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Differing Bilateral Benefits for Spatial Release From Masking and Sound Localization Accuracy Using Bone Conduction Devices

Fatima M. Denanto,[1,2] Jeremy Wales,[1,2] Bo Tideholm,[1,3] and Filip Asp[1,2]

Objectives: Normal binaural hearing facilitates spatial hearing and therefore many everyday listening tasks, such as understanding speech against a backdrop of competing sounds originating from various locations, and localization of sounds. For stimulation with bone conduction hearing devices (BCD), used to alleviate conductive hearing losses, limited transcranial attenuation results in cross-stimulation so that both cochleae are stimulated from the position of the bone conduction transducer. As such, interaural time and level differences, hallmarks of binaural hearing, are unpredictable at the level of the inner ears. The aim of this study was to compare spatial hearing by unilateral and bilateral BCD stimulation in normal-hearing listeners with simulated bilateral conductive hearing loss.

Design: Bilateral conductive hearing loss was reversibly induced in 25 subjects (mean age = 28.5 years) with air conduction and bone conduction (BC) pure-tone averages across 0.5, 1, 2, and 4 kHz (PTA_4) <5 dB HL. The mean (SD) PTA_4 for the simulated conductive hearing loss was 48.2 dB (3.8 dB). Subjects participated in a speech-in-speech task and a horizontal sound localization task in a within-subject repeated measures design (unilateral and bilateral bone conduction stimulation) using Baha 5 clinical sound processors on a softband. For the speech-in-speech task, the main outcome measure was the threshold for 40% correct speech recognition when masking speech and target speech were both colocated (0°) and spatially and symmetrically separated (target 0°, maskers ±30° and ±150°). Spatial release from masking was quantified as the difference between colocated and separated masking and target speech thresholds. For the localization task, the main outcome measure was the overall variance in localization accuracy quantified as an error index (0.0 = perfect performance; 1.0 = random performance). Four stimuli providing various spatial cues were used in the sound localization task.

Results: The bilateral BCD benefit for recognition thresholds of speech in competing speech was statistically significant but small regardless if the masking speech signals were colocated with, or spatially and symmetrically separated from, the target speech. Spatial release from masking was identical for unilateral and bilateral conditions, and significantly different from zero. A distinct bilateral BCD sound localization benefit existed but varied in magnitude across stimuli. The smallest benefit occurred for a low-frequency stimulus (octave-filtered noise, CF = 0.5 kHz), and the largest benefit occurred for unmodulated broadband and narrowband (octave-filtered noise, CF = 4.0 kHz) stimuli. Sound localization by unilateral BCD was poor across stimuli.

Conclusions: Results suggest that the well-known transcranial transmission of BC sound affects bilateral BCD benefits for spatial processing of sound in differing ways. Results further suggest that patients with bilateral conductive hearing loss and BC thresholds within the normal range may benefit from a bilateral fitting of BCD, particularly for horizontal localization of sounds.

Key words: Bilateral conductive hearing loss, Binaural hearing, Bone conduction, Sound localization, Spatial release from masking, Speech recognition in competing speech.

Abbreviations: AC = air conduction; ANOVA = analysis of variance; BAHA = Bone Anchored Hearing Aid (Cochlear Baha System); BC = bone conduction; BCD = bone conduction hearing device; EI = error index; ILD = interaural level difference; ITD = interaural time difference; NH = normal hearing; PTA_4 = pure-tone average, frequencies 0.5, 1, 2, 4 kHz; SNR = signal to noise ratio; SRM = spatial release from masking; SRT = speech recognition threshold.

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INTRODUCTION

Binaural hearing facilitates everyday listening tasks such as accurate horizontal sound localization, or understanding speech despite simultaneous competing sounds (Bronkhorst & Plomp 1988; Wightman & Kistler 1992; Zurek 1993; Bronkhorst 2000; Hawley et al. 2004). In normal hearing through air conduction (AC), sounds reach the two ears at different time and intensity resulting in interaural time differences (ITD) and interaural level differences (ILD) which are crucial for binaural hearing (Bronkhorst & Plomp 1988). The interaural differences arise as a consequence of the physical separation between the ears and the attenuation of the head. The ITD is defined as the difference in arrival time of a sound between the two ears, and the ILD is due to the head shadow affecting the level of the sound that reaches the two ears. The ITDs are dominant for signals below 1000 Hz, whereas the ILDs are dominant for frequencies above 1500 Hz (Blauert 1997).

Interaural differences facilitate auditory stream segregation and selective attention to a target signal (Bregman 1990). In environments with multiple spatially separated sound sources, as in many daily listening situations, the spatial separation between target and masking sound sources improves the recognition of target speech as compared with when they are colocated (Hawley et al. 1999; Bronkhorst 2000; Asp & Reinfeldt 2019, 2020). This phenomenon is extensively studied and commonly referred to as spatial release from masking (SRM; Culling et al. 2004; Kidd et al. 2010; Litovsky 2012; Glyde et al. 2013b). SRM may be achieved by a monaural process (Hawley et al. 2004) where a listener attends to the ear with the highest signal to noise ratio (SNR), for example, when a masking sound is on one side of the listener and a target sound is on the other

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[1]Division of Ear, Nose and Throat Diseases, Department of Clinical Science, Intervention and Technology, Karolinska Institutet, Stockholm, Sweden; [2]Karolinska University Hospital, Stockholm, Sweden; and [3]Division of Surgery, County Hospital, Nykoping, Sweden

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side of the listener. Associated with the ILD cue, the masking sound is attenuated by the head shadow giving rise to better ear listening available to the ear closest to the target. However, masking sounds are commonly distributed around a listener and the target sound is located between these interferers. In such conditions, binaural processing contributes to SRM. The binaural SRM is thought to stem from the disparity of ITD and ILD between target and maskers (Culling et al. 2004; Hawley et al. 2004; Kidd et al. 2010; Glyde et al. 2013b). In addition, in environments with multiple sound sources, listeners with normal hearing seem able to attend to the information from the ear with the better SNR at each specific point in time. Such "better-ear glimpsing" occurs either by a binaural (Brungart & Iyer 2012; Glyde et al. 2013a) or a monaural (Edmonds & Culling 2006) process, and substantially contributes to performance in speech-on-speech tasks (Schoenmaker et al. 2017). The potential for SRM increases when interfering sounds are intelligible and qualitatively similar to the target. For such conditions, the masking effect of the interfering sounds is perceptual (often referred to as "informational masking") beyond the masking occurring as a consequence of energy overlap of acoustic signals in the auditory periphery, and colocated speech recognition thresholds (SRTs) are elevated (Marrone et al. 2008; Rothpletz et al. 2012).

Accurate horizontal sound localization also depends on binaural processing of interaural differences (Rayleigh 1907; Jeffress 1948; Middlebrooks & Green 1991), specifically the ITD (Wightman & Kistler 1992). Horizontal sound localization may also be achieved by a monaural process, since the head-shadow effect results in a level cue for the location of a sound (Wightman & Kistler 1997; Wanrooij & Opstal 2004). This monaural level cue, however, is ambiguous for unknown sound intensities and therefore more useful for a fixed and known sound level than for roving or unpredictable sound levels (Wanrooij & Opstal 2004).

For patients with a bilateral conductive or mixed hearing loss who are not able to use conventional hearing aids due to, for example, chronic suppurative middle ear infections, eczema of the ear canal, or congenital malformations, one rehabilitation solution is a bone conduction hearing device (BCD). In hearing by bone conduction (BC) stimulation, the sound is transmitted from one point of stimulation through the skull bone and soft tissue to both cochleae with small differences in time and level (Stenfelt 2005; Stenfelt & Goode 2005). The level difference between the two cochleae arises from the transcranial attenuation which is highly variable between and within subjects depending on the method of measurement, positioning of the stimulation (Stenfelt 2012) and stimulus frequency (Stenfelt 2012; Stenfelt & Zeitooni 2013). At low frequencies, the transcranial attenuation is close to 0 dB, increasing up to 10 dB at higher frequencies (Stenfelt 2012; Stenfelt & Zeitooni 2013). Because of the limited transcranial attenuation, the binaural cues may be compromised for bilateral BC stimulation. Results from a cadaver study using bilateral bone conduction stimulation and pure-tone signals show complex intracochlear pressure patterns as a result of the interactions of signals presented from the left and right (Farrell et al. 2017). Specifically, if the transcranial attenuation is substantial, ILD should be the most useful binaural cue for bilateral BC since the relative amplitudes of intracochlear pressure patterns between the ears are modulated as a function of ILD (Farrell et al. 2017). Also, there is a transcranial time delay between the responses in the two cochleae that depends on the propagation velocity of BC sound through the skull (Tonndorf & Jahn 1981). The bilateral BC stimulation leads to frequency-dependant fluctuations of the intracochlear pressure, due to phase-dependant interactions (Farrell et al. 2017). Thus, both ILD and ITD cues in bilateral BC sound lead to different and complex interactions in both cochleae, as compared with AC sound, that could potentiate the binaural benefit.

A small number of clinical studies have shown a benefit in patients implanted with bilateral BCD in terms of sound localization ability and speech recognition in quiet and noise for relatively symmetrical BC thresholds (Bosman et al. 2001; Priwin et al. 2004; Janssen et al. 2012). The groups studied are small and heterogenous in terms of severity and duration of hearing loss, patient age and comorbidity as well as number of years use of bone conduction hearing devices. The masking signals used to study bilateral speech recognition benefits in challenging conditions in previous studies were noise or speech babble rather than intelligible speech signals, both when testing normal-hearing listeners using bilateral BCD under simulated hearing loss conditions (Gawliczek et al. 2018; Hilly et al. 2020), and in clinical cohorts (Bosman et al. 2001; Dutt et al. 2002; Priwin et al. 2004). For sound localization, accuracy improves with bilateral as compared with unilateral BCD (Bosman et al. 2001; Priwin et al. 2004; Janssen et al. 2012; Snapp et al. 2020). While there are data on the magnitude of the bilateral BCD benefit for low- and high-frequency stimuli available (Bosman et al. 2001; Priwin et al. 2004), the difference in magnitude of the benefit between low-frequency signals (mainly providing ITD cues) and broadband signals allowing access to ILD, ITD and monaural level and spectral cues is unknown.

