Published in final edited form as:

Ear Hear. 2012 ; 33(4): 445–457. doi:10.1097/AUD.0b013e318257607b.

Sound localization in noise by normal-hearing listeners and cochlear implant users

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Abstract

Objectives—This study aimed to characterize horizontal-plane sound localization in interfering noise at different signal-to-noise ratios (SNRs) and to compare performance across normal-hearing listeners and users of unilateral and bilateral cochlear implants (CIs). CI users report difficulties with listening in noisy environments. While their difficulties with speech understanding have been investigated in several studies, the ability to localize sounds in background noise has not extensively been examined, despite the benefits of binaural hearing being greatest in noisy situations. Sound localization is a measure of binaural processing and is thus well suited to assessing the benefit of bilateral implantation. The results will inform clinicians and implant manufacturers how to focus their efforts to improve localization with CIs in noisy situations.

Design—Six normal-hearing listeners, four unilateral and ten bilateral CI users indicated the perceived location of sound sources using a light pointer method. Target sounds were noise pulses played from one of 11 loudspeakers placed between -80° and $+80^\circ$ in the frontal horizontal plane in the free-field. Localization was assessed in quiet and in diffuse background noise at SNRs between $+10$ and -7 dB. Speech reception thresholds were measured and their relation to the localization results examined.

Results—Localization performance declined with decreasing SNR: Target sounds were perceived closer to the median plane and the standard deviation of responses increased. Localization performance across groups was compared using a measure of “Spatial Resolvability” (SR). This measure gives the angular separation between two sound sources that would enable an ideal observer to correctly distinguish them 69.1% of the time. For all participants SR increased with decreasing SNR, i.e. at low SNRs the spatial separation between sound sources remained distinguishable only when it was larger. Normal-hearing participants performed best, with SR between 1.4° and 5.1° in quiet. Bilateral CI users showed SR between 8.3° and 43.6° in quiet, corresponding approximately to the spatial resolution of normal-hearing listeners at an SNR of -5 dB. Most bilateral CI users had lost the ability to correctly determine which side the sound came from at an SNR of -3 dB. Overall, the SNR had to be at least $+7$ dB to achieve localization performance near to that in quiet for all bilateral CI users. No significant correlation was found between spatial resolution and speech reception thresholds, but the speech-processor sensitivity setting did significantly affect performance. Unilateral CI users showed the most severe localization problems, with only two of four participants being able to correctly determine which side sounds came from in quiet.

Conclusions—This study is the first to examine sound localization with CIs at various SNRs and to compare it to normal hearing. The results confirm that localization with CIs is strongly disrupted in noisy situations. Bilateral CIs were shown to be clearly superior over unilateral CIs

for localization in quiet and in noisy situations. With bilateral CIs localization declined at moderately high absolute noise levels (> 63 dB SPL), suggesting that an extension of the acoustic dynamic range to higher levels would be beneficial. The absence of a relation between speech reception thresholds and spatial resolution highlights the need for additional clinical tests to assess the binaural benefit of a second implant.

Keywords

sound localization; bilateral cochlear implant; binaural hearing; noise; compression

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Introduction

The ability to correctly localize sounds is an important feature of the auditory system directly linked to the ability to extract binaural information from the sound. Binaural information is particularly helpful in difficult listening situations, which are characterized by the presence of noise and reverberation. In such situations, sound localization can help a listener to quickly identify and orient themselves toward the talker in a group conversation. This is particularly important for cochlear implant (CI) users, because other cues for speaker identity, such as voice pitch, are diminished (Loizou 2006).

Several studies have shown that good sound localization ability is possible with bilateral CIs (van Hoesel & Tyler 2003; Nopp et al. 2004; Seeber et al. 2004; Verschuur et al. 2005). Bilateral CI users generally outperform unilateral CI users suggesting that binaural information is used (e.g., Seeber et al. 2004). However, all these studies were done in favourable quiet or anechoic conditions. It is less clear if sound localization is possible with CIs in the presence of background sounds, and thus if bilateral implantation provides a clear benefit in difficult listening situations.

Truly quiet conditions are rare. Listening usually takes place in the presence of background sound which mixes with the target signal. The background sound might consist of multiple interferers in different locations. It might also be composed of reverberation, the effect of sound reflecting from the room surfaces in quick succession. In both cases, the background tends to be diffuse in nature, i.e. the waveforms are de-correlated between the ears. However, previous studies on auditory localization have mostly focused on single interferers and normal-hearing listeners (e.g. Abel & Hay 1996; Good & Gilkey 1996; Lorenzi et al. 1999a,b). Only a few studies tested localization against a background of multiple speech (Hawley et al. 2004; Kopco et al. 2010) or noise (Brungart et al. 2005) interferers.

To the authors' knowledge there are three studies which examined localization in noise with bilateral CIs (van Hoesel et al. 2008; Mosnier et al. 2009; Zheng et al. 2011). The two earlier studies examined performance at a single, relatively high signal-to-noise ratio (SNR) and found only a minor impact of the background noise. However, using the Speech-, Spatial and Qualities of Hearing Scale (Gatehouse and Noble 2004) several CI users in our study reported problems with localizing in noisy situations. A recent study by Zheng et al. 2011. tested localization performance at several SNRs with two bilateral CI users and found a marked increase in RMS localization error with decreasing SNR. The present study examined localization at various SNRs with more participants in order to characterize the expected performance decrease with lowering SNR and to estimate the tolerable level of background noise at which reasonably accurate sound localization is still possible.

Studies with normal-hearing listeners have shown a remarkable resistance of localization ability to background noise (Good & Gilkey 1996; Lorenzi et al. 1999a,b; Brungart et al. 2005). This is most likely because normal-hearing listeners can use a multitude of

complementary cues to judge the location of a sound source: interaural level differences (ILDs), interaural time differences (ITDs) in the signal waveform or envelope, and monaural spectral cues. The availability of multiple cues provides a redundancy that should be especially helpful if some cues are more affected by interfering sounds than others. However, it has been shown that cochlear implant users base their localization in quiet mostly on a single binaural cue, ILDs (van Hoesel & Tyler 2003; Seeber & Fastl 2008). This would prevent them from relying on other, potentially more salient cues which might result in more disrupted localization in the presence of noise.

