Dillon *et al.*, 2003; Stone, Moore, 2003; Winkler *et al.*, 2016). Because of this, closed fittings are typically used when there is a risk of acoustic feedback or when the user has low-frequency HL.

4.4. Processing delay

Propagation delay refers to the time it takes for sound to travel from the HA microphone to the user's ear canal (Groth, Birkmose, 2004). This delay has been extensively studied for both open and closed fittings. This study focuses on the implications of delay for sound localisation in open fittings. For further details on the impact of delay in closed fittings (see Agnew, Thornton, 2000; Stone, Moore, 1999; 2002; 2003; 2005).

With the advent of digital feedback cancellation, open fittings have become widely used. The open fitting configurations result in a mixture of two versions of the same sound: on the one hand, the real-time sound with low attenuation that enters directly into the ear canal, and, on the other hand, the delayed and amplified sound provided by the HA (Stone *et al.*, 2008). Problems can arise from the interaction between the delayed signal and the non-delayed reference signal (Roth *et al.*, 2024). Since this delay is mostly due to digital processing, the challenge is to find the balance between the desired functionality and the time required to process it.

One of the outcomes is the comb-filtering effect, which occurs when certain frequency components interfere constructively or destructively, resulting in an alternating pattern of peaks and valleys in the overall frequency response. This leads to alteration of the sound's timbre (colouration), often described as 'barrel', 'sea shell', or 'listening through a pipe'. This effect is most noticeable with short delays (<15 ms) and when the direct and delayed sounds are of equal amplitude (Stone *et al.*, 2008).

The introduction of a high-pass filter in the processed signal path can diminish the comb-filtering effect by reducing the bandwidth of the transition zone (zone affected by both low-frequency direct sound and high-frequency delayed sound) (Denk *et al.*, 2019). Bramsløw (2010) investigated this approach using a Bradley–Terry–Luce (BTL) model (Bradley, 1984) and concluded that a signal path delay of up to 10 ms can be tolerated without compromising sound quality. The study also found no significant impact of different combinations of delays and high-pass filters on speech intelligibility.

Another undesirable consequence of processing delay is the echo effect. With longer delays, the delayed sound may be perceived as an echo. This effect is strongest when the direct and delayed sounds are equal in amplitude. The tolerable delay (i.e., the point at which listeners report being bothered or annoyed by changes in sound quality) has been reported as 24 ms–30 ms for other's speech when the delay is consistent across frequencies, and around 15 ms when the delay varies, as is often the case with HA filtering (Stone, Moore, 1999; 2002). However, for the user's own voice, tolerable delays have been reported to be 9 ms–10 ms (Agnew, Thornton, 2000; Bramsløw, 2010; Groth, Birkmose, 2004; Stone *et al.*, 2008).

It is important to note that Alexander (2016) indicated that commercial HAs have processing delays between 2 ms and 8 ms, with minimal impact even when additional functionalities are activated. These values, which are below the above-mentioned tolerable delays, have remained consistent despite major technological advancements throughout the recent years.

The effect of delay on sound source localisation was studied by Denk *et al.* (2019). They revealed that the influence of a vent and processing delays generally showed no large effect in vertical-plane localisation performance. The spectral ripples produced did not significantly bias relevant spectral directional cues, especially above 4 kHz, where the ripple decreased. In lateral localisation, errors increased under HA conditions. The disruptive effect of delay is approximately additive to the effect of microphone location. Moreover, Denk *et al.* (2019) showed that a simulated leakage component that directly enters the ear canal and carries unbiased directional cues in the low-frequency regime did not improve lateral sound localisation. This finding contrasts with the claim that improving sound localisation is one of the many motivations behind the use of vented or open-fitting devices (Akeroyd, Whitmer, 2016; Noble *et al.*, 1998). These alterations originate from fluctuations in ITD and contribute to increased source widths. The effects on lateral localisation were slightly reduced by minimising comb-filtering effects through proper filter design (Denk *et al.*, 2018c).

Derleth *et al.* (2021) warned that in the case of audio frame swapping (as in binaural HAs), the overall system delay is usually increased. This may degrade sound quality and can be detrimental to localisation in the lateral dimension.

4.5. Bandwidth

Most HAs have an effective frequency limit ranging from 5000 Hz to 6000 Hz (Levy *et al.*, 2015; Moore *et al.*, 2001), with more recent studies showing an extension up to 7000 Hz–8000 Hz (Van Eeckhoutte *et al.*, 2020). Bandwidth limitation modifies spectral cues, increasing front-back confusions and elevation errors, which frequently manifest as biased responses (Hofmann *et al.*, 1998).