This study has sought to expand on the limited knowledge available to the audiologist or surgeon when designing a rehabilitation strategy for a patient with a conductive hearing loss. The goals were to (i) study whether there is a benefit with bilateral BCDs, as compared with unilateral, on recognition thresholds and SRM in a speech-on-speech masking task, and (ii) find whether the bilateral BCD benefit for sound localization differs across stimuli to determine what sound localization cues are available with bilateral BCDs. Finally, since loss of inner ear function may affect hearing by BC, it would be of clinical interest and comparative value to obtain data from individuals with normal hearing where the conductive hearing loss is artificially induced.

Aim of Study and Hypothesis

The aim of the study was to compare spatial hearing between unilateral and bilateral bone conduction stimulation in normal-hearing listeners with simulated bilateral conductive hearing loss.

Our null hypothesis was that no bilateral BCD benefit existed for recognition thresholds in competing speech and horizontal sound localization accuracy.

MATERIALS AND METHODS

The study was approved by the National Ethical committee in Sweden (Ethical permit no. 2019-04696). All participants received oral and written information about the study before volunteering and a written informed consent was obtained for all participants.

Study Design

This study was an experimental cross-sectional study using a within-subject repeated measures design. The subjects' ears were blocked to simulate a bilateral conductive hearing loss. The subjects were subsequently fitted with bone-anchored hearing aids (BAHA; Cochlear Bone Anchored Solutions, Mölnlycke, Sweden) on a softband. The degree of the induced conductive hearing loss as well as hearing thresholds for unilateral and bilateral listening conditions were quantified. The subjects participated in two suprathreshold listening tests in sound field: speech recognition in competing speech where the masking speech was either colocated with or spatially and symmetrically separated from the target speech, and sound localization accuracy using four different stimuli. The measurements were performed with a BCD on softband both unilaterally and bilaterally. For the unilateral condition, the right ear was chosen for all subjects to minimize the number of variables. The total time for the procedure was approximately 2 hrs.

The speech in competing speech and sound localization accuracy tests were performed sequentially in two different audiometric sound booths. The listening condition (unilateral or bilateral) and test order (target and masking speech separated or colocated for the speech in competing speech test; order of stimulus for the sound localization accuracy test) was randomized and counterbalanced. Both BCDs remained on the softband at the subject's head at all times whether one BCD was deactivated or not. Neither the subjects nor the test administrator were informed whether unilateral or bilateral stimulation was provided until after all test procedures were completed.

A priori power analyses based on pilot experiments (n = 5) were performed to guide recruitment of subjects. Analyses indicated an 82% chance of correctly rejecting the null hypothesis of no bilateral speech recognition benefit for spatially separated competing speech with 22 participants with a α-error probability of 0.01. For the sound localization test, there was a 98% chance of correctly rejecting the null hypothesis of no bilateral BCD benefit in sound localization accuracy for the 4 kHz stimulus (see Section "Stimuli") with 4 subjects with an α-error probability of 0.01. The corresponding power and α-error existed with 9 subjects for the 0.5 kHz stimulus (see Section "Stimuli"). Accordingly, 25 subjects were recruited.

Subjects

Twenty-five adults with normal hearing (mean age = 28.5 years; range: 18 to 40 years; 13 females) volunteered for the study. All participants fulfilled the following inclusion criteria: native speakers in Swedish, AC hearing thresholds ≤25 dB HL at octave frequencies ranging between 125 and 8000 Hz, BC hearing thresholds ≤20 dB HL at octave frequencies ranging between 500 and 4000 Hz, age between 18 and 40 years and no history of noise exposure or frequent middle ear disease. The upper age limit of the inclusion criteria was based on a previously demonstrated interaction between age and SRTs in the speech recognition task used in the present study (Asp & Reinfeldt 2020). The pure-tone average across 0.5, 1, 2, and 4 kHz (PTA_4) for AC thresholds were 3.13 and 2.21 dB for the right and left ear, respectively, and PTA_4 for BC thresholds were 0.38 and 0.58 dB for the right and left ear, respectively. At all tested frequencies, the interaural AC threshold difference was ≤15 dB (median = 0 dB, except at 6 kHz where it was 5 dB).

Simulation and Quantification of Bilateral Conductive Hearing Loss and Aided Thresholds

A simulated conductive hearing loss was achieved by bilaterally filling the inner part of the ear canal toward the tympanic membrane with Terracortril thick ointment (Pfizer) and then placing a foam earplug (polyuretan, SwedSafe, Art no. 330098, European standard EN 352) in the outer part of the ear canal. The conchae of the pinnae were then filled with a silicone mold material (Otoform A soft, Dreve Otoplastik GmbH). The procedure was performed in the same way by the same otolaryngologist for all subjects.

The degree of the simulated conductive hearing loss was estimated by measuring frequency-modulated tone thresholds at 0.5, 1, 2, 3, 4, and 6 kHz in sound field using a fixed-frequency Bekesy technique, see details in Asp et al. (2018), Berninger et al. (2014). The same Bekesy technique was used to estimate hearing thresholds for unilaterally and bilaterally aided conditions, respectively. Thresholds were recorded with subjects seated at frontal incidence, 1.8 m from a loudspeaker at 0° azimuth, in a double-walled sound booth (4.0 m × 2.6 m × 2.1 m; mean ambient sound level = 20 dB [A] obtained during 15 sec measurement; reverberation time T_{30} = 0.09 sec at 500 Hz, as recorded with a B&K 2238 Mediator and a B&K 2260 Investigator [Brüel & Kjær, Nærum, Denmark]).

Fitting of BCD

BAHA 5 sound processors were fitted with a softband on the mastoid just behind the pinnae on each subject. The softband was tightly adjusted around the head as per each subject's comfort. No measurement of the pressure of the softband to the mastoid was performed. The processors were programmed based on each subject's nonaided AC thresholds and for each test condition (unilateral and bilateral) according to Cochlear's recommended standard fitting procedure for conductive hearing loss, using the most recent software (Cochlear BAHA Fitting Software 5.4, Cochlear Inc.) and in situ BC-direct measurements. Overall gain modifications per ear were allowed depending on subjective perception of loudness. Subjects were asked to aim for a percept of interaural loudness balance of the voice of the individual performing the fitting. The automatic scene classifier in the processors was active, so that gain, microphone directionality and noise reduction was adjusted automatically.

Recognition of Speech in Competing Speech

The same speech recognition in competing speech task has previously been used on normal-hearing subjects as well as subjects with unilateral profound or simulated hearing loss (Asp et al. 2018; Asp & Reinfeldt 2020). SRM for monaural AC conditions in the speech in competing speech test has previously been demonstrated to be half of the magnitude of binaural AC conditions (Asp & Reinfeldt 2020). This allows for comparison of performance on SRT and SRM with the present study.

Stimuli and Setup

Recognition of speech in competing speech was assessed using the Swedish Hagerman sentences (Hagerman 1982) in the same room as used for determination of the frequency-modulated tone thresholds. The Hagerman sentences are grammatically correct five-word sentences in a fixed syntax, with low semantic predictability. Twelve lists (and one training list), each containing 10 sentences, were used. The sentences (female voice) were presented from a frontal loudspeaker (0° azimuth). The masking sound consisted of four noncorrelated competing speech signals (one male voice reading out of a novel) that was either colocated (0° azimuth) with, or spatially and symmetrically separated (±30° and ±150° azimuth) from the target speech, thus creating a quasi-free sound field (Fig. 1). The height of the loudspeakers was aligned with the ears of the subject. The level of the masking speech was fixed at 63 dB SPL (L_{eq}, 12 min recording time) as measured at the position of the subject's head in absentia.

Test Procedure

An adaptive psychoacoustic task was used to estimate the SRT in competing speech. The training started at a SNR of +10 dB. For the following training sentences, the target speech level decreased up to three times in 5 dB steps, then up to three times in 3 dB steps, and then in 2 dB steps until the number of correct words was two out of the five words per sentence. Following training, the scheme for level adjustment of the target speech was +2 dB for zero correctly identified words, +1 dB for one correctly identified word, 0 dB for two correctly identified words, −1 dB for three correctly identified words, −2 dB for four correctly identified words, and −3 dB for five correctly identified words, aiming at a threshold of 40% words correct. This threshold and the adaptive scheme for level adjustment were based on computer simulations and analysis of the maximum steepness of the psychometric function (Hagerman 1979, 1982; Hagerman & Kinnefors 1995). The SRT was defined as the mean of the SNRs for the last 10 presented sentences (Plomp & Mimpen 1979; Hagerman & Kinnefors 1995).

