Binaural VoiceStream Technology™ permits the ability to exchange full bandwidth audio data between hearing instruments in real time. As a result, Phonak hearing instruments are now capable of providing truly binaural solutions for hearing-instrument users in complex and challenging listening situations.

Abstract

For many years (e.g., Cherry, 1953), hearing care professionals have understood the advantage of listening with two ears compared with one. In addition to improved intelligibility of speech in quiet, noisy, and reverberant environments, binaural versus monaural listening improves perceived sound quality and decreases the effort listeners must expend in order to understand a target voice of interest. Importantly, the recent development of full audio streaming between two hearing aids is poised to realize these benefits for individuals with impaired hearing. This paper will describe in detail why full audio streaming between hearing instruments is beneficial to the hard-of-hearing with a particular emphasis on the importance of binaural processing in challenging listening environments.

Introduction

Hearing loss is a significant health concern and currently affects roughly 40% of adults older than 65 years (Yueh et al., 2003). Untreated hearing loss has far-reaching consequences in psychosocial, emotional, physical, cognitive, and behavioral domains of one’s life (Dalton et al., 2003). World Health Organization estimates indicate that hearing loss is the second leading cause of years lived with a disability at a global level. In order to ameliorate the burden of impaired hearing, the most common method of rehabilitation is to provide listeners with hearing instruments coupled with counseling.

For most individuals with bilateral hearing impairment, the body of evidence collected across nearly three decades of research has found that the provision of two compared with one hearing aid yields significant benefit for the listener. Although research continues to more fully understand why listening with two ears compared with one ear is advantageous for most listeners, much has already been learned. What follows in this paper is some background information about research on the "cocktail party" problem, a brief summary of the major advantages of binaural compared with monaural listening, followed by a more detailed description of the potential benefits arising from a significant technological advancement in hearing instrument development, namely the capacity to wirelessly stream an audio signal from one hearing instrument to the other.
For over 50 years, researchers have attempted to better understand how listeners are able to perform extremely complex auditory tasks in "cocktail party" listening situations (Cherry, 1953). In cocktail party situations, a listener selectively attends to and identifies the speech from a single talker among a mixture of background conversations in a multitalker situation (for reviews see Bregman, 1990; Bronkhorst, 2000). Speech identification in the presence of background speech is a nontrivial challenge that results in a phenomenon called masking, which is the process by which the detection threshold for a sound (i.e., target) is made more difficult by the presence of another (i.e., masker) sound. When identifying target speech in the presence of speech maskers, the difficulties arise from two different types of masking. Whereas energetic masking (French & Steinberg, 1947) occurs when a target and masker compete for representation in a channel of information at the level of the auditory periphery (e.g., in a cochlear filter or on proximal portions of the auditory nerve), informational masking refers to the additional masking that is observed when there is competition for representation at higher or more central levels of processing (Durlach et al., 2003). The challenge of listening in environments where there is a relatively poor signal-to-noise ratio (SNR) for target compared with masking sounds is particularly deleterious for hearing-impaired and many older listeners (Pichora-Fuller & Singh, 2006).

In order to overcome the cocktail party problem, all but especially hearing impaired listeners rely heavily on the fact that humans come equipped with two ears. Before we take some time to consider why listening with two ears compared with one ear is important, let us quickly review some of the benefits associated with bilateral hearing instrument use. The advantages of bilateral compared with unilateral hearing instrument fittings include better understanding of speech in quiet (e.g., Nabelek & Pickett, 1974) and in noisy listening situations (e.g., McArdle et al., 2012), better sound localization performance on both objective (e.g., Kobler & Rosenhall, 2002) and subjective (e.g., Noble & Gatehouse, 2006) indices of sound localization abilities, improved sound quality (e.g., Balfour & Hawkins, 1992), decreased listening effort necessary to understand speech in the presence of background noise (Noble & Gatehouse, 2006), reduced auditory deprivation in aided compared with unaided ears (e.g., O’Neil, Connelly, Limb, & Ryugo, 2011), increased consumer satisfaction (e.g., Kochkin & Kuk, 1997), and higher scores on measures assessing self-perceived quality of life (e.g., Kochkin, 2000). In light of the potential benefits arising from the use of two compared with one hearing instrument, it should perhaps not be surprising that when given the choice, bilaterally hearing-impaired individuals strongly prefer bilateral instead of unilateral hearing aid fittings (e.g., Boymans et al., 2008).