Significant deterioration in localisation occurs when the upper cutoff frequency is reduced to 6000 Hz, and vertical localisation is severely impaired when it drops to 4000 Hz (Byrne, Noble, 1998). Therefore, accurate sound localisation performance requires this range to be extended. Although an 8000 Hz cutoff frequency is sufficient for proper speech intelligibility, speech contains information between 8000 Hz and 16 000 Hz that is essential for accurate vertical localisation. Up-down cues are located mainly in the 6 kHz–12 kHz band, while front-back cues are in the 8 kHz–16 kHz range (Langendijk, Bronkhorst, 2002). Best *et al.* (2005) showed that people exhibited a polar angle error of 30.9° when localising broadband speech, which increased to 46.4° when the speech was low-pass filtered at 8000 Hz. Furthermore, it is important to note that, when the bandwidth is limited to this frequency, there are small differences between HARTFs of different HA form factors. Only the BTE devices exhibit noticeable distortions (see Fig. 3) due to a different pattern of peaks across the whole frequency range (Best *et al.*, 2010; Durin *et al.*, 2014).

4.6. Processing algorithms

Signal-processing features, such as highly directional microphone technology or wide dynamic range compression (WDRC), can affect ILDs. In both cases, the signal appears to originate directly in front of the listener, rather than from their actual location (Diedesch, 2016; Picou *et al.*, 2014; Wiggins, Seeber, 2011).

4.6.1. Directional microphones

The deterioration that HAs cause in horizontal localisation becomes greater when additional algorithms, such as adaptive directional microphones, are activated, resulting in an increase in errors between 1.5° and 10° compared to an omnidirectional microphone condition (Keidser *et al.*, 2006; Van den Bogaert *et al.*, 2006). Directional microphones, also known as beamformers, enhance sounds coming from a particular direction, usually the front, while suppressing noise coming from other directions (Dillon, 2012). Directional microphones are not designed to improve localisation but to improve the signal-to-noise ratio (SNR) and thus speech intelligibility in noisy conditions (Byrne, Noble, 1998). Higher directionality offers better speech recognition, although makes it difficult to detect sources not located in front of the listener (Picou *et al.*, 2014). Directional microphones significantly reduce horizontal localisation accuracy compared to omnidirectional ones, with accuracy decreasing to around 50 % at high directionality levels (Akeroyd, Whitmer, 2016; Picou *et al.*, 2014). ITD cues are likely to be affected because different internal time delays are used to implement each specific polar pattern (Keidser *et al.*, 2006; Van den Bogaert *et al.*, 2006). ILDs are also affected because the polar pattern response shapes differ between the right and left devices, altering the level differences between ears. Spectral cues also change with the direction of the sound depending on the polar pattern used, since it is both frequency- and direction-dependent. However, front-back confusions can be reduced via a weak beamformer for frequencies above 1 kHz, which approximates the directionality of the pinna (Keidser *et al.*, 2006; 2009).

If the directionality is adaptive – meaning the devices can switch between omnidirectional and directional modes within each ear depending on changes in the noise scenario or acoustic environment – a mismatch may occur between the directionality modes of the HAs, causing a distortion of binaural cues and significantly increasing lateral-plane localisation errors (Van den Bogaert *et al.*, 2006).

Several methods aim to maximise the SNR while partially preserving binaural cues. A basic approach involves using an open-fit earmould or applying the beamformer only at mid and high frequencies, which helps to maintain ITDs intact at low frequencies (Derleth *et al.*, 2021). This is essential for maintaining localisation abilities, as ITDs dominate over ILDs in determining sound localisation. On the other hand, studies like those by Piechowiak *et al.* (2015)

and Jespersen *et al.* (2021) suggest adapting the microphone mode – switching between omni-directional and directional – depending on the acoustic scene. Finally, additional approaches include the binaural multichannel Wiener filter with HRTF preservation (Marquardt *et al.*, 2015) and the Jackrabbit method (Gomez, 2019), both of which incorporate algorithms designed to preserve spatial cues while enhancing SNR.

4.6.2. Dynamic range compression

WDRC reduces the range of ILD and introduces unwanted fluctuations when applied independently. This produces a conflict between unaltered ITDs and distorted ILDs, which can impair sound localisation for some stimuli, increase diffusivity, cause possible image separations, and reduce the externalisation of sound sources (Hassager *et al.*, 2017; Wiggins, Seeber, 2011). However, listeners exhibit a considerable capacity to adapt to abnormal ILDs. The impact on localisation ability varies depending on the compression ratio. According to Bakke (1999), a 2:1 compression ratio (reducing the ILD by half) in a single band does not affect localisation, whereas complete removal of ILDs degrades localisation accuracy. It is worth noting that the exception to this criterion is observed in low-frequency stimuli, where localisation remains unaffected even with 100 % attenuation of ILDs.