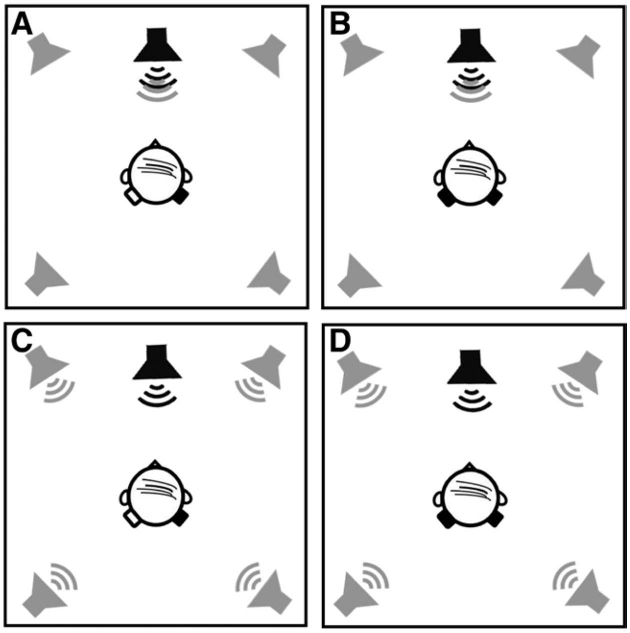

Fig. 1. Schematic illustration of setup for speech recognition in competing speech. Filled square denotes active BCD. A, Target speech and masking speech colocated at 0° azimuth, with unilateral BCD. B, Target speech and masking speech colocated at 0° azimuth, with bilateral BCD. C, Target speech at 0° azimuth and masking speech at ±30° and ±150°, with unilateral BCD. D, Target speech at 0° azimuth and masking speech at ±30° and ±150°, with bilateral BCD. BCD indicates bone conduction hearing devices.

For each listening condition (unilateral/bilateral) and presentation mode (separated/colocated target and masker), the subjects were presented with the same training list and subsequently tested with two randomly ordered lists. The subjects were seated in the center of the room, 1.8 m from the frontal speaker. Outside the room, a test administrator was seated with visual supervision of the subjects. Subjects were told to face forward at all times. They were not informed that the target signal originated from the frontal loudspeaker (0° azimuth) or which spatial presentation mode was used (separated/colocated target and masker) as this may influence SRM (Ihlefeld et al. 2006). They were instructed to repeat the words as accurately as possible. Guessing was encouraged, and no feedback was provided. The test administrator listened to the target signal and the subject's responses through a feedback system and scored the responses after each sentence. Words had to be repeated grammatically correct to be scored as correct.

The SRM for unilateral and bilateral listening conditions was calculated as the difference in SRT between separated and colocated target and masker presentation modes.

Sound Localization Accuracy

The horizontal sound localization accuracy task has previously been described in detail (Asp et al. 2016). The same presentation and response methodology as in Asp et al. (2016) was used here since it has high reliability (the estimated 95% confidence interval for a single sound localization accuracy measurement is ±0.054), detects differences between binaural and simulated monaural listening conditions (Asp et al. 2018), and allows for comparison with performance of individuals with normal hearing (Asp et al. 2018). In addition, the technique allows for rapid determination of localization accuracy (approximately 3 min recording time per measurement) which was deemed appropriate given the relatively taxing measurement protocol of the study.

Setup

Sound localization accuracy was measured in sound field in a double-walled sound booth (4.1 m × 3.3 m × 2.1 m) with low ambient sound level (25 dB [A]), and short reverberation time (T_{30} = 0.11 sec at 500 Hz), as recorded with a B&K 2238 Mediator and a B&K 2260 Investigator (Brüel & Kjær), respectively. Twelve active loudspeakers (ARGON 7340A, Argon Audio, Sweden) were placed equidistantly in a 110° arc in the frontal horizontal plane, resulting in loudspeaker positions at ±55°, ±45°, ±35°, ±25°, ±15°, and ±5° relative to the subject who was seated facing the loudspeaker array (Fig. 2). Seven-inch video displays were mounted below each loudspeaker. The loudspeakers and the loudspeaker stands were covered in black cloth, so that only the video displays were visible. The approximate distance from the head of the subject to the loudspeakers and the video displays was 1.2 and 1.1 m, respectively. The loudspeakers were at ear level, and vertically adjusted along with the video displays to accommodate different heights of the subjects.

An eye-tracking system (Smart Eye Pro, Smart Eye AB, Gothenburg, Sweden) was used to record the gaze of the subjects in relation to the video displays and loudspeakers (see Asp

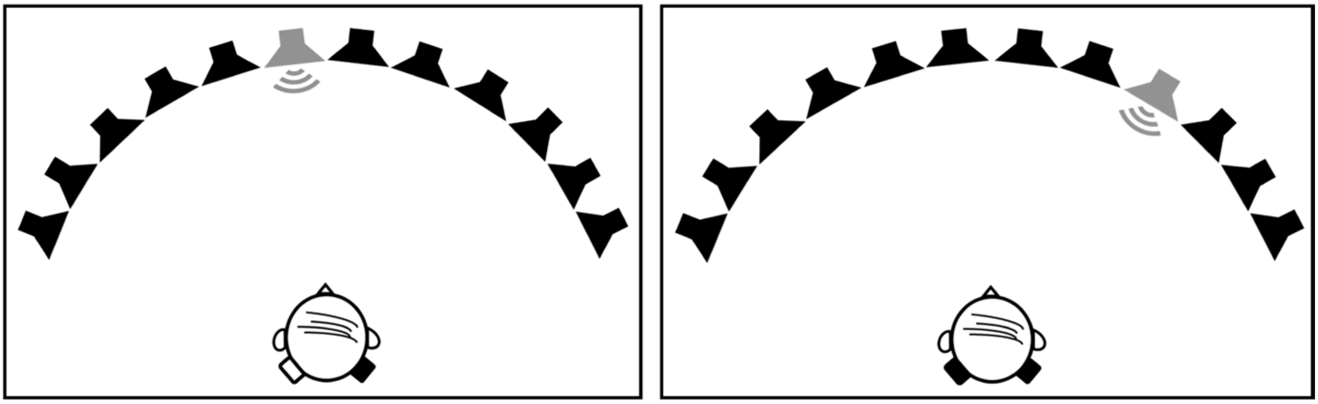

Fig. 2. Schematic illustration of setup for sound localization. Twelve loudspeaker/display pairs arranged equidistantly in an 110° arc in the frontal horizontal plane. A display is placed above each loudspeaker (not visualized). Target signal switching randomly to different loudspeakers. Filled square denotes active BCD. Left panel: Unilateral BCD. Right panel: Bilateral BCD. BCD indicates bone conduction hearing devices.

et al. 2016 for details). The coordinates of the video displays and loudspeakers were defined in three dimensions in the eye-tracking system, resulting in areas of interest (AOI; Gredebäck et al. 2010; Asp et al. 2016). In total, 12 AOIs, each with width 0.17 m and height 0.55 m, constituted a continuous array of AOIs in a 3D model, corresponding to the physical loudspeaker/display pairs.

Stimuli

To assess the contribution of different spatial cues to sound localization, four different stimuli were used.

Two stimuli were broadband and thus made ILD and ITD cues available. These stimuli had long-term frequency spectra similar to the unmodulated noise used with the Hagerman Sentences, and thus similar to the spectrum of a female voice (Hagerman 1982). One of these two stimuli was a musical melody (Asp & Reinfeldt 2018, 2020; Johansson et al. 2019; Eklöf et al. 2020) that minimized monaural level cues by naturally occurring amplitude modulations. The other broadband stimulus was a stationary noise, thus increasing the availability of monaural level cues compared with the musical melody. The rationale for using these two stimuli were to allow a comparison between conditions with and without distinct monaural level cues while ITD and ILD cues were available when localization was by BC, and to allow comparison with published data in individuals with normal hearing for the musical melody (Asp et al. 2018).

To assess the contribution of ILD and ITD cues to localization accuracy separately, localization accuracy was also measured using two octave-filtered noises with center frequencies (CF) at 0.5 and 4 kHz, providing interaural time and level cues, respectively. The 4 kHz stimulus also allowed access to monaural level cues, whereas the 0.5 kHz stimulus minimized monaural cues. All 4 stimuli for unilateral and bilateral conditions were presented at 63 dB SPL (in total 8 sound localization tests).

To assess to what extent AC stimulation (e.g., sound reaching the cochleae despite the simulated conductive hearing loss) contributed to sound localization performance, two additional tests (unilateral and bilateral) was performed. For these tests, an individual presentation level for the musical melody was used. This presentation level was obtained by presenting the stimulus at frontal incidence at 63 dB SPL when subjects were unaided, decreasing the level in 1-dB steps until the subject indicated by raising a hand that the stimulus was inaudible. The individual presentation level was then used to test the sound localization accuracy for aided conditions, assuming minimal AC contribution to sound localization. The melody was chosen since it was more ecologically valid than the other stimuli.

Test Procedure

Immediately before each test session, a calibration of the subjects' gaze relative to the visual displays was performed (Asp et al. 2016).

The stimulus was presented continuously and, in each of the four stimuli tests, started from the loudspeaker and display at −5°, just to the left of frontal incidence. After an average time interval of 7 sec, the visual stimulus was stopped and the sound was instantaneously shifted to a randomized loudspeaker. The visual stimulus was reintroduced after a sound-only period of 1.6 sec to allow sustained acquisition of gaze toward the video-screens. During the 1.6-sec sound-only period, the subjects were guided by audition only as to where the active sound source was located. The subjects were informed that they were allowed to move their eyes and heads freely. They were instructed to follow the auditory-visual stimulus and that sound-only periods would occur during which they should move their gaze to the screen where they believed the auditory stimulus came from. Once the visual stimulus showed, they would correct (or stay with) their gaze toward that screen. The auditory and visual shifts were repeated 24 times at random with the constraint that no loudspeaker/display was used a second time before each of the 12 loudspeaker/display pairs had been used.

Subjects' pupil positions relative to the loudspeaker/display pairs were sampled at 20 Hz. The resulting gaze/AOI intersections were derived from the output of the eye tracker and stored as a function of time. The perceived auditory azimuth was defined as the median of the final 10 gaze/AOI intersection samples obtained during the 1.6-sec sound-only period, that is, a 500-msec sampling period. Sound localization accuracy was quantified by an error index (EI; Gardner & Gardner 1973; Asp et al. 2011; Asp & Reinfeldt 2018) which was calculated as follows:

$$\mathrm{EI} = \frac{\sum_{(i,\ k)\in P} |i-k|}{\left(\sum_{i\in P}\sum_{k=1}^{n} |i-k|\right)/\mathrm{n}},$$

where P is the set of loudspeakers (1 to 12), i = the presented loudspeaker (1 to 12), k = the perceived loudspeaker (1 to 12), and n = 12 (the number of loudspeakers). The EI ranged from 0 (perfect performance) to 1 (random performance). The data from the sound localization test were also analyzed as perceived versus presented sound source azimuth. A Monte Carlo simulation showed that the 95% confidence interval for random performance using the current procedure was (0.72–1.28).