Unlike localization ability, speech understanding in noise has been extensively studied with CI users, and the results confirm the problems subjectively reported by the patients. In a recent review, Wilson and Dorman (2008) reported an average of 52% correct sentence scores with CIs at an SNR of +5 dB, which roughly corresponds to a speech reception threshold (SRT) of +5 dB. Normal-hearing listeners show lower SRTs, well below 0 dB across a variety of conditions (Bronkhorst 2000). The extent to which (monaural/diotic) speech understanding and localization in noise are related in CI users is an interesting, yet inconclusively answered question. Although there is not necessarily a common underlying mechanism, there might still be common causal factors, e.g., the neural survival. To date, several studies have dealt with the relation between localization in quiet and speech understanding (Dunn et al. 2005; Tyler et al. 2006; Litovsky et al. 2009), but results between them are inconsistent. Only Litovsky et al. found a significant correlation. This raises the question if speech and localization outcomes are correlated when both tests are done in background noise.

The aim of the present study was to determine if and how background noise impairs localization performance for users of cochlear implants, particularly those with devices in both ears. Measurements were done at different SNRs to show the impact of increasing background noise levels on localization performance and to find the tolerable level of noise for localization with CIs. The tests were completed by a group of bilateral CI users (“BiCI”) as well as true unilateral CI users (“UnCI”) in order to assess the benefit from the second device. Identical tests were also administered to normal-hearing listeners in order to judge the performance gap between listeners with bilateral CIs and normal hearing. Finally, the correlation between localization performance in noise and speech reception thresholds was calculated to estimate the predictive power of one test on the other. The results show a severe impact of noise on localization with bilateral CIs, and thus support the complaints raised by implantees about listening in noisy acoustic environments.

Materials and Methods

Participants

Six normal-hearing listeners and 14 postlingually deafened cochlear implant users (4 unilateral, 10 bilateral) participated in the study. All unilateral CI users were implanted in only one ear (“true unilateral”) and were not using a hearing aid in the contralateral ear. Normal hearing was verified using pure tone audiometry and was defined by thresholds below 20 dB HL at audiometric frequencies between 250 and 8000 Hz. NH05 exceeded this criterion at one frequency, showing 25 dB HL at 8000 Hz on the right ear. The median age of the normal-hearing participants was 28 years.

Further details about the cochlear implant users are given in Table 1. All CI patients used 22 electrode Scala Tympani devices manufactured by Cochlear Ltd (Patrick et al. 2006) and were stimulated by nonsimultaneous biphasic current pulses delivered in monopolar mode. With the exception of BiCI10, all participants had their devices switched on for at least 1.7

years and used them regularly. Although BiCI10 had his second implant for a shorter duration (0.5 years) test results were superior to most other participants.

All but three CI users used a Nucleus Freedom speech processor: UnCI03 and BiCI10 had been switched to the CP810 (Nucleus 5) speech processor half a year before testing and BiCI02 was a user of an Esprit 3G device. Patients were tested using their standard everyday programme which encoded signals using either the “Advanced Combination Encoder” (ACE) or the “Spectral Peak” (SPEAK) coding strategies. “Adaptive Dynamic Range Optimization” (ADRO; Blamey 2005), the standard input processing scheme recommended by Cochlear, was switched on for nine patients. The others had no input processing activated. BiCI10 was additionally using “AutoSensitivity” on his everyday programme. Both input processing schemes, ADRO and “AutoSensitivity”, act on time constants much longer than the stimuli used in this study and thus should not influence the results (Patrick et al. 2006).

The participants received payment for taking part in the study. Ethics permission was granted before study outset by the NHS North Nottinghamshire Research Ethics Committee.

Setup and Procedure

All experiments were conducted using the “Simulated Open Field Environment” (Seeber et al. 2010). Thirty-six loudspeakers of the setup, spanning a full 360°, were used for this study. They were arranged in the horizontal plane at 10° steps. Loudspeakers at angles between -120° and 120° (left to right) were hidden behind acoustically transparent curtains which were also used as projection screens. Participants sat in a chair facing the loudspeaker at 0° azimuth (front) with their ears at loudspeaker height and their head supported by a headrest.

Target sounds were played from a randomly chosen loudspeaker at 0°, ±10°, ±20°, ±40°, ±60°, or ±80°, followed by the appearance of a light spot directly in front of the listener. Participants moved the light-spot to the perceived horizontal direction of the target sound using a trackball (*ProDePo*-method; Seeber 2002). They confirmed their judgment by pressing the left button on the trackball. If participants perceived the sound as coming from behind they were instructed to point to the mirror direction in the front and press the right button on the trackball. This method proved quick, easy and accurate with a theoretical accuracy of 0.06° (Seeber et al. 2010).

Target sounds were either localized in quiet or in a diffuse background noise. In the “quiet condition” no artificial background noise was added, but the video projectors created an ambient noise level of 32 dB(A) (Seeber et al. 2010). In this condition, the resulting SNR was at least 32 dB(A) for the lowest roving level. In trials with added artificial background noise, uncorrelated samples of noise were played simultaneously from all 36 loudspeakers, creating diffuse noise at the listener’s position.

Participants always started the localization experiments without added background noise. CI patients were advised to use their standard, everyday program and the volume and sensitivity settings of the speech processors were adjusted to optimize localization performance in quiet. To this end, the experimenter spoke directly in front of the participants and bilateral CI users were asked to alternately remove the implant coils, compare, and adjust the loudness between the two devices. This procedure was intended to facilitate localization symmetrical about the median plane. Before data collection started, all participants received training until they felt confident with the task. This training was also used to verify the sensitivity setting of the speech processors with the CI users and, if necessary, the sensitivity was re-adjusted. After measuring localization in quiet, participants

completed the experiment with background noise. The background noise experiment was divided into runs which lasted less than 15 minutes. In total, a minimum of 550 trials were performed ($11 \text{ directions} \times 5 \text{ SNRs} \times 5 \text{ roving levels} \times 2 \text{ trials}$) by each participant. All trials were presented in random order.

A potential confounding variable for localization tests in background noise is the audibility of the target sounds. To ensure that the majority of target sounds were audible at the lowest SNR tested, two measures were taken: (i) In the training runs participants were asked if they heard the target sounds at the lowest SNRs; (ii) An additional test with an altered instruction was completed with most CI users at the lowest SNR. In this test they were instructed to indicate the location of a target sound when it was audible and confirm this by pressing the left trackball button. Trials with inaudible target sound were indicated by pressing the right trackball button.