Why listening with two ears is important

The benefits from the availability of two ears arise from a number of monaural and binaural auditory cues that facilitate speech identification in noise. Specifically, these benefits stem from:

1. The "better-ear" effect
2. Binaural directivity
3. Binaural loudness summation
4. Binaural redundancy
5. Binaural comparisons

What follows next is a more detailed discussion of each of these processes.
The “better-ear” effect

Likely the most important cue that listeners use to enhance hearing in noisy situations is the monaural cue arising because of the better-ear effect (Zurek, 1993). When target and masker signals are produced from different locations, there is a resulting SNR advantage at one ear relative to the other. This SNR advantage is acoustical in nature because the head acts as an acoustic barrier which produces a level difference between the ears (i.e., head diffraction effects). For example, compare a situation in which both target and masker signals are located to the listener’s left to a situation in which the target is on the right and the masker is on the left. Moving the target from left to right dramatically improves the SNR at the right ear, a process largely arising because of the sound shadow cast by the listener’s head. Alternatively, if the target is located to the left of the listener and the masker is located to the right of the listener, the resulting SNR will be more deleterious at the right ear and the listener can take advantage of the better SNR available at the left ear. Assuming spatial separation of a target and masker, the use of two ears provides the listener with the option to allocate attentional resources to the ear with the better SNR, regardless of the location of the target or masker, thus improving speech identification in noise (e.g., Hornsby, Ricketts & Johnson, 2006). An additional benefit is that the “decision” to attend to the better ear is largely a reflexive process when listeners are trying to understand speech presented in the background of noise and/or reverberant environments. Importantly, the listening advantage arising because of the better ear effect has been reported to be as large as 8 dB (Bronkhorst & Plomp, 1988).

Binaural directivity

As sound travels from the free field to the eardrum, the human torso, head and pinnae induce a number of direction-dependent acoustic transformations that help listeners localize auditory objects (Shaw, 1974). Importantly, by knowing where to listen, both younger and older listeners experience considerable benefit by focusing attention toward the target (e.g., Singh et al., 2008). Historically, studies investigating body-related acoustic transformations have focused on monaural acoustic effects; however, more recent research has focused on how the auditory system integrates monaural directivity (e.g., Sivonen, 2011), a process increasingly relevant for hearing instrument developers given the advances with binaural signal processing algorithms. Hence, binaural directivity is the directional listening advantage arising from listening with two ears compared with one. The philosophy motivating the development of binaural directivity signal processing strategies is to exploit a listener’s ability to focus attentional resources along a spatial vector.
Binaural loudness summation

The second important benefit of listening with two ears compared with one ear is that listeners experience an increased perception of loudness, a phenomenon known as binaural loudness summation (Reynolds & Stevens, 1960). Importantly, there are two characteristics of binaural loudness summation that make it particularly intriguing for developers of hearing instruments. First, let us consider the magnitude of the increase of loudness perception arising from binaural loudness summation. In general, threshold-based estimates of binaural loudness summation yield increases of loudness perception of approximately 3 dB (Keys, 1947). In contrast, loudness perception for supra-threshold signals is higher than that observed with near-threshold signals, with typical values ranging from approximately 6-10 dB (Haggard & Hall, 1982). Hence, this leads to our first interesting finding regarding binaural loudness summation – namely, that there is a significant listening advantage (i.e., 6-10 dB) when listening with two ears compared with one ear.

The second characteristic of binaural loudness summation that developers of hearing instruments find especially intriguing is that unlike several phenomena where hearing-impaired listeners typically demonstrate significantly poorer abilities than normal-hearing listeners (e.g., less spatial unmasking [Best, Mason & Kidd, 2011], less binaural noise reduction [Peissig & Kollmeier, 1997], increased susceptibility to forward masking [Oxenham & Plack, 1997]), hearing-impaired listeners demonstrate binaural summation values similar to that found with normal-hearing listeners (Hawkins et al., 1987; see Figure 1). This is an important detail because as hearing instruments continue to be developed so as to take advantage of the effect of binaural loudness summation, it suggests that all listeners can potentially experience benefit regardless of degree of hearing impairment.

![Figure 1 Mean binaural summation in dB for 500 Hz and 4000 Hz pure tones and speech spectrum noise (SSN) for normal hearing and hearing-impaired listeners. This figure was generated from Table 4 "MCL-B" from Hawkins et al. (1987).](image)

Binaural redundancy

Imagine a situation where a person experiences a loss of vision in both eyes, but remarkably, the loss is conspicuously different for each eye. For the left eye, the person experiences extreme tunnel vision and has no peripheral vision (as can happen with retinitis pigmentosa). For the right eye the person experiences a complete loss of central vision but peripheral vision remains completely intact (as can happen with macular degeneration). Although vision would be severely restricted when using only one eye, in theory, the use of both eyes would provide almost full access to a visual scene, as higher cognitive centers would integrate input from each eye in order to form a more unified and less fragmented image of the world. This scenario highlights the benefit of redundancy in the visual system arising from the availability of having two eyes (see Figure 2). Interestingly, a parallel process occurs in the human auditory system.