Sound localization accuracy was measured according to the test procedure described above for unilaterally and bilaterally aided conditions for all four stimuli (i.e., eight tests).

Statistical Analyses

SRT values, SRM values, EI values, and PTA_4 values were normally distributed. Main effects of listening condition (unilateral versus bilateral) and spatial condition (separated versus colocated target and masker), and possible interactions, were analyzed with a 2 × 2 repeated measures analysis of variance (ANOVA) for the speech recognition data. Simple linear regression analyses were performed to study the effect of hearing thresholds on the separated and colocated SRT within the unilateral and bilateral listening condition, respectively. Main effects of listening condition (unilateral versus bilateral) and stimuli, and possible interactions, were analyzed with a 2 × 4 repeated measures ANOVA for the sound localization data. All statistical analyses were performed using Statistica version 13 (Statsoft, Inc., Tulsa, OK).

RESULTS

Quantification of Simulated Conductive Hearing Loss and Aided Thresholds

The mean (SD) PTA_4 for the simulated conductive hearing loss was 48.2 dB (3.8 dB) (n = 25). The mean (SD) aided PTA_4 was 20.8 dB (3.0 dB) and 19.3 dB (2.8 dB) for the unilateral and bilateral BCD condition, respectively, corresponding to an average binaural summation of frequency-modulated tones of 1.5 dB. Mean and individual thresholds at 0.5, 1, 2, 3, 4, and 6 kHz are shown in Figure 3. The interindividual variability in the aided thresholds was larger at high frequencies than at low frequencies. For example, in the bilateral BCD condition, the range was 5.2 to 39.6 dB at 3 kHz and 16.0 to 34.0 at 0.5 kHz.

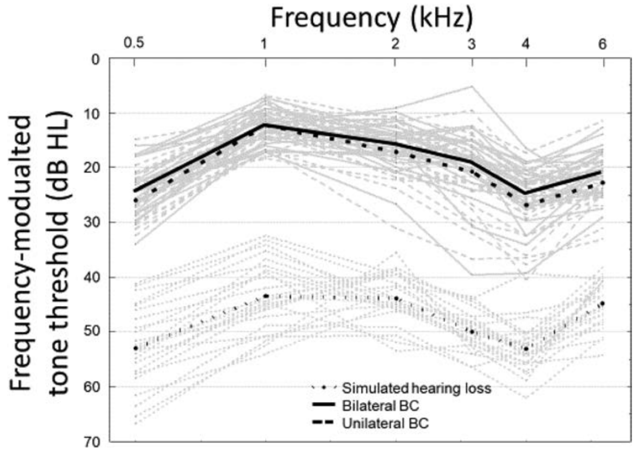

Fig. 3. Mean (black) and individual (gray) thresholds for detecting frequency-modulated tones in sound field (n = 25). Solid, dashed, and dotted lines denote bilateral BC stimulation, unilateral BC stimulation, and unaided simulated conductive hearing loss conditions, respectively. BC indicates bone conduction.

Recognition Thresholds for Speech in Competing Speech

Mean SRTs across listening conditions are shown in Figure 4A. A repeated measures ANOVA with two within-subject factors; listening condition (unilateral and bilateral) and spatial condition (separated and co-located target and masker), showed a significant main effect of listening condition [$F(1,24) = 6.7$, $p = 0.015$], and of spatial condition [$F(1,24) = 62.7$; $p < 0.001$], on the SRT. There was no interaction between listening condition and spatial condition.

In the separated target and masking speech condition, the mean SRT (SD) was −10.4 dB (±2.1 dB) for unilateral and −11.1 dB (±2.6 dB) for bilateral BCD. In the colocated target and masking speech condition, the mean SRT (SD) was −8.1 dB (±1.7 dB) for unilateral BCD and −8.8 dB (±2.3 dB) for bilateral BCD. This corresponded to a bilateral BCD benefit of 0.7 dB for both spatial conditions.

Individual Data and the Effect of Hearing Thresholds on SRT

Sixteen (64%) and 17 (68%) out of 25 subjects in the separated and colocated target and masking speech condition, respectively, had a bilateral SRT benefit (Fig. 4C, D). The range in SRTs in the separated target and masking speech condition varied from -14.6 dB to -6.5 dB for unilateral and -15.6 dB to -5.6 dB for bilateral BCD. For the colocated target and masking speech condition, the SRT ranged from −12.3 to −5.2 dB for unilateral and −13.7 to −5.4 dB for bilateral BCD. Five of 25 subjects (20%) showed an increased SRT with bilateral BCD for both spatial conditions (denoted by filled symbols in Fig. 4B, C).

There was no correlation between the SRT and the PTA_4 across spatial and listening conditions (p's > 0.05), suggesting that the variability in SRT was not related to hearing sensitivity with the BCDs. However, in the colocated target and masking speech condition, there was a significant correlation between the bilateral SRT benefit and the bilateral PTA_4 benefit (Bilat SRT benefit = 0.28 + 0.30 × Bilat PTA benefit, $r = 0.41$; $p = 0.04$; Fig. 5). No correlation existed between the bilateral SRT benefit and bilateral PTA_4 benefit in the separated target and masking speech condition ($r = 0.07$; $p = 0.72$).

Spatial Release From Masking

The mean SRM was 2.3 dB for unilateral as well as bilateral BC conditions (Fig. 6, left panel). SRM values ranged from −0.5 to 5.3 dB for unilateral BC and from −0.8 to 5.8 dB for bilateral BC (Fig. 6, right panel).

Sound Localization Accuracy

A repeated measure ANOVA with two within-subject factors; listening condition (unilateral and bilateral) and stimulus (musical melody, stationary noise, octave-filtered noise with CF at 0.5 and 4 kHz), showed a significant interaction between listening condition and stimulus [$F(3,66) = 5.1$, $\eta_p^2 = 0.19$;

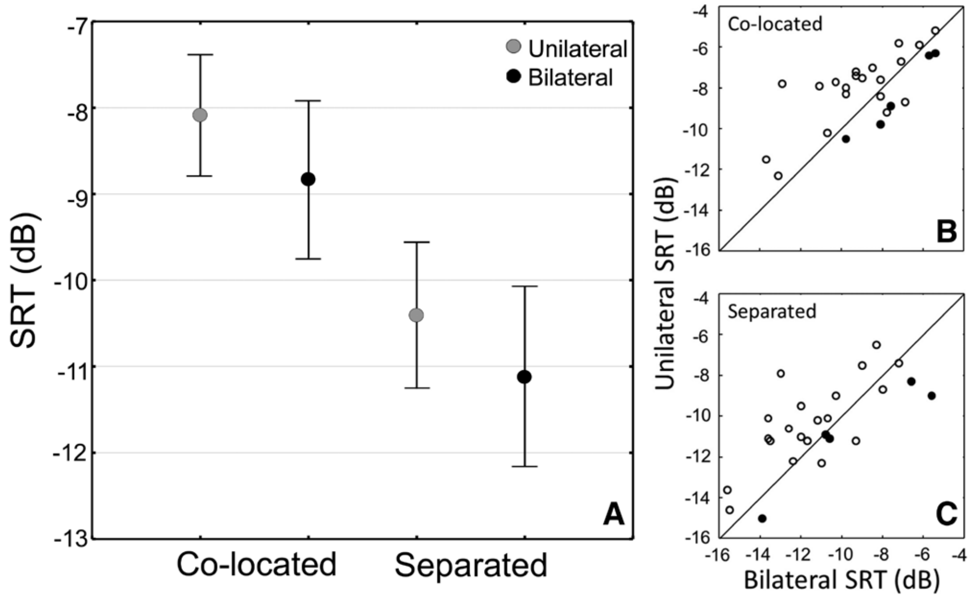

Fig. 4. Recognition thresholds for speech in competing speech. Symbols denote means, and error bars denote 95% confidence intervals. Right panels: Symbols denote individual data for unilateral SRT as a function of bilateral SRT in colocated and separated target and masking speech condition. Symbols above the line of equality reflects subjects with a benefit in SRT with bilateral BCD. Filled symbols in (B) and (C) corresponds to subjects who had a bilateral disbenefit for both spatial conditions. BCD indicates bone conduction hearing devices; SRT, speech recognition threshold.

p = 0.003], suggesting that the magnitude of the bilateral BCD benefit interacted with the acoustical properties of the stimulus. Main effects analysis showed that listening condition [$F(1,22) = 133.7$, $\eta_p^2 = 0.86$, $p < 0.0001$] and stimulus [$F(3,66) = 20.5$, $\eta_p^2 = 0.48$; $p < 0.001$] had significant effects on the EI.

The mean EIs for the different stimuli with unilateral BCD and bilateral BCD are shown in Figure 7. The mean unilateral EI was within the 95% confidence interval for random performance (cf. Fig. 7A) except for the speech-weighted stationary noise, whereas the mean EIs for bilateral BCD were significantly different from random performance (p's < 0.001). For bilateral BC, the octave-filtered noise with CF = 0.5 kHz had the highest mean EI (0.61), whereas the speech-weighted stationary noise had the lowest (i.e., best) mean EI (0.39). The mean bilateral BCD benefit in EI was largest for octave-filtered noise with CF = 4 kHz (mean EI difference = 0.42), whereas the bilateral BCD benefit was smallest for the octave-filtered noise with CF = 0.5 kHz (mean EI difference = 0.21).