Stimuli

Target sounds and background noise were composed of uniform exciting noise (UEN; Zwicker and Fastl 2007), a noise with equal energy in each Bark band. Target sounds were trains of six pulses with 10 ms duration separated by gaps of 120 ms, resulting in a total target duration of 660 ms. Each pulse had Gaussian ramps of 2 ms and was cut out of a continuous UEN of 60 dB SPL (long-term) with a bandwidth of 300 Hz - 10 kHz. The background noise was a stationary UEN identical in bandwidth to that of the target pulse trains. In trials with added background noise, different SNRs were produced by varying the level of the background noise relative to the target sounds. An SNR of 0 dB, for example, meant that the background noise was presented at a long-term SPL of 60 dB, equivalent to the level of the target pulses. Note that this level/SNR definition did not consider the pauses in the target sound. It has the benefit that the SNR directly reflects the relative levels of the simultaneously present portions of target and masker noises. If levels were instead calculated by integrating over the entire target sound duration, including the pauses between pulses, the SNR would be 10.8 dB lower. SNRs between -7 dB and +10 dB were tested, depending on the participant. All normal-hearing participants were tested with the same SNRs, i.e. -7 dB, -5 dB, -3 dB, 0 dB, +3 dB, and +5 dB. Cochlear implant users were tested with selected SNRs out of -3 dB, 0 dB, 3 dB, 5 dB, 7 dB and 10 dB. The lowest individual test SNR was chosen to ensure audibility of the targets, and a number of adjacent ascending SNRs were chosen dependent on time constraints of the individual participant. The presentation of a target sound always started 500 ms after the masking noise and ended 340 ms before the background noise was turned off. This non-simultaneous onset of target and masker improves their segregation.

For each participant ten target waveforms were pre-calculated and stored on disc. Each of these target waveforms was presented once from each target direction. The ten trials collected for a single target direction were thus obtained using independent noise waveforms. Using the same ten waveforms for each target direction facilitated comparison between directions.

A level rove was applied on each trial to disrupt monaural localization cues. The levels of target and masker sounds were simultaneously shifted by ± 6 , ± 3 , or 0 dB, thus maintaining the nominal SNR. Two different target waveforms were assigned to each of the five roving steps to yield the ten trials tested per direction.

CI signal processing

Cochlear implant speech processors employ dynamic range compression to amplify the signal depending on the input level. The compression is necessary to match the relatively

small dynamic range when electrically stimulating the auditory system to the large dynamic range of everyday sounds. However, the compression could alter the experimental stimuli in an unpredictable manner and lead to a clipping of high input levels, thus, for example, rendering a level rove less effective.

The Cochlear Nucleus Freedom devices use dynamic range compressors in two different stages of the signal processing chain, in the automatic gain controller (AGC) in the front-end and in the pulse-mapping stages in the back-end where the actual stimulation pulses are defined. Both compressors use a compression curve with infinite compression (“limiter”) and with instantaneous attack times (James et al. 2003; Patrick et al. 2006). Input signals exceeding a certain level, the compressor knee-point, will be limited to that level before being fed to the later signal processing stages. However, whilst the AGC operates on the broadband signal before it is being split into several frequency bands, the compression in the pulse mapping stage is applied separately in each frequency channel.

CI users can adjust the compressor knee-points with the “Sensitivity” control of the speech processor. It is graded into 20 discrete steps (0-20), with each step shifting the knee-point by 1.5 dB. Higher sensitivity settings denote lower knee-point values. To quantify the knee-point value we recorded stimulation pulses from a CI worn by a KEMAR acoustic manikin in our test environment. Narrow-band sounds were played from the frontal (0°) loudspeaker and a single CI channel centred around 1000 Hz was recorded. At a sensitivity setting of “12” the compressor knee-point was measured to be 59.5 dB SPL. This reflects the knee-point of the compressor in the pulse-mapping stage, because narrow-band stimuli were used and the AGC knee-point in the front-end is defined to be 7.5 dB above that in the pulse-mapping stage (James et al. 2003). Thus, the AGC knee-point amounts to 67 dB at a sensitivity setting of “12”. Note that the level definition equals that used for the test stimuli, i.e. in the middle of the head in absentia.

All but one of the participants in our study used sensitivity settings of “12” or smaller (c.f. Table 1), which suggests that the test stimuli used will have been hardly affected by the dynamic range compressors. In the experiments the highest target level encountered with CIs was 70.8 dB SPL, i.e. at an SNR of -3 dB and a level rove of +6 dB. Only in this extreme condition some CI users might have experienced signal degradations by the dynamic range compressor in the AGC.

Speech test

Speech reception thresholds (SRTs) were measured for all cochlear implant users. The SRT is the relative level of a target sentence at which 50% of the words are understood correctly in background noise. The procedure suggested by Plomp & Mimpen (1979) was followed. Sentences were presented at 65 dB SPL and the level of the noise was varied. IHR sentence lists were used (Macleod & Summerfield 1990) which are organised in 10 equally intelligible lists of 15 sentences based on the BKB sentences (Bench et al. 1979). Unmodulated speech shaped noise served as an interferer. The speech test was performed in the free field with speech and background noise presented from the front, thus minimising any influence of binaural cues. SRTs for five different sentence lists were measured for each participant, and the median of these five results was used to express the participant’s overall speech-in-noise performance.

Results

Normal-hearing participants

Localization results for normal-hearing participants are presented in Figure 1 and Table 2. When testing in quiet, localization responses of all listeners were close to the target location

and absolute localization error was between 2.3° and 6.6° . The median root-mean-squared error (RMS error) was not much larger (2.8° - 7.3°), indicating the presence of only few discordant responses. The compact response pattern was also evident from the small interquartile range of at most 3.9° . Additionally, line fits to the individual localization responses were derived for each SNR condition and participant using a least-square approximation. The slopes for these line fits were between 0.92 and 1.09 and had a maximum offset of 5.5° . Perfect localization performance would be represented by a slope of 1.0 and an offset of 0.0° .

Responses of all normal-hearing participants followed similar trends in background noise in that they shifted closer to the median plane with decreasing SNR (Fig. 1). This resulted in a decreased slope of the line fits at lower SNRs. This trend was supported by a positive correlation between SNR and slope in 3 of the 6 participants (Spearman Rank correlation over 7 SNRs, $p < 0.05$). Across all participants the slope at the highest SNR was significantly greater than at the lowest SNR of -7 dB (Wilcoxon signed-rank test, one-tailed, $p < 0.05$). Participants never reported hearing any of the target sounds in the back, regardless of SNR.