Binaural redundancy is the advantage obtained from receiving identical information about the signal in both ears (also referred to as diotic listening). One of the costs of listening with one instead of two ears is that there is only one opportunity for the auditory system to capture the available information in a signal. In other words, there is a loss of redundancy of cues available across the two ears. Binaural redundancy describes a process whereby the brain has two “looks” at each sound (Dillon, 2001). This process is particularly relevant for listeners with asymmetrical hearing losses because the auditory cues available in a given signal may be more readily accessible for one ear compared with the other. For example, consider an individual with a high-frequency hearing loss in the left ear and a low-frequency hearing loss in the right ear. By presenting a signal to both ears, the listener will be able to access low- and high-frequency cues with the left and right ear, respectively.
Listening can also be enhanced by making comparisons between the two ears, a process arising from the fact that when sounds arrive from a location in space (other than when presented directly in front of or behind a listener), the sound will first arrive at one ear relative to the other (resulting in an interaural timing difference or ITD cue), and the sound will be louder at the ear closer to the signal relative to the far ear (resulting in an interaural level difference or ILD cue) (for a review see Bronkhorst, 2000). Both cues are critically important for localization performance and their availability can facilitate speech understanding in complex listening environments when target sounds originate from unexpected listening locations (Singh, Pichora-Fuller & Schneider, 2008). In addition to providing ILD and ITD cues, binaural processing of interaural differences enables higher perceptual systems to take advantage of the subtle spectro-temporal differences between the target and masker signals arriving at each ear via a process known as interaural cross-correlation (ICCs) (e.g., Colburn et al., 2006; Culling, Hawley & Litovsky, 2004). For example, Akeroyd and Summerfield (2000) found that in difficult listening situations with low SNRs, listeners benefit from making fine-tuned comparisons of highly correlated spectral profiles of a signal arriving at one ear relative to the other. Importantly, the contribution of ILDs, ITDs, and ICCs to listening performance is relatively well understood in simple, highly-controlled, and anechoic listening environments. However, there is still much to learn about the benefit of these cues in noisy, reverberant, and multitalker listening environments, because all of these cues combine in complex ways that do not permit useful analysis with currently available experimental methodologies.

Importantly, the term binaural redundancy is frequently interchanged with binaural summation, a term not to be confused with binaural loudness summation which refers to the combination of information that results in an increased loudness percept. Improvements of 1-2 dB SNR are typically observed from experiments on diotic listening (e.g., Bronkhorst & Plomp, 1988). Importantly, both individuals with normal and impaired hearing can take advantage of the binaural redundancy effect (Day et al., 1988).

Figure 2
Left: Retinitis pigmentosa: Extreme tunnel vision (complete loss of peripheral vision).
Middle: Macular degeneration: No central vision (peripheral vision is undisturbed).
Right: Result: Access to most visual cues and a resulting percept that is more unified.

Binaural comparisons

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Although all the major manufacturers of hearing instruments have developed hearing aids capable of wirelessly exchanging information with each other, it is important to consider the sophistication of the data streaming capabilities available between the manufacturers. Currently, the most sophisticated hearing instruments are capable of sending and receiving information at approximately 300 Kbits/second. It is at these exchange rates that hearing instruments are capable of sending and receiving a full bandwidth audio signal, thus establishing a new and exciting frontier for developers and especially users of hearing instruments.

Moreover, the ability to copy, send, receive, and present ongoing audio signals between hearing instruments will continue to foster new innovations that take into consideration decades of research on binaural processing.

As previously discussed, in noisy and reverberant listening situations, speech understanding is greatly enhanced by attending to the ear with the better SNR, a phenomenon known as the better-ear effect. One of the significant advancements of modern hearing instruments is the capacity for the hearing instrument to calculate the amount of signal present relative to the amount of noise (i.e., SNR), a capability that can be performed at a resolution of individual frequency bands. In light of the ability to stream the full audio signal from one hearing instrument to the other, and because each hearing instrument is able to calculate SNR, it is now possible to stream a copy of the audio signal from the hearing instrument with the better SNR to the hearing instrument with the poorer SNR, thus providing the listener with the output of the "better ear" at not one, but both ears.