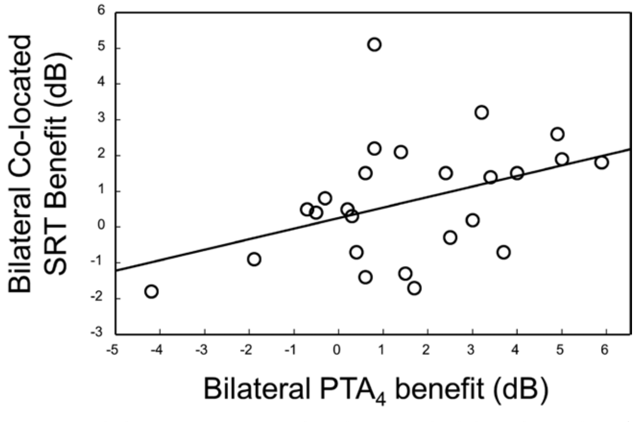

Fig. 5. Simple linear regression analysis between the bilateral BCD benefit in SRT and the bilateral BCD benefit in hearing thresholds for bone conduction stimulation ($y = 0.28 + 0.30 \times x$, $r = 0.41$, $p = 0.04$). BCD indicates bone conduction hearing devices; SRT, speech recognition threshold.

Individual EIs are shown in Figure 7B–E. The data in these panels illustrate several results. First, the interindividual variability in localization accuracy was relatively high for unilateral as well as bilateral BC conditions. For comparison, the SD of the EI for the musical melody in listeners with normal hearing is 0.021, with a mean of 0.054 (Asp et al. 2016). Second, interindividual variability in the bilateral BC condition was higher for the 0.5 kHz stimulus (EI range: 0.36 to 1.14) in comparison with the remaining stimuli containing energy at higher frequencies (EI range musical melody: 0.27 to 0.77; EI range 4 kHz: 0.11 to 0.68; EI range stationary noise: 0.27 to 0.64). Third, a few individuals seemed able to achieve EI values <0.5 (corresponding to an mean angular error <18°, see [Asp et al. 2016]) in the unilateral BC condition for the stimuli that contained energy at high frequencies (Fig. 7B, C, E), whereas the lowest unilateral EI value was 0.62 (corresponding to an mean angular error = 22°) for the stimulus that contained energy in the low frequencies (Fig. 7D). Fourth, regardless of stimulus, the majority of the subjects showed a better localization accuracy (i.e., lower EI) with bilateral BC, as illustrated by markers above the line of equality.

To visualize sound localization response variability across azimuths for unilateral and bilateral listening conditions, the perceived versus presented azimuth across stimuli for the entire study group are presented in Figure 8. The larger the circle in Figure 8, the more perceived azimuths at that presented azimuth. For the bilateral listening condition (right column in Fig. 8), large circles are aligned along the line of equality, suggesting better sound localization accuracy than for the unilateral listening condition (left column in Fig. 8) for which the pattern of perceived azimuths was more scattered.

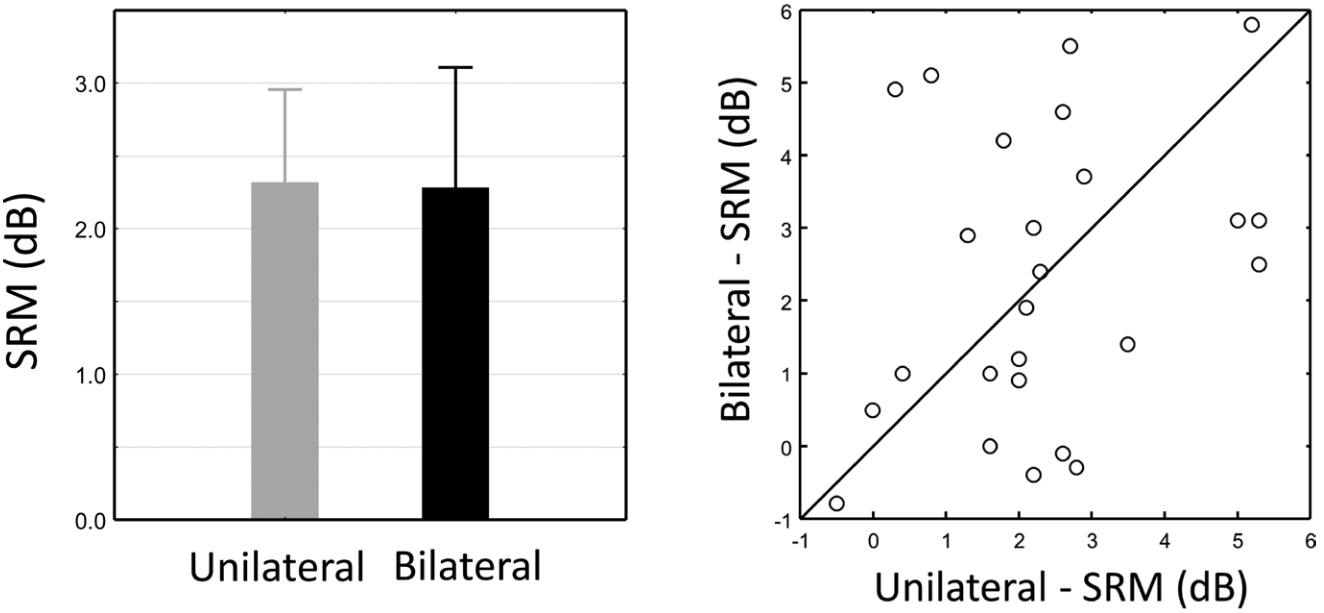

Fig. 6. Spatial release from masking for unilateral and bilateral BC conditions. Left panel: Mean SRM for unilateral (gray) and bilateral (black) BC conditions. Error bars denote 95% confidence intervals. Right panel: individual SRM values for bilateral BC as a function of unilateral BC. Symbols above the line of equality reflect subjects with a bilateral SRM benefit, whereas symbols below the line of equality reflect subjects with a bilateral SRM disbenefit. BC indicates bone conduction; SRM, spatial release from masking.

Effect of Decreased Presentation Level on Sound Localization Accuracy

To study the possible contribution of AC stimulation on sound localization accuracy, sound localization measurements were performed at an individual presentation level inaudible in the unaided condition using the musical melody stimulus. For the bilateral condition, a distinct and statistically significant difference in EI between the original presentation level (63 dB SPL, mean [SD] EI = 0.47 [0.12]) and the individual presentation level (mean [SD] = 43.9 [4.4] dB SPL, mean [SD] EI = 0.64 [0.15]) existed ($p < 0.001$, $t = -5.8$), suggesting a significant contribution of AC sound to sound localization accuracy for presentation levels comparable with normal conversational sound pressure levels. No difference in the EI between the original (mean [SD] EI = 0.74 [0.11]) and individual presentation levels (mean [SD] EI = 0.78 [0.12]) existed for the unilateral listening condition ($p = 0.08$, $t = -1.9$).

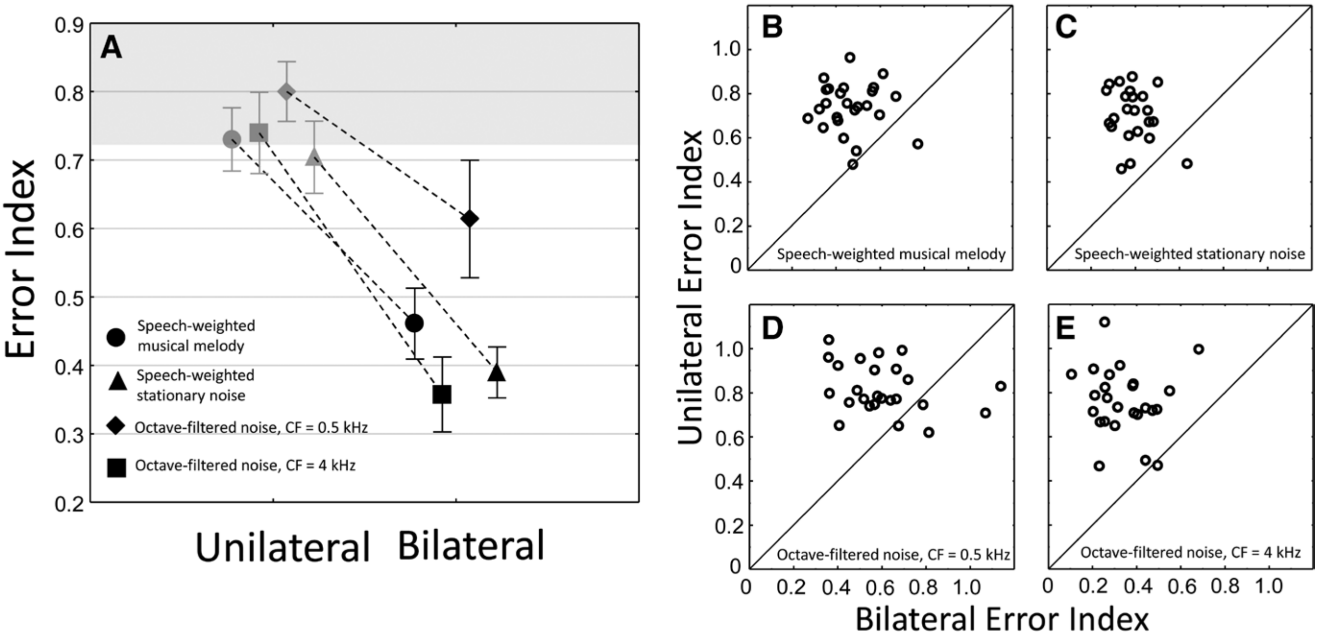

Fig. 7. Horizontal sound localization accuracy with unilateral (gray) and bilateral (black) bone conduction stimulation. A, Symbols denote means, and error bars denote 95% confidence intervals. The gray shaded area reflects random performance. B–E, Symbols denote individual sound localization accuracy data. Symbols above the line of equality reflect subjects with a bilateral sound localization benefit, whereas symbols below the line of equality reflect subjects with a bilateral sound localization disbenefit. CF indicates center frequencies.