A second general trend which can be observed in Figure 1 is an increase of the interquartile ranges with decreasing SNR. The increase was most pronounced at frontal directions, where the audibility of the target sound is worst (Sabin, 2005). The increase of averaged interquartile ranges (median across all test directions) was significant for 5 of the 6 participants, excluding NH01 (Spearman rank correlation, $p < 0.01$). Different to other participants, NH01's results showed smaller interquartile ranges in the front. For this participant target sounds were often inaudible at the lowest SNRs and the participant responded by not moving the light spot, thus artificially reducing the interquartile ranges.

For 5 of 6 participants the most basic sound localization ability, i.e. the ability to name the correct side of sound incidence, was preserved for the worst tested SNR of -7 dB (Sign test comparing all responses to targets on the left with those on the right, $p < 0.05$). The absolute presentation level of the sounds did not systematically affect sound localization in noise for normal-hearing listeners.

Unilateral cochlear implant users

Unilateral CI users showed generally poor localization performance in all experimental conditions (Fig. 2). Interestingly, the median localization responses of the best performing unilateral CI user (UnCI04) were close to the target location, however, responses showed large interquartile ranges and a high median RMS error. The error was larger than that of any bilateral CI user and the regression line slope was shallower, indicating that localization performance was poorer (Table 2). Individual localization responses were assessed to determine which participants could identify the side of sound incidence correctly in quiet. Only UnCI02 and UnCI04 showed significant side discrimination ability (Sign test, $p < 0.001$). Their localization performance in quiet was analyzed further. UnCI02 and UnCI04 showed median RMS errors of 28.8° and 65.6° , slopes for line fits of 0.19 and 0.61, and interquartile ranges of 18.3° and 64.9° , respectively.

Adding background noise affected localization responses similarly to normal-hearing participants, i.e. line slopes got shallower and RMS errors as well as interquartile ranges increased with decreasing SNR. However, the effects were less pronounced because performance was already poor in quiet conditions.

Bilateral cochlear implant users

All bilateral CI users showed clear localization ability in quiet (left panels in each column of Fig. 3). Median RMS errors ranged from 14.8° to 44.8°, interquartile ranges were 11.6° to 60.4°, and the slopes of the line fits were between 0.67 and 1.21 (Table 2).

As for normal-hearing listeners, the slopes of the lines fitted to bilateral CI users' localization responses decreased with decreasing SNR. The individual correlations between SNR and line-fit slope were, however, significant only for three of the ten bilateral CI users (Spearman rank correlation over the 5-8 SNRs tested with a particular participant, $p < 0.05$). Therefore, the line fit slopes calculated in quiet conditions were grouped for all bilateral CI users and compared with their grouped results at 0 dB SNR. The line fit slopes were significantly shallower at an SNR of 0 dB than in quiet (Wilcoxon sign rank test, one-tailed, $p < 0.001$). The SNR of 0 dB was chosen for analysis as it was the lowest SNR tested with all bilateral CI users. At the same SNR the slope for normal-hearing listeners was not significantly affected by the background noise.

Bilateral CI users, like normal-hearing participants, tended to show increased interquartile ranges with decreasing SNR. A Spearman rank correlation between median interquartile range and SNR was negative for 7 of the 10 bilateral CI users, but reached statistical significance in only two listeners ($p < 0.05$). There are two likely reasons why the trend toward increased interquartile ranges was not as pronounced for bilateral CI users: (i) Most bilateral CI users already showed large interquartile ranges in quiet conditions, leaving less scope for a further increase in added noise. (ii) At an SNR of 0 dB, stimuli in front of the listener were not always audible for some CI users which made them respond by not moving the light spot, thus artificially reducing interquartile ranges (e.g. BiCI07).

Eight of ten bilateral CI users were able to detect the correct side of sound incidence at an SNR of 0 dB (Table 2). However, decreasing the SNR by a further 3 dB rendered the side discrimination ability of all but two bilateral CI users insignificant (Sign test, $p > 0.05$). Unlike for the normal-hearing listeners, the SNR at which side discrimination was lost depended systematically on the absolute presentation level of the sounds (Table 2, rightmost columns). When stimuli were presented at higher absolute levels (i.e. for roving steps +3 and +6 dB) most bilateral CI users already lost side discrimination ability at higher SNRs, i.e. in better listening conditions. In addition, at an SNR of 0 dB the median regression line slope across all participants was 0.11 for sounds presented at high roving levels. For sounds presented at low roving levels it was 0.58, a difference that proved significant (Wilcoxon signed rank test, two-tailed, $p < 0.01$). Thus, localization responses moved closer to the median plane at higher presentation levels.

Three of the ten bilateral CI users heard some of the frontal target sounds as coming from behind them. The number of front-back reversals increased with decreasing SNR. At 0 dB SNR the percentage of front-back confusions for listeners BiCI01, BiCI06, and BiCI08 was 20%, 34.5%, and 10.9%, respectively.

Comparison between participant groups

To compare performance between different participants and groups a measure of "Spatial Resolvability" (SR) was defined and calculated individually from the raw localization data for each participant. First, the standard deviations of the localization responses were calculated for each target direction and the median value was calculated across these 11 directions. This median standard deviation was then divided by the slope of the least-squares regression line to the localization responses to yield the SR. SR is measured in degrees and corresponds to the angular displacement of two sound sources which are perceived one standard deviation of the localization responses apart. This allows an ideal observer to

choose correctly between the two sound sources 69.1 % of the time. The measure is related to the minimum-audible-angle, frequently used in psycho-acoustic experiments to judge location discrimination. However, the MAA is a direct discrimination measure for two sources around a fixed reference location, and thus depends on this reference location (Mills 1958). In contrast, the SR measure denotes a performance average over the full frontal hemifield derived from the results of a true localization experiment. The SR has the advantage over common error measures that it is not biased by a constant localization shift which often occurs for CI users, e.g. if the volume of both speech processors is not perfectly matched. Further, by considering both standard deviation and regression slope, SR can often describe average localization performance more precisely and with higher sensitivity than the RMS error (c.f. UnCI02, who shows an RMS error similar to BiCI01, BiCI06 and BiCI07, but noticeably poorer localization ability because median responses were strongly biased to the center). However, in situations where mean responses show a sigmoid shape SR can suggest too good performance (c.f. Fig. 3, BiCI06 at +5 dB SNR). This can occur when participants overestimate laterality for sources in the front, while sources on the side are all localized at a similar location on the side (compressive shape), which may average to an “ideal” regression slope of one. For judging a patient’s performance it is thus advisable to consider a range of measures (c.f. Table 2) and to refer to the raw localization responses.