In order to preserve the original ILDs, some manufacturers implement a binaural exchange of amplification parameters between bilateral devices (Derleth *et al.*, 2021) to perform what is known as 'linked compression' or 'binaural compression'. This ensures that the original loudness difference is preserved at the outputs of both HA devices. However, as reported by Korhonen *et al.* (2015), there is a slight improvement in horizontal localisation yet it is not statistically significant. In contrast, with unlinked fast-acting compression, greater spatial separation between the target source and the masking source is needed to maintain spatial selective auditory attention (Schwartz, Shinn-Cunningham, 2013). This may require increased auditory effort, especially in noisy environments.

5. Technological advancements with potential impact on sound localisation

Many recent technological advances in HAs are associated with the application of wireless connectivity and deep learning (DL) methods (Hohmann, 2023).

Wireless connectivity in HAs was developed primarily to enhance speech understanding. However, it also contributes to improved spatial perception and sound localisation. A major advancement in this area is ear-to-ear (E2E) transmission between bilaterally fitted devices, which enables two key modalities: a) control data transmission, which synchronises programs and volume adjustments to preserve ILDs in bilateral linked operation; b) audio data transmission, which facilitates joint processing of acoustic signals for enhanced beamforming and noise-cancellation algorithms in binaural operation (Georganti *et al.*, 2020; Mecklenburger, Groth, 2016). However, E2E transmission involve a trade-off between optimising SNR and preserving spatial binaural cues, requiring careful balancing of these competing objectives (Neher *et al.*, 2017). Modern HAs primarily utilise two wireless technologies: Bluetooth – whose adoption is increasing (Picou, 2020; 2022) – and near-field magnetic induction (NFMI). While Bluetooth is mainly used for audio streaming, NFMI prevails in E2E transmission due to its technical advantages. However, there are cases where 2.4 GHz wireless technology (e.g., Bluetooth) is also employed for E2E (Derleth *et al.*, 2021).

In addition, recent studies applied DL methods to improve sound source localisation in indoor and reverberant environments (Chen *et al.*, 2025; Grumiaux *et al.*, 2022; Song *et al.*, 2022; Vecchiotti *et al.*, 2019; Zhang *et al.*, 2016), with some approaches incorporating head movements (García-Barrios *et al.*, 2022; Ma *et al.*, 2017). However, their implementation in current HAs remains challenging primarily due to the limited processing power, memory, latency constraints, and energy consumption. Deep neural networks, for example, typically employ multiple layers of interconnected nodes and time-frequency representations of raw audio to preserve optimal spatial representations, demanding substantial computational and memory resources (Goli, van de Par, 2023). In terms of latency, some algorithms require relatively long time windows to achieve optimal results (García-Barrios *et al.*, 2022). High computational demands also lead to increased energy consumption, which can compromise the battery life of compact devices (Khan *et al.*, 2025). Alternative approaches, such as cloud processing or smartphone co-processors, have been proposed but may introduce additional delays and additional points of failure (Fabry, Bhowmik, 2021). Addressing these limitations requires developing low-power, high-speed processing architectures, including edge AI and neuromorphic computing (Khan *et al.*, 2025).

6. Summary

Sound source localisation is an important function of human hearing that is impaired in people with HL, even when HAs are used. However, the extent to which HAs affect localisation performance varies according to different critical factors summarized in a list and in Table 1 for a quick and concise overview.

- Bilateral and binaural fitting and operation: there is evidence supporting the superiority of bilateral

Table 1. List of the main features of HAs affecting sound source localisation;
✓ best performance; – low performance; × worst performance; ⋆ does not significantly affect.