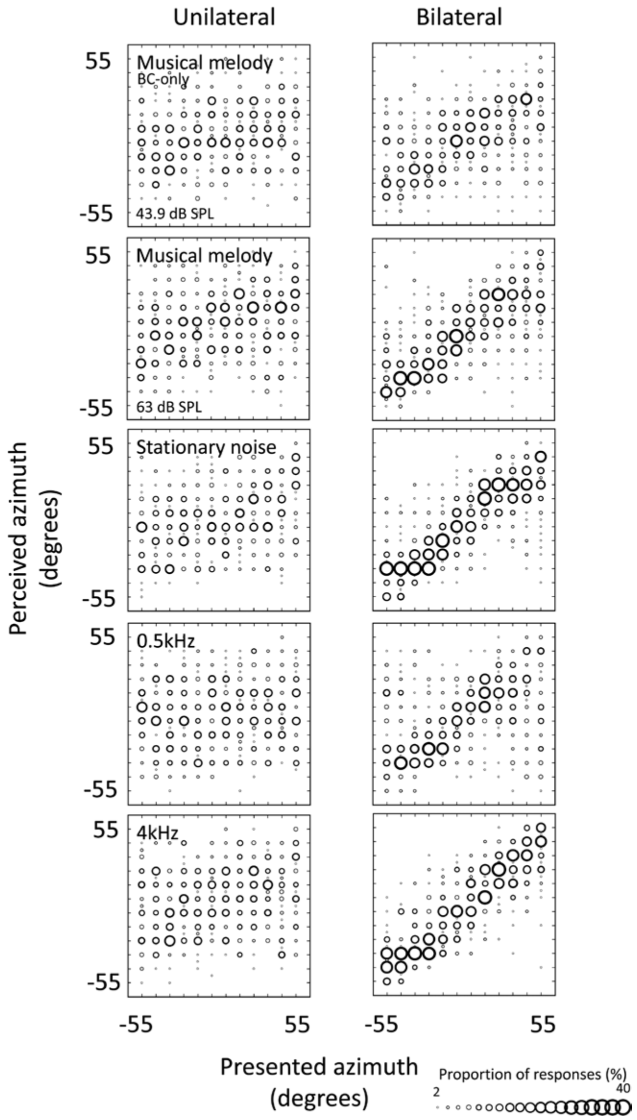

Fig. 8. Scatterplot of horizontal sound localization accuracy for unilateral (left column) and bilateral (right column) BC stimulation across five different stimuli (one stimulus per row). The size of the circles reflects the proportion of perceived azimuths across presented azimuths. Each panel illustrates data for 600 presentations of the corresponding stimulus (25 subjects, 24 presentations). For the BC-only condition (top row), the same musical melody was used as stimulus as shown in row 2, but presented at an individual level (mean = 43.9 dB SPL, n = 25) inaudible by air conduction.

The effect of AC contribution to sound localization accuracy in the bilateral listening condition is further demonstrated in Figure 8. Perceived azimuths as a function of presented azimuths are not gathered near the line of equality for the individual presentation level (top row in Fig. 8) to the same extent as for the original 63 dB SPL-presentation level (second row from the top in Fig. 8).

Crucially, the bilateral BCD benefit found at 63 dB SPL remained for the individual and reduced presentation level ($p < 0.01$, $t = -3.4$).

DISCUSSION

This study compared spatial hearing between unilateral and bilateral bone conduction stimulation conditions in normal-hearing individuals with simulated bilateral conductive hearing loss. To our knowledge, this is the first study to estimate the bilateral BCD benefit for recognition of speech in competing speech rather than speech babble or noise, and for sound localization accuracy for broadband as well as narrowband stimuli. The results demonstrated a substantial benefit with bilateral input in sound localization that was modulated by the frequency content and the amplitude fluctuations of the sound.

In contrast, while a small bilateral BCD benefit for recognition of speech in competing speech existed, spatial benefits (i.e., SRM) for symmetrically arranged masking speech seem comparable for unilateral and bilateral BCD.

Simulated Hearing Loss

The PTA_4 of the simulated bilateral conductive hearing loss in this study was 48.2 dB HL which falls within the range of a moderate hearing loss (41 to 55 dB HL). The level is similar to what was obtained in previous studies with simulated bilateral conductive hearing loss where the mean thresholds ranged from 39 dB HL (using earplug only [Snapp et al. 2020] or earplug and earmuff [Hilly et al. 2020]) to 49 dB HL (using earplug and silicone mold in pinnae [Gawliczek et al. 2018]).

Speech Recognition in Competing Speech

The mean bilateral BCD speech recognition benefit was numerically identical (0.7 dB) for conditions with and without spatial differences between target and masking speech. While this benefit was statistically significant, thus rejecting our null hypothesis, it is small (corresponding to a bilateral benefit of about 7% given the approximate slope of 10%/dB for the speech recognition test used [Hagerman 1997; Berninger & Karlsson 1999]). The large individual variability, however, indicate that some individuals may benefit from a bilateral fitting. Five of 25 subjects (20%) showed a disbenefit with bilateral BCD on both spatial listening conditions. A comparison of these 5 subjects' aided PTA_4 thresholds for unilateral (20.1 dB HL) and bilateral (19.0 dB HL) BC conditions did not indicate any difference from the thresholds for the entire group (unilateral: 20.8 dB HL; bilateral: 19.3 dB HL). Underlying mechanisms for the benefit or disbenefit warrant further experimental and clinical research. To our knowledge, no previous study has investigated the bilateral BCD benefit when speech and masking speech were colocated. The basic mechanism for such "binaural summation" in speech-in-speech tasks is unclear for normal AC conditions. It is suggested that binaural summation depends on two independent observations, one for each ear, of the target stimuli (Schooneveldt & Moore 1989), and that it exists for speech-in-speech tasks (Rothpletz et al. 2012; Asp & Reinfeldt 2020). Asp & Reinfeldt (2020) computed the threshold difference between normal binaural conditions and profound unilateral hearing loss conditions for the colocated target and masker speech-in-speech task in the current setup as an estimate of the binaural summation. It was found to be 1.5 dB, that is, about a factor of 2 larger than found in the present study (0.7 dB). Possibly, transcranial transmission plays a role in the limited binaural summation demonstrated here.

Here, a simple linear regression analysis indicated that the bilateral BCD benefit in hearing sensitivity was related to the bilateral speech recognition benefit for colocated masking speech and explained some of the variability (17%) in that benefit (Fig. 5). This suggests that binaural summation of frequency-modulated tones for BC stimulation may to some extent predict binaural summation of speech signals. Clinically, this could be important since a relatively rapid and language-independent test of hearing sensitivity could reveal those subjects that will likely be disadvantaged in speech recognition, and those who would benefit from bilateral input.

Recognition of Speech in the Spatially Separated Competing Speech and SRM

Asp and Reinfeldt (2020) estimated the monaural and binaural contributions to SRM in the present setup to 1.8 and 1.9 dB, respectively, using the same methodology and procedures as in the present study (i.e., the total SRM was 3.7 dB). They suggested that the symmetrical placement of maskers allowed listeners moment-by-moment "better-ear glimpsing" of the target signal (Brungart & Iyer 2012; Glyde et al. 2013a) based on the twice as large SRM for normal binaural listening (3.7 dB) compared with monaural listening (1.8 dB). Assuming the "better-ear glimpsing" process to be key for achieving a spatial benefit for conditions with separated intelligible interferers, it is not surprising that the SRM for bilateral BC conditions found in the present study (2.3 dB) is lower. When listening by bilateral BCD, transcranial transmission of energy contained in the masking speech signals placed to the left and right of the listener should reduce the possibility to exploit moment-by-moment better SNRs for each ear. The acoustical energy from any of the lateral masking speech signals will reach both cochleae continuously in a frequency-dependent manner (likely with large individual variability; Stenfelt 2012). It is interesting that, the SRM achieved by unilateral BC was numerically identical to that found for bilateral BC. Accordingly, when masking speech is symmetrically separated from target speech, release from masking is possible by unilateral BC. We interpret the SRM achieved by unilateral BC in symmetrically separated masking speech to be based on a head-shadow effect since two of the four masking speech signals were presented on the unaided side. The similar SRM magnitude for unilateral and bilateral BC indicates that "better-ear glimpsing" does not increase SRM when listening by BC.

The SRM difference between normal binaural conditions and bilateral BC conditions found in the present study is comparable with findings from a within-subject comparison of SRM obtained for symmetrical masking sounds by AC and BC in listeners with normal hearing (Stenfelt & Zeitooni 2013; Zeitooni et al. 2016).

We are not aware of any studies quantifying the difference between unilateral and bilateral SRM by BC. However, we identified two previous studies that quantified the bilateral BCD benefit for the SRT in multi-source noise that was spatially and symmetrically separated from the target signal. Priwin et al. (2004) showed, in a clinical cohort, a bilateral SRT benefit of 2.8 dB in uncorrelated speech-weighted noise presented from 11 loudspeakers symmetrically arranged around the listener. The presentation level of the speech was fixed and individually adjusted between 50 and 80 dB HL. Hilly et al. (2020) estimated a "bilateral gain" of 3.1 dB for subjects with normal hearing and simulated bilateral conductive hearing loss. In that study, a white noise was symmetrically distributed on both sides of the listener who was required to repeat sentences presented at frontal incidence at a fixed presentation level of 40 dB HL. The "bilateral gain" estimate was based on three different fixed SNRs, and probably affected by ceiling effects at the most favorable SNR. The fixed presentation level in those two studies should be an important distinction from the present study and possibly explain the larger bilateral BCD benefit found. The difference may also be due to the type of noise signals used (i.e., noise rather than speech), or a combination of both. Gawliczek et al. (2018) employed test paradigm relatively similar to the present study. They simulated bilateral conductive hearing loss in normal-hearing subjects and used an adaptive procedure to obtain an SRT in surrounding uncorrelated babble noise. While the Gawliczek et al. study was primarily designed to compare two noninvasive options for BC stimulation, they reported no significant SRT difference between unilateral and bilateral BCD. An important difference between the Gawliczek et al. study and this study was that the babble noise was presented at the same azimuth as the target speech simultaneously with spatially separated babble noise, and that the babble noise probably was unintelligible since it consisted of a mixture of 30 spoken sentences. It would be of value if future research on spatial hearing by BC addressed the possible impact of "informational masking," that is, perceptual masking beyond the masking occurring as a consequence of energy overlap of acoustic signals in the auditory periphery. While the present study used interfering speech sounds and thus to some extent perceptual masking, "informational masking" was not maximized since target and interferers were different-sex talkers.