SR increased for all participants with decreasing SNRs (Fig. 4), with higher magnitudes meaning worse spatial resolution. The increase was already visible at favourable SNRs for most participants, demonstrating the high sensitivity of this measure.

Normal-hearing listeners showed the best performance with SRs of about 3° in quiet. At +5 dB SNR there was already a small, but statistically significant, increase in SR (Wilcoxon signed rank test, one-tailed, $p < 0.05$). This increase was solely caused by increased standard deviations at +5 dB SNR. SR continued to decline with worsening SNR, reaching 75° at an SNR of -7 dB.

Unilateral CI users showed the worst localization performance. SR was already high without added background noise, leaving little scope for further increases with decreasing SNR. The best SR achieved with unilateral cochlear implants was comparable to that for normal-hearing listeners at an SNR of -7 dB, the most adverse SNR tested.

Performance of bilateral CI users was between that of the normal-hearing listeners and the unilateral CI users. SR in quiet was comparable to that of normal-hearing listeners at an SNR of -5 dB with magnitudes about three times smaller than for unilateral CI users in quiet. Most bilateral CI users already showed a decline of resolvability at the most positive test SNRs compared to the quiet condition. At an SNR of +5 dB, SR was already significantly higher than in quiet (Wilcoxon signed rank test, $p < 0.05$). Unlike for normal-hearing listeners, the increase in SR was not only mediated by an increase in standard deviations, but also by a shift of localization responses toward the median plane. Finally, at an SNR of 0 dB a decline of resolvability was apparent for all bilateral CI users, with SR between two and eight times larger than in quiet.

Relation of localization ability to speech understanding and CI processing

Speech reception thresholds of the CI users were between 0 and 14 dB (Table 1). The worst score was measured for a unilateral cochlear implant user (UnCI04). However, this should not be attributed to the use of a single implant, but rather to the fact that UnCI04 was the only participant not having English as a first language, which can negatively affect performance on the task (Lecumberri et al. 2010).

Cochlear implant users routinely have their speech understanding measured as part of their clinical assessment. Binaural hearing measures, such as sound localization, are instead rarely taken. While one would assume that both are primarily measures for different auditory mechanisms, there might nevertheless be common factors underlying performance in both, e.g. the neural survival. Thus, the relationship between speech scores and localization performance was analysed.

The correlation between SRT and SR for bilateral CI users in quiet was not significant (Fig. 5, B), but the two participants with the best resolvability also showed the lowest (best) SRTs. Likewise, the ratio of SR at an SNR of 0 dB relative to the SR baseline in quiet (“SR decline”) did not significantly correlate with SRT (Fig. 5, D). Speech reception thresholds thus did not correlate with localization performance of bilateral CI users in this study (Pearson correlation, $p > 0.05$).

The Nucleus Freedom Speech processor used in this study allows adjustment of the sensitivity which selects the acoustic-dynamic range that is mapped into the electro-dynamic range. For bilateral CI users the sensitivity setting was significantly correlated to the SR decline at 0 dB SNR, i.e. to the difference in SR at an SNR of 0 dB and in quiet (Fig. 5, panel E; Pearson correlation of 0.81, $p < 0.01$). For CI patients with higher sensitivity settings, localization performance declined more strongly at 0 dB SNR. However, there was no clear relation between the sensitivity setting and SR in quiet (panel C) or SRT (panel A), and both correlation coefficients failed to reach statistical significance.

Discussion & Conclusions

This study assessed sound localization with normal-hearing listeners and cochlear implant users in diffuse background noise. It is the first study that demonstrates the benefit of bilateral CIs over true unilateral CIs for sound localization in noise at different signal to noise ratios (SNRs). Further, the performance gap between bilateral CI users and normal-hearing listeners was established.

In background noise, participants in all groups perceived target sounds closer to the median plane as the SNR decreased. In addition, the standard deviation of responses increased. A measure of “Spatial Resolvability” (SR) was defined to quantitatively compare results across conditions. SR is derived from localization responses to sources located across the frontal hemifield and reflects the angular separation of two sound sources that are localized one standard deviation of the responses apart. It thus bears some similarity with the minimum audible angle frequently studied in psychoacoustics, but represents a theoretically discriminable angle from an average across all test locations (Mills 1958). SR increased for all participants with decreasing SNR, i.e. spatial resolution got worse. Normal-hearing participants performed best with SRs in quiet between 1.4° and 5.1°. Their SR at an SNR of -5 dB was still as good as that of most bilateral CI users in quiet, with SR for the latter ranging from 8.3° to 43.6°. At -3 dB SNR side discrimination ability had vanished for all but two CI users. Spatial resolution with bilateral CIs was marginally worse for SNRs above +7 dB than in quiet. Note that our definition of SNR yields values approximately 10 dB higher than SNR definitions based on time averaging methods with standard time constant “fast” frequently used in other studies (c.f. Methods section). Only two of the four unilateral CI users could discriminate the side of sound origin in quiet. For these two participants, SR was 61.9° and 96.3°, which was about three times worse than for the bilateral CI users. No significant correlation between spatial resolution, as measured by SR, and speech reception thresholds was found for bilateral CI users, but speech processor sensitivity did significantly affect spatial resolution in noise.

Localization results

Only three studies have assessed localization performance of CI users in background noise (van Hoesel et al. 2008; Mosnier et al. 2009; Zheng et al. 2011). Van Hoesel et al. (2008) tested participants at an SNR of 0 dB. However, because of different definitions, this corresponds to an SNR of +10.8 dB in our study, an SNR at which we found little effect of noise on localization performance. Van Hoesel et al. measured RMS errors in noise of between 26° and 36° which correspond well with the errors obtained from bilateral CI users in quiet in the present study. A comparison of our data to the data in Mosnier et al. (2009) is difficult because they used individual SNRs for each participant. Their SNRs were linked to speech scores that were not individually reported. Note that we did not find any significant correlation between the diotic speech reception threshold and spatial resolution. Finally, Zheng et al. (2011) showed an increase of RMS localization error from approximately 38° in quiet to approximately 58° at an SNR of -8 dB with two BiCI participants. Their RMS errors in quiet are comparable to the median RMS errors of the poorer performing participants in the quiet condition of this study. Unfortunately, Zheng et al. did not provide a detailed explanation on how they defined the SNR, making a comparison with our results difficult.