The capability to stream from the ear with a high SNR to the ear with a low SNR is perhaps best illustrated by the DuoPhone feature (see Figure 3). When using a phone with conventional hearing instruments, it is straightforward that there exists an ear where the SNR is relatively good (i.e., the phone where the ear is placed) and an ear where the SNR is relatively poor (i.e., the other ear). By wirelessly streaming the signal from the better ear so that a copy of the signal is presented at the poorer ear, the listener will experience an enhanced ability to understand speech on the phone (Picou & Ricketts, 2011). Although this example highlights the benefit of real-time audio exchange between hearing instruments when using the phone, there is potential for application of this technology in any situation where the hearing instrument detects a more favorable SNR at one ear relative to the other.

Importantly, Binaural VoiceStream Technology™ yields another important and unique benefit when coupled with standard directional microphone technology. In most modern hearing instruments, directional processing is achieved using the two omnidirectional microphones found on one hearing instrument. However, with the advent of full bandwidth audio streaming between hearing instruments, it is now possible to achieve directional processing that coordinates the signals from the four microphones available with a bilateral hearing aid fitting, thus permitting a truly binaural beamformer. As a result, it is now possible to achieve more advanced beamformer polar responses that were previously unavailable with directional microphone systems that coordinate input from two microphones. With StereoZoom, for example, Phonak is now able to achieve a more focused beam pattern compared with traditional monaural beamformers, resulting in significantly improved speech understanding performance (Kreikemeier et al., 2012).

**Figure 3**
Nyffeler (2010) depicting benefit on the Just Follow Conversation (JFC) test. Change is calculated by subtracting the level of the speech required when listening with DuoPhone from the level of the speech required when listening to a monaurally presented signal (positive values signify an improvement).
The reason listening abilities improve with full audio streaming between hearing instruments is largely because the hearing instruments are able to capitalize on the better ear effect, and this is critically important because of the additional benefits bestowed by binaural loudness summation and binaural redundancy. Recall that better-ear effects are perhaps the most important reason why intelligibility improves in challenging listening environments when target and masker signals originate from different locations (Brungart & Simpson, 2002). By copying the audio signal at the hearing instrument located at the better ear and presenting this signal also from the hearing instrument with the poorer SNR, listeners experience a more favorable listening situation. Specifically, the signal available at the “better ear” is processed and routed not just through the hearing instrument located at the “better ear”, but instead is processed and routed through both hearing instruments.

Importantly, the benefit of full audio streaming between hearing instruments is not limited to strategic exploitation of the better ear effect. In addition, wireless streaming of the full audio signal takes advantage of both the binaural loudness summation and binaural redundancy effect. As previously indicated, binaural summation provides listeners with a robust listening advantage of 6-10 dB, and importantly, the ability to exploit the benefit of binaural loudness summation appears to be fully preserved for listeners with sensorineural hearing loss. Finally, by presenting a signal to both ears, the auditory system is provided with multiple rather than just one opportunity to access auditory cues available in the signal (i.e., binaural redundancy). As previously indicated, binaural redundancy typically results in improvements of 1-2 dB SNR and are likely most important for individuals with asymmetrical hearing losses.

Lastly, recall that as sound travels from the free field to the eardrums, the human body produces a number of direction-dependent acoustic transformations that serve as important localization cues for listeners. Notably, the cues available to each ear combine a process resulting in binaural directivity or the directional listening advantage when listening with two ears compared with one ear. Both StereoZoom and autoStereoZoom are designed to mimic binaural directivity for bilaterally hearing-impaired listeners via coordination of the two dual-microphone systems available with bilateral hearing instrument fittings, a capability uniquely available with Binaural VoiceStream Technology™.

Conclusions

- **Binaural VoiceStream Technology™** is the capability to wirelessly exchange full bandwidth audio signals between hearing instruments. This represents a significant technological advancement in hearing instrument development and opens up the possibility to exploit decades of research on binaural processing.
- There is the potential to apply the full audio streaming technology in any listening situation where the hearing instrument detects a more favorable SNR in any frequency band of one of the hearing instruments relative to the other.
- **Binaural VoiceStream Technology™** takes advantage of several mechanisms critical for improving intelligibility in difficult listening environments. These mechanisms include the better-ear effect, the binaural loudness summation effect, and the binaural redundancy effect.
- **Binaural VoiceStream Technology™** when used in conjunction with directional microphone technology enables StereoZoom and autoStereoZoom, features which take advantage of the listening benefit arising from binaural directivity.
References