Sound Localization Accuracy

The presence of a bilateral sound localization benefit is consistent with previous clinical studies (Bosman et al. 2001; Priwin et al. 2004), and with studies simulating conductive hearing loss in subjects with normal hearing (Gawliczek et al. 2018; Hilly et al. 2020). Previous clinical studies comparing sound localization accuracy for unilateral and bilateral BC conditions found a significant bilateral BCD benefit (Bosman et al. 2001; Priwin et al. 2004), consistent with data demonstrated here. Those studies used narrowband (1/3 octave), short-duration (1 sec) noise bursts with CFs of 0.5 and 2 kHz, to investigate whether ITD and ILD cues could be used to localize with bilateral BCD. A bilateral BCD benefit existed for both stimuli, and unlike the present study had similar magnitude. Here, two similar stimuli were used, with the difference that they had higher bandwidth (i.e., octave-filtered) and the high-frequency stimulus had a higher CF (i.e., 4 kHz). The magnitude of the bilateral benefit was two orders of magnitude larger for the high-frequency stimulus than for the low-frequency stimulus (cf. Fig. 7). At least some of the bilateral BC benefit difference between previous studies and the present study may be due to the differences in acoustical properties of the stimuli; higher bandwidth and higher CF for the high-frequency stimulus in this study compared with previous studies likely resulted in more prominent ILD and monaural level cues (Shaw & Vaillancourt 1985). However, methodological differences between the present and previous studies such as BCD characteristics, stimulus duration (Thurlow & Mergener 1970; Makous & Middlebrooks 1990), recording of localization responses (Makous & Middlebrooks 1990; Wightman & Kistler 1997), and the azimuthal range of the localization setup may also account for the larger bilateral BC benefit for high-frequency sound demonstrated here.

In addition to narrowband stimuli, two broadband sounds were used in the present study, one of which was nonstationary and hence reduced monaural level cues. The bilateral BCD benefit was quite large across broadband and narrowband stimuli (cf. Fig. 7), and the mean EIs for the bilateral BC listening condition were substantially lower than random performance. In contrast, EIs for the unilateral BC condition were relatively high and comparable to random performance, also for the 4 kHz stimulus, suggesting that monaural level cues are not sufficient for horizontal sound localization for unilateral BC. Moreover, the magnitude of the bilateral BCD benefit interacted with the acoustical properties of the stimulus, such that the bilateral BCD benefit was smaller for modulated broadband sounds (i.e., monaural level cues minimized) and low-frequency sounds (i.e., ILD and monaural level cues minimized) than for stationary broadband and high-frequency sounds.

Results from the bilateral BC condition indicate that sounds with energy at high frequencies were more accurately localized than sounds with energy at low frequencies, suggesting that ILD cues are most important for sound localization by bilateral BC, opposite to normal binaural AC conditions for which ITD cues are dominant (Wightman & Kistler 1992). However, the 0.5 kHz stimulus was localized with higher accuracy than chance, suggesting either that ITD cues are not entirely discarded by BC, or that any ILD cues that were conveyed by BC could be used for localization. Cadaver studies suggest that both cues may be useful in bilateral BC stimulation (Farrell et al. 2017).

Furthermore, visual inspection of Figure 7 suggests that stationary sounds with energy at high frequencies (i.e., the 4 kHz stimulus and the speech-weighted noise) are easier to localize than sounds with amplitude modulation (e.g., the musical melody), indicating that monaural level cues are important for sound localization by bilateral BC. All stimuli were substantially less accurately localized than by normal-hearing listeners tested using the same technique, where EIs ranged from 0.054 (EI = 0.47 in this study) for the musical melody (Asp et al. 2016) to 0.11 (EI = 0.34 in this study) for the 4 kHz stimulus (unpublished data).

An interesting and clinically relevant finding from the sound localization test was the performance decrease occurring when the presentation level was decreased until it was inaudible by AC (mean EI = 0.64 as compared with 0.47 for the original presentation level). It is unlikely that the decreased presentation level per se reduced sound localization accuracy by BC, since localization performance is high for a range of suprathreshold levels (Sabin et al. 2005). The results from the present test indicate that the contribution from AC (if any, depending of the degree of the conductive hearing loss) for a listener using BC devices may be beneficial for localization accuracy, motivating the use of various presentation levels in future studies of localization performance in patients with conductive hearing losses. The results also suggest that a bilateral benefit when listening by BC seems to exist without any AC stimulation since there was still a statistically significant difference between the EIs achieved with unilateral and bilateral BC stimulation.

Study Limitations

The use of BCDs on a softband in the present study limits to some extent the possibility of comparing the results to clinical practice, in which patients with conductive hearing loss usually are fitted with BCDs on a skin-penetrating screw. For example, we did not measure the force with which the BCD was pressed to the skin and skull. When fitted on a softband, stimulation by BC is attenuated by the skin so that sensitivity at higher frequencies is reduced (Håkansson et al. 1984). Possibly, SRT values would be different in a clinical population given the significance of mid-to-high frequency information for speech recognition in noise (Smoorenburg et al. 1982; Hagerman 1984). The acute testing of subjects not used to the processing of hearing by BC, as well as the possible interaural asymmetry of the simulated hearing loss and/or fitting of the BCDs may have affected, for example, interaural cues and hence the results of our experiments. In addition, occlusion effects occurring as a consequence of the blocking of the ear canal opening may have affected the results. While attempts to reduce the occlusion effect was made by minimizing the cavity between the tympanic membrane and the artificial conductive hearing loss (Stenfelt & Reinfeldt 2007), the occlusion was not quantified.

Summary and Conclusions

A human model of bilateral conductive hearing loss was used to study spatial hearing when stimulation was by bone conduction. Results suggest that the well-known transcranial transmission of bone-conducted sound affects bilateral BCD benefits for spatial hearing in differing ways. SRM obtained in conditions with symmetrically arranged competing speech was similar for unilateral and bilateral BC stimulation, whereas sound localization accuracy was distinctly higher for bilateral BC for a range of stimulus conditions. The magnitude of the bilateral sound localization BCD benefit was modulated by available sound localization cues, where the stimuli allowing access to ILD cues resulted in larger benefit as compared with the stimuli allowing access to ITD cues. For unilateral BC conditions, localization accuracy was poor across stimuli. The bilateral BCD benefit for recognition thresholds for speech in competing speech was statistically significant but small regardless if masking speech signals were co-located with, or spatially and symmetrically separated from the target speech. Results suggest that patients with bilateral conductive hearing loss and BC thresholds within the normal range may benefit from a bilateral fitting of BCD, particularly for horizontal localization of sounds.

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Address for correspondence: Fatima M. Denanto, Department of ENT, Karolinska University Hospital Huddinge, 141 86 Stockholm, Sweden. E-mail: fatima.moumen.denanto@ki.se

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REFERENCES

Asp, F., & Reinfeldt, S. (2018). Horizontal sound localisation accuracy in individuals with conductive hearing loss: Effect of the bone conduction implant. *Int J Audiol, 57*, 657–664.

Asp, F., & Reinfeldt, S. (2019). Effects of simulated and profound unilateral sensorineural hearing loss on recognition of speech in competing speech. Ear Hear.

Asp, F., & Reinfeldt, S. (2020). Effects of simulated and profound unilateral sensorineural hearing loss on recognition of speech in competing speech. *Ear Hear, 41*, 411–419.

Asp, F., Eskilsson, G., Berninger, E. (2011). Horizontal sound localization in children with bilateral cochlear implants: Effects of auditory experience and age at implantation. *Otol Neurotol, 32*, 558–564.

Asp, F., Olofsson, Å., Berninger, E. (2016). Corneal-reflection eye-tracking technique for the assessment of horizontal sound localization accuracy from 6 months of age. *Ear Hear, 37*, e104–e118.

Asp, F., Jakobsson, A. M., Berninger, E. (2018). The effect of simulated unilateral hearing loss on horizontal sound localization accuracy and recognition of speech in spatially separate competing speech. *Hear Res, 357*, 54–63.

Berninger, E., & Karlsson, K. K. (1999). Clinical study of Widex Senso on first-time hearing aid users. *Scand Audiol, 28*, 117–125.

Berninger, E., Olofsson, A., Leijon, A. (2014). Analysis of click-evoked auditory brainstem responses using time domain cross-correlations between interleaved responses. *Ear Hear, 35*, 318–329.

Blauert, J. (1997). Spatial *Hearing*, MIT Press.

Bosman, A. J., Snik, A. F., van der Pouw, C. T., Mylanus, E. A., Cremers, C. W. (2001). Audiometric evaluation of bilaterally fitted bone-anchored hearing aids. *Audiology, 40*, 158–167.

Bregman, A. S. (1990). Auditory *Scene Analysis: The Perceptual Organization Of Sound*. MIT Press.