The major contribution of the present study is the comprehensive assessment of localization performance at different relative levels of diffuse background noise. Such an assessment has previously only been done with normal-hearing and hearing-impaired participants, or with few bilateral CI users. One of the most comprehensive studies on the subject was done by Good and Gilkey (1996). They defined SNR relative to the masked threshold of the target which makes a quantitative comparison with the present study difficult. Nevertheless, observed interquartile ranges and localization errors were qualitatively similar to ours, in that they increased with decreasing SNR. A clear trend for the line-fit slope was not visible in their data. Additionally, Good and Gilkey found an increase in back-to-front reversals with decreasing SNR. In the present study, instead, three of the ten bilateral CI users showed an increase in front-to-back reversals.

Lorenzi et al. (1999a,b) tested localization in background noise for normal-hearing and hearing-impaired participants and reported similar findings: With decreasing SNR the slopes of the line fits decreased and interquartile ranges and localization errors increased. Lorenzi et al. analyzed r^2 -values for a linear regression fit as a function of SNR. The r^2 -values for normal-hearing participants in quiet were similar to those measured here (Table 2). Although Lorenzi et al. did not test CI users it is nevertheless interesting to compare their data of hearing-impaired participants with our measurements for CI users. In their study hearing-impaired participants showed r^2 -values better than 0.85 in quiet conditions, a magnitude hardly reached by the CI users in our study. In addition, for hearing-impaired listeners r^2 started to decrease at about 3-6 dB higher SNR than for normal-hearing listeners.

Disruption of localization cues by noise and CI processing

The increased vulnerability to background noise with CIs might stem from the unavailability of complementary binaural localization cues. The technology used in current CI devices only facilitates the use of interaural level differences (ILDs) and interaural time differences (ITDs) in the envelope as binaural cues for localization. Other cues are not (e.g. ITD in the waveform) or only partially (e.g. spectral cues) transmitted by the devices (Seeber & Fastl 2008). Lorenzi et al. (1999b) reviewed how different binaural cues are affected by background noise. Based on the findings of Yost (1974) and Gaskell and Henning (1981) they concluded that the mechanism sensitive to envelope ITDs is “significantly more susceptible” to background noise than that dealing with ILDs and waveform ITDs. According to Lorenzi et al., the latter two are about equally susceptible to background noise.

This leaves aside that physically the broadband ITD would be a highly reliable cue for localization in the presence of interfering sources (e.g. Hartmann et al. 2005; Shinn-Cunningham et al. 2005). The implication is that, given current CI technology, even if CI users were able to make good use of envelope ITDs, they might be left with ILDs as the only localization cue in background noise. This is in agreement with van Hoesel et al. (2008) who assessed ILDs in noise and related them to localization performance. ILDs accounted for as much as 99% of the variance in the mean responses of CI listeners.

Our results showed that localization responses moved toward the median plane with decreasing SNR. Nevertheless, perception of sound sources well off the median plane remained at the correct side, which is likely related to their better detectability relative to sources at the front. This was reported by our participants and confirmed by the detectability data measured with CI users (representative example data for one user in Fig. 6). The better detectability at the sides is likely a consequence of a higher signal-to-noise ratio due to head shadow effects rather than an effect of binaural unmasking. Few studies have addressed binaural unmasking with everyday speech processors, and it is thought to be small with current implants (Long et al. 2006, van Hoesel et al. 2008, Lu et al. 2010). Instead, we have simulated the effective SNR at the ear toward the target source in order to relate it to the nominal SNR defined in the head center. Head related transfer functions of a KEMAR were used for a sound source at 60°. The SNR at the shadowed ear was 9.4 dB lower than the nominal SNR when averaged over the stimulus bandwidth (300-10000 Hz). Conversely, on the ear toward the source the broadband SNR was 3.5 dB higher. Thus, for the lower nominal SNRs used in our experiments, target sounds were most likely inaudible at the shadowed ear but well audible at the ear toward the source. Nevertheless, most BiCI users still assigned a target sound to a roughly correct location, suggesting that they either used the diminished ILD to extract the location (c.f. compression in the responses, BiCI10), or that they indicated a location on the side of the ear in which they heard the target (c.f. variance pattern of BiCI08).

Localization ability was more disrupted at higher signal levels, an effect previously seen in other studies (van Hoesel et al. 2002; Nopp et al. 2004). This might be caused by the limiting of the dynamic range in either the AGC or the pulse-mapping stage of the CI speech processor. The limiting would lead to reduced ILDs which would be visible as localization responses shifted toward the median plane. Although we defined the target stimuli so that compressor activation in the CI occurs for the highest signal levels and for some participants only, in the actual experiment the effect might have been somewhat larger, because the initial compressor measurements were done for frontal sound sources, not considering that more lateral sources elicit higher levels at the ipsilateral ear.

To directly investigate the directional effects on compression we measured the ILD in a single CI channel for a target source at 60°, using a sinusoid with a frequency corresponding to the center frequency of the measurement channel (1934 Hz, Figure 7). The sensitivity setting was “12”. At approximately 50 dB SPL the compression started to reduce ILDs, and ILDs were absent for levels exceeding 62 dB SPL. Note that here the limiting took only place in the pulse mapping stage of the speech processor, because the AGC kneepoint for the used speech processor setting was at 67 dB (broadband SPL). However, in our experiments UEN was used as the target signal which had a 13 dB higher overall level than the level in a single CI channel. Since ILD compression started at 50 dB SPL for sinusoids, it would have affected the UEN target stimuli above 63 dB SPL, i.e. in quiet only the highest roving level of 66 dB SPL would have been affected by compression. Consequently localization results in quiet did not show level effects. However, in the presence of background noise levels rose to 70.8 dB (at -3 dB SNR), leading to ILD compression for some participants at the higher absolute levels tested. To completely avoid this ILD

compression the knee-point would have to be shifted upwards by 7.8 dB, which corresponds to approximately six sensitivity steps in the CI speech processors. Thus, participants with sensitivity settings below 6 should have been unaffected by ILD compression. For the others ILD compression has likely occurred in some conditions which would partially explain the positive correlation between speech processor sensitivity and SR in background noise. To maximize performance in noisy situations CI users should thus consider using a low sensitivity setting.