<table>
<tr><th colspan="2" rowspan="2">Features</th><th colspan="2">Localisation in the horizontal plane</th><th rowspan="2">Localisation in the vertical plane</th></tr>
<tr><th>ITD</th><th>ILD</th></tr>
<tr><td rowspan="3">Fitting</td><td>Unilateral</td><td colspan="2">× Unilateral configurations tend to be worse for horizontal localisation (Akeroyd, Whitmer, 2016)</td><td>× Vertical localisation is affected on the ipsilateral side, depending on the HARTFs</td></tr>
<tr><td>Bilateral</td><td colspan="2">– Bilateral fittings offer better localisation compared to unilateral fittings (Boymans et al., 2008; 2009; Köbler, Rosenhall, 2002; Noble, Gatehouse, 2006)</td><td>× Vertical localisation is affected on both sides</td></tr>
<tr><td>Binaural</td><td colspan="2">✓ Binaural or bilateral-linked HAs provide a better preservation of acoustic cues (Van den Bogaert et al., 2009b)</td><td>× Vertical localisation is affected on both sides</td></tr>
<tr><td colspan="2">Form factor</td><td colspan="2">⋆ No significant differences between different form factors (Akeroyd, Whitmer, 2016; Van den Bogaert et al., 2009a)</td><td>× BTE HAs impair vertical cues, increasing front-back confusions, compared to aids with microphones at the ear canal (Best et al., 2010; Denk et al., 2018a; Diedesch, 2016; Durin et al., 2014)</td></tr>
<tr><td rowspan="2">Acoustic coupling</td><td>Open</td><td>✓ Best localisation performance due to undistorted access to low frequencies and ITDs through the vent (Byrne et al., 1996; Diedesch, 2016; Mueller et al., 2012; Noble et al., 1998)</td><td>⋆</td><td>⋆</td></tr>
<tr><td>Closed</td><td>× Worst horizontal localisation performance (Diedesch, 2016)</td><td>⋆</td><td>⋆</td></tr>
<tr><td colspan="2">Delay</td><td>× Delayed output impairs horizontal sound localisation due to fluctuations in ITD (Denk et al., 2019)</td><td>⋆</td><td>⋆ Spectral ripple created by the delay does not significantly bias the relevant spectral directional cues (Denk et al., 2019)</td></tr>
<tr><td colspan="2">Bandwidth</td><td>⋆</td><td>⋆</td><td>× Narrow HA bandwidth negatively affects vertical localisation performance, as high-frequency spectral cues are eliminated (Best et al., 2005; 2010; Dillon, 2012; Durin et al., 2014; Langendijk, Bronkhorst, 2002; Levy et al., 2015)</td></tr>
<tr><td colspan="2">Directional microphones</td><td>× ITD cues are likely to be affected because different internal time delays are used to implement each specific polar pattern (Keidser et al., 2006; Van den Bogaert et al., 2006)</td><td>× ILD is affected because the polar pattern response shapes differ between the right and left devices, altering the level differences between ears (Keidser et al., 2006; Van den Bogaert et al., 2006)</td><td>× The spectral cues also change with the direction of the sound, depending on the polar pattern used (Keidser et al., 2006)
✓ Front/back confusions can be reduced using a weak beamformer for frequencies above 1 kHz (Keidser et al., 2009)</td></tr>
<tr><td colspan="2">Dynamic range compression</td><td>⋆</td><td>× Reduces ILDs (Hassager et al., 2017; Wiggins, Seeber, 2011), with impact varying depending on the compression ratio (Bakke, 1999)</td><td>⋆</td></tr>
</table>

fittings over unilateral ones in improving localisation. Binaural operation or bilateral linked operation, which allows for coordinated processing between the two devices, offers even greater benefits.

– Form factor and microphone location: the location of HA microphones significantly affects HARTFs. Devices with microphones at the ear canal entrance better preserve natural pinna cues and directional information, which users can partially relearn. In contrast, BTE models capture fewer directional spectral cues, leading to impaired vertical localisation and increased front-back confusions.

– Acoustic coupling: open fittings generally preserve spatial hearing cues better than closed fittings, particularly for low-frequency sounds and ITDs. However, this comes at the expense of reduced effectiveness of directional microphones, noise reduction, and overall gain.

– Signal processing delay: while spectral ripples caused by processing delays does not significantly affect monaural cues, they can impact lateral localisation due to fluctuations in ITDs.

– Bandwidth: the typically narrow bandwidth of HAs negatively impacts vertical sound localisation by eliminating high-frequency spectral cues that are crucial for this function.
– Directional microphones and WDRC: these technologies can alter ILDs, potentially affecting localisation performance. However, some modern devices incorporate design constraints to partially preserve binaural cues. Moreover, users often adapt to compression effects and can relearn horizontal-plane localisation over time.

7. Conclusions

This review has examined the impact of various HA features on sound source localisation, revealing several key insights. A general consensus in the literature points to the superiority of binaural and open fittings, particularly those with microphones positioned at the ear canal entrance and with extended bandwidth, in enhancing localisation performance. The findings also highlight the intricate relationship between HA characteristics and their influence on spatial hearing abilities.

This underscores the need for a balanced approach in HA development, weighing the advantages of different technologies and design choices against their potential impact on localisation capabilities. Future developments in HA technology should aim to enhance natural localisation cues without compromising usability or advanced signal-processing features.

Finally, an effort has been made to compile quantitative findings across studies; however, direct comparisons or concise summaries are often challenging due to differences in experimental designs and methodologies. Nevertheless, this review attempted to provide valuable information to guide future innovations in HA technology that seek to improve user's hearing experience and their integration into the environment.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution

All authors conceptualized the study and wrote the original draft. Fermín Scaliti curated the data and conducted the investigation process. Diego A. Evin and Fabián C. Tommasini supervised the work and Fabián C. Tommasini acquired funding. All authors reviewed and approved the final manuscript.

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