Bronkhorst, A. W. (2000). The cocktail party phenomenon: A review of speech intelligibility in multiple-talker conditions. Acta Acust United *Acust*, *86*, 117–128.

Bronkhorst, A. W., & Plomp, R. (1988). The effect of head-induced interaural time and level differences on speech intelligibility in noise. *J Acoust Soc Am, 83*, 1508–1516.

Brungart, D. S., & Iyer, N. (2012). Better-ear glimpsing efficiency with symmetrically-placed interfering talkers. *J Acoust Soc Am, 132*, 2545–2556.

Culling, J. F., Hawley, M. L., Litovsky, R. Y. (2004). The role of head-induced interaural time and level differences in the speech reception threshold for multiple interfering sound sources. *J Acoust Soc Am, 116*, 1057–1065.

Dutt, S. N., McDermott, A. L., Burrell, S. P., Cooper, H. R., Reid, A. P., Proops, D. W. (2002). Speech intelligibility with bilateral bone-anchored hearing aids: the Birmingham experience. J Laryngol Otol Suppl, *28*, 47–51

Edmonds, B. A., & Culling, J. F. (2006). The spatial unmasking of speech: Evidence for better-ear listening. *J Acoust Soc Am, 120*, 1539–1545.

Eklöf, M., Asp, F., Berninger, E. (2020). Sound localization latency in normal hearing and simulated unilateral hearing loss. *Hear Res, 395*, 108011.

Farrell, N. F., Banakis Hartl, R. M., Benichoux, V., Brown, A. D., Cass, S. P., Tollin, D. J. (2017). Intracochlear measurements of interaural time and level differences conveyed by bilateral bone conduction systems. *Otol Neurotol, 38*, 1476–1483.

Gardner, M. B., & Gardner, R. S. (1973). Problem of localization in the median plane: Effect of pinnae cavity occlusion. *J Acoust Soc Am, 53*, 400–408.

Gawliczek, T., Wimmer, W., Munzinger, F., Caversaccio, M., Kompis, M. (2018). Speech understanding and sound localization with a new non-implantable wearing option for Baha. *Biomed Res Int, 2018*, 5264124.

Glyde, H., Buchholz, J., Dillon, H., Best, V., Hickson, L., Cameron, S. (2013a). The effect of better-ear glimpsing on spatial release from masking. *J Acoust Soc Am, 134*, 2937–2945.

Glyde, H., Buchholz, J. M., Dillon, H., Cameron, S., Hickson, L. (2013b). The importance of interaural time differences and level differences in spatial release from masking. J Acoust Soc Am, 134, EL147–152.

Gredebäck, G., Johnson, S., von Hofsten, C. (2010). Eye tracking in infancy research. *Dev Neuropsychol, 35*, 1–19.

Hagerman, B. (1979). Reliability in the determination of speech reception threshold (SRT). *Scand Audiol, 8*, 195–202.

Hagerman, B. (1982). Sentences for testing speech intelligibility in noise. Scand Audiol, 11, 79–87.

Hagerman, B. (1984). Clinical measurements of speech reception threshold in noise. *Scand Audiol, 13*, 57–63.

Hagerman, B. (1997). Attempts to develop an efficient speech test in fully modulated noise. *Scand Audiol, 26*, 93–98.

Hagerman, B., & Kinnefors, C. (1995). Efficient adaptive methods for measuring speech reception threshold in quiet and in noise. *Scand Audiol, 24*, 71–77.

Håkansson, B., Tjellström, A., Rosenhall, U. (1984). Hearing thresholds with direct bone conduction versus conventional bone conduction. *Scand Audiol, 13*, 3–13.

Hawley, M. L., Litovsky, R. Y., Colburn, H. S. (1999). Speech intelligibility and localization in a multi-source environment. *J Acoust Soc Am, 105*, 3436–3448.

Hawley, M. L., Litovsky, R. Y., Culling, J. F. (2004). The benefit of binaural hearing in a cocktail party: Effect of location and type of interferer. *J Acoust Soc Am, 115, 833–843.*

Hilly, O., Sokolov, M., Finkel, R. B., Zavdy, O., Shemesh, R., Attias, J. (2020). Hearing in noise with unilateral versus bilateral bone conduction hearing aids in adults with pseudo-conductive hearing loss. *Otol Neurotol, 41*, 379–385.

Ihlefeld, A., Sarwar, S. J., Shinn-Cunningham, B. G. (2006). Spatial uncertainty reduces the benefit of spatial separation in selective and divided listening. J Acoust Soc Am, *119*, 3417–3417.

Janssen, R. M., Hong, P., Chadha, N. K. (2012). Bilateral bone-anchored hearing aids for bilateral permanent conductive hearing loss: A systematic review. *Otolaryngol Head Neck Surg, 147*, 412–422.

Jeffress, L. A. (1948). A place theory of sound localization. *J Comp Physiol Psychol, 41*, 35–39.

Johansson, M., Asp, F., Berninger, E. (2019). Children with congenital unilateral sensorineural hearing loss: Effects of late hearing aid amplification-a pilot study. Ear *Hear*,

Kidd, G. Jr, Mason, C. R., Best, V., Marrone, N. (2010). Stimulus factors influencing spatial release from speech-on-speech masking. *J Acoust Soc Am, 128*, 1965–1978.

Litovsky, R. Y. (2012). Spatial release from masking. Acoust *Today*, 8, 18–25.

Makous, J. C., & Middlebrooks, J. C. (1990). Two-dimensional sound localization by human listeners. *J Acoust Soc Am, 87*, 2188–2200.

Marrone, N., Mason, C. R., Kidd, G. (2008). Tuning in the spatial dimension: Evidence from a masked speech identification task. J Acoust Soc Am, 124, 1146–1158.

Middlebrooks, J. C., & Green, D. M. (1991). Sound localization by human listeners. *Annu Rev Psychol, 42*, 135–159.

Plomp, R., & Mimpen, A. M. (1979). Improving the reliability of testing the speech reception threshold for sentences. *Audiology, 18*, 43–52.

Priwin, C., Stenfelt, S., Granström, G., Tjellström, A., Håkansson, B. (2004). Bilateral bone-anchored hearing aids (BAHAs): An audiometric evaluation. *Laryngoscope, 114*, 77–84.

Rayleigh, L. (1907). XII. On our perception of sound direction. The London, Edinburgh, and Dublin Philosophical Magazine J Sci, 13, 214–232.

Rothpletz, A. M., Wightman, F. L., Kistler, D. J. (2012). Informational masking and spatial hearing in listeners with and without unilateral hearing loss. *J Speech Lang Hear Res, 55*, 511–531.

Sabin, A. T., Macpherson, E. A., Middlebrooks, J. C. (2005). Human sound localization at near-threshold levels. *Hear Res, 199*, 124–134.

Schoenmaker, E., Sutojo, S., van de Par, S. (2017). Better-ear rating based on glimpsing. *J Acoust Soc Am, 142*, 1466.

Schooneveldt, G. P., & Moore, B. C. (1989). Comodulation masking release for various monaural and binaural combinations of the signal, on-frequency, and flanking bands. *J* Acoust Soc Am, 85, 262–272.

Shaw, E. A., & Vaillancourt, M. M. (1985). Transformation of sound-pressure level from the free field to the eardrum presented in numerical form. *J Acoust Soc Am, 78*, 1120–1123.

Smoorenburg, G. F., de Laat, J. A., Plomp, R. (1982). The effect of noise-induced hearing loss on the intelligibility of speech in noise. Scand Audiol Suppl, 16, 123–133.

Snapp, H., Vogt, K., Agterberg, M. J. H. (2020). Bilateral bone conduction stimulation provides reliable binaural cues for localization. *Hear Res, 388*, 107881.

Stenfelt, S. (2005). Bilateral fitting of BAHAs and BAHA fitted in unilateral deaf persons: Acoustical aspects. *Int J Audiol, 44*, 178–189.

Stenfelt, S. (2012). Transcranial attenuation of bone-conducted sound when stimulation is at the mastoid and at the bone conduction hearing aid position. *Otol Neurotol, 33*, 105–114.

Stenfelt, S., & Goode, R. L. (2005). Bone-conducted sound: Physiological and clinical aspects. *Otol Neurotol, 26*, 1245–1261.

Stenfelt, S., & Reinfeldt, S. (2007). A model of the occlusion effect with bone-conducted stimulation. *Int J Audiol, 46*, 595–608.

Stenfelt, S., & Zeitooni, M. (2013). Binaural hearing ability with mastoid applied bilateral bone conduction stimulation in normal hearing subjects. *J Acoust Soc Am, 134*, 481–493.

Thurlow, W. R., & Mergener, J. R. (1970). Effect of stimulus duration on localization of direction noise stimuli. *J Speech Hear Res, 13*, 826–838.

Tonndorf, J., & Jahn, A. F. (1981). Velocity of propagation of bone-conducted sound in a human head. *J Acoust Soc Am, 70*, 1294–1297.

Wanrooij, V., & Opstal, V. (2004). Contribution of head shadow and pinna cues to chronic monaural sound localization. J *Neurosci*, 24, 4163–4171

Wightman, F. L., & Kistler, D. J. (1992). The dominant role of low-frequency interaural time differences in sound localization. *J Acoust Soc Am, 91*, 1648–1661.

Wightman, F. L., & Kistler, D. J. (1997). Monaural sound localization revisited. *J Acoust Soc Am, 101*, 1050–1063.

Zeitooni, M., Mäki-Torkko, E., Stenfelt, S. (2016). Binaural hearing ability with bilateral bone conduction stimulation in subjects with normal hearing: Implications for bone conduction hearing aids. *Ear Hear, 37*, 690–702.

Zurek, P. M. (1993). Binaural advantages and directional effects in speech intelligibility. In G. A. Studebaker & I. Hochberg (Eds.), Acoustical Factors Affecting Hearing Aid Performance (pp. 255–276). Boston: Allyn and Bacon.