There are additional mechanisms why localization could be poorer at high levels in the presence of intense background noise. Since current spread increases at high levels it is possible that current spreading from channels containing no substantial ILDs, e.g. low-frequency channels dominated by noise, reduced the effectiveness of the current from channels containing ILDs. Also, patients used stimulation strategies which select specific channels for stimulation (ACE, SPEAK). Particularly at negative SNRs it is not guaranteed that the channels dominated by the target are predominantly chosen, potentially leading to a loss of ILD information.

Localization ability and speech perception

No significant correlation between localization performance in quiet or in noise with speech reception thresholds for speech and noise from the front was found. Whilst such comparisons had previously been done for localization in quiet, this study adds the comparison with localization performance in noise.

At first sight, this outcome is not surprising, because the scores compared here are essentially of a different nature: Localization is based on binaural hearing whereas speech perception, as measured here, is essentially a monaural task. Other studies also failed to find a correlation between speech scores and localization in quiet, but in those studies speech scores were also derived for speech and noise from different locations, thus facilitating the use of binaural cues (Dunn et al. 2005; Tyler et al. 2006). However, Litovsky et al. (2009) found a positive correlation between speech reception thresholds and localization errors in quiet, even with speech and noise from the front like in our study. This correlation, however, might reflect the wide performance range of their subjects: CI users who are good in a certain task like speech understanding likely have, for example, better fitted speech processors, better nerve survival, or a better positioned implant electrode array resulting in an improved electrode-nerve interface. All these factors would help them to perform better in other auditory tasks, including localization. In the present study, instead, all bilateral CI users were generally good performers who had SRTs lower or equal to +10 dB, a good score compared to reports in other studies like Litovsky et al. (2009), where SRTs were as high as +25 dB (c.f. also Wilson & Dorman 2008). Thus, the generally high performance level of the participants tested in our study might have prevented us from observing a correlation.

Results from this and other studies (e.g. Besing & Koehnke 1995) suggest that speech scores alone are not a comprehensive measure to assess everyday performance of bilateral CI users. Speech scores miss out on predictions for localization performance and thus for binaural ability. But exactly these binaural abilities are important in difficult situations, e.g. to ease listening effort by quickly finding the talker in a group conversation. Simple and clinically applicable measures for binaural benefit exist and would be a worthwhile extension for clinical test protocols (c.f. Koehnke & Besing 1999).

Recommendations for cochlear implant design and fitting

The background noise levels used in this study were representative of the levels encountered in real environments (Legget and Northwood 1960; Plomp 1977), and were not

extraordinarily high (70.8 dB SPL for CI users at most, i.e. the sum of target pulses at 66 dB SPL and background noise at 69 dB SPL, a combination that occurs for an SNR of -3 dB and a level rise of $+6$ dB). However, for the CI devices this ambient noise level was already too high to leave headroom for encoding the target sounds on top of the noise, because the background noise alone already triggered the dynamic range compressors and caused maximum electric stimulation in some situations. In order to overcome this, the acoustic dynamic range needs to be extended to higher levels. One approach is the use of an adjustable sensitivity setting. While this allows for higher acoustic input, low level sounds will become inaudible as long as the acoustic dynamic range is kept constant. As a solution, the sensitivity setting can be made dependent on the ambient sound level (“AutoSensitivity”, Patrick et al. 2006). However, “AutoSensitivity” is not activated in the standard programme of most adult users of the Nucleus device (Wolfe & Schafer 2010). Since the present results suggest that “AutoSensitivity” would benefit binaural hearing in noise, an in-depth analysis of the benefits and problems associated with this feature is needed.

The “AutoSensitivity” setting acts independently at the two ears, bearing the danger that at times different sensitivity settings may be engaged at the two ears. Results from the present study show that the sensitivity setting affects ILDs, and different sensitivity settings at the two ears might exacerbate the negative effects on ILDs. The sensitivity setting should thus be equal in the two devices which could be achieved by a communication link between them. A link would also be beneficial for CI users who set the sensitivity manually since it would prevent them from accidentally using different values at the two ears.

Noise reduction schemes are designed to help with listening in noise. Obviously, these algorithms must preserve binaural information if localization performance is to be maintained. While preserving ILDs, the algorithms would have to ensure that the SNR for a target sound does not drop below approximately $+7$ dB. At this SNR localization responses were still reasonably well preserved for most bilateral participants in the present study (Fig. 4) and spatial resolution was only marginally affected in most. This is an ambitious aim considering that conversations in most cocktail parties take place at an SNR of 0 dB (Bronkhorst 2000), meaning that the algorithms would have to enhance the SNR by $+7$ dB.

Acknowledgments

This study was funded by the Intramural Programme of the Medical Research Council (UK) and Cochlear Europe Ltd. We thank Paula Greenham and Brendan Murray at Cochlear Ltd. for their support. We would also like to express our gratitude to our participants who donated their time and gave invaluable input on what it means to listen through a CI in noisy situations. We are thankful for help with patient recruitment to Helen Cullington at the South of England Cochlear Implant Centre, Southampton, to Louise Craddock and Sandra Gerges at the Birmingham Adult Cochlear Implant Programme, to Simon Freeman and Deborah Mawman at the University Department of Otolaryngology – Head and Neck Surgery at Manchester Royal Infirmary, to Tracey Twomey and Ellen Jeffs at the Hearing Services Ropewalk House, Nottingham, to Gerard O’Donoghue at the ENT department, Queens Medical Centre, Nottingham, and to The Ear Foundation in Nottingham. Finally, we thank Ian Wiggins for proof reading the manuscript, and the Associate Editor Wesley Grantham and two anonymous reviewers for their helpful comments on an earlier version of the manuscript.

This study was funded through the Intramural Programme of the Medical Research Council (UK) and by Cochlear Europe Ltd.

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Figure 1.

Localization data of normal-hearing participants for conditions in quiet (each left panel), at +5dB SNR (middle panel) and at -5 dB SNR (right panel). Medians and quartiles of the localized directions are given as a function of target directions. Results for different participants are organized along rows across two columns with the participant code given in each left panel.

Figure 2.

As Figure 1 but data for unilateral CI users. Note that the rightmost graph in each panel now refers to an SNR of 0 dB.

Figure 3.
Localization results in noise for bilateral CI users presented as in Figure 2.

Figure 4.

Spatial Resolvability (SR) for all participants as a function of SNR. The participant code is given in the individual panels. For the normal-hearing listeners medians and quartiles over individually calculated SRs are presented (NH avg). Only the two unilateral CI patients with significant side discrimination ability were included.

Figure 5.

Relations of speech understanding in noise, speech processor sensitivity and spatial resolution in quiet and at 0 dB SNR for the bilateral CI users. Pearson correlation coefficients and their significance level are shown in each panel.

Left column: Correlations of SRT with Spatial Resolvability (SR) in quiet (panel B) and with SR decline at 0 dB SNR (panel D). The SR decline is expressed as the ratio between the SR at an SNR of 0 dB and the SR in quiet.

Right column: Correlations of speech processor sensitivity with SRT (panel A), with SR in quiet (panel C) and with SR decline (panel E).

Figure 6. Percentage of audible target sounds as a function of source direction at an SNR of 0 dB. Data were measured with BiCI07. The SNR of 0 dB was the worst SNR tested with this participant.

Figure 7.

Interaural level differences as a function of nominal SPL for a sound source at 60° measured through a Nucleus Freedom speech processor. The ILD is expressed as the difference in stimulation current between the bilateral processors. The measurement was done in a single CI channel around 1934 Hz, using a sinusoid of the same frequency. The speech processor was set to a sensitivity of “12”. T_{SPL} and C_{SPL} were at 25 dB SPL and 65 dB SPL respectively. Maximum and minimum stimulation currents (C-level and T-level) were at 200 CU and 105 CU.

Table 1

Participant details for cochlear implant users.

Code	Age and sex	Duration of deafness or PTA HL ^a		Onset of hearing loss	Etiology	CI experience [years]		Strategy	Median SRT and upper/lower quartile [dB]	Speech processor type ^c	Speech processor sensitivity
		Left	Right			Left	Right				
UnCI01	49 (f)	108 dB	?	Progressive	unknown	n/a	6.3	ACE	2 +2.0/-0.0	FD	?
UnCI02	62 (m)	105 dB	>10 ys	Progressive	Noise damage	n/a	4.3	ACE	6 +0.0/-0.5	FD	?
UnCI03	68 (m)	28 ys	70 dB	Progressive	Noise damage ?	4.8	n/a	ACE	6 +0.5/-2.0	N5	5
UnCI04	43 (f)	2 ys	117 dB	Progressive	Viral infection	1.7	n/a	ACE	14 +0.5/-4.0	FD	5
BiCI01	77 (m)	35 ys	37 ys	Progressive	Hereditary	10.9	7.6	SPEAK	6 +0.5/-0.0	FD	12
BiCI02	52 (m)	8 ys	2 ys	Sudden	Meningitis	8.6	12.9	ACE	8 +4.0/-0.5	3G	3.6
BiCI03	78 (m)	4 ys	2 ys	Progressive	Meniere's	9.0	11.2	ACE	6 +0.5/-2.0	FD	9
BiCI04	67 (f)	2 ys	2 ys	Progressive	Ear infection?	9.6	10.5	SPEAK	4 +2.5/-2.0	FD	10 ^b
BiCI05	75 (m)	19 ys	19 ys	Progressive	Ototoxicity	10.1	8.3	ACE	10 +2.0/-0.5	FD	20
BiCI06	69 (m)	10 ys	13 ys	Sudden	Trauma (Explosion)	9.6	12.8	SPEAK	2 +2.0/-0.5	FD	12
BiCI07	68 (m)	41 ys	42 ys	Progressive	Hereditary	10.3	9.4	SPEAK	6 +4.5/-0.5	FD	5
BiCI08	41 (f)	22 ys	22 ys	Sudden	German measles	11.7	10.5	SPEAK	4 +1.0/-2.5	FD	0
BiCI09	30 (m)	0.5 ys	0.5 ys	Sudden	Trauma	3.2	3.2	ACE	0 +0.0/-0.5	FD	4
BiCI10	49 (m)	34 ys	36 ys	Progressive	Cochlear malformation	2.8	0.5	ACE	0 +2.5/-0.5	N5	12

^aThe Duration of deafness was assessed retrospectively by the participants and refers to the years (ys) of impaired hearing before first implantation. Additionally this column gives pure tone averages (averaged dB HL at 500, 1000, 2000 Hz) for the unilateral CI users at the un-implanted ear at the time of testing.

^bThe sensitivity setting for BiCI04 is averaged over both channels, actual magnitudes were 11 (left) and 9 (right).

Table 2

Baseline localization performance in quiet and side discrimination ability in noise for all participants. Within participant groups results are sorted according to Spatial Resolvability.

Participant	Median error		Linear regression ^d				SNR with non-significant side discrimination ^f			
	Absolute ^a	RMS ^b	Interquartile ^c	Slope	Offset	r ²	Spatial Resolvability (SR) ^e		All	High levels
	[°]	[°]	[°]		[°]		[°]	[dB]	[dB]	[dB]
NH 02	2.5	2.8	1.8	0.98	2.0	0.999	1.4	<-7	<-7	<-7
NH 03	2.3	2.8	2.8	1.01	2.1	0.993	2.9	<-7	-7	-7
NH 05	5.6	5.9	2.8	0.92	-4.5	0.992	3.0	<-7	<-7	<-7
NH 06	6.6	7.3	3.9	1.09	5.5	0.983	3.3	<-7	<-7	<-7
NH 04	4.7	5.7	3.3	1.05	5.1	0.985	3.6	-7	-7	-7
NH 01	5.2	5.6	3.6	1.03	-1.3	0.978	5.1	<-7	-7	<-7
UnCI02	28.0	28.8	18.3	0.19	19.6	0.001	61.9	<0	<0	0
UnCI04	48.8	65.6	64.9	0.61	-13.8	0.166	96.3	-3	0	<-3
UnCI01	31.2	33.8	19.2	-0.07	14.1	0.048	-	-	-	-
UnCI03	53.8	67.5	100.8	-0.04	-59.9	0.277	-	-	-	-
BiCI09	16.7	17.8	11.6	0.92	-15.9	0.648	8.3	<-3	<-3	c.n.d. ^g
BiCI 10	12.3	15.1	13.7	0.97	0.4	0.872	12.8	<0	<0	5
BiCI03	12.1	14.8	19.9	0.83	-0.3	0.570	14.1	-3	<-3	3
BiCI04	15.1	19.7	20.8	0.67	-14.2	0.660	23.7	-3	-3	-3
BiCI05	35.3	38.6	48.2	1.21	-12.7	0.839	23.7	3	3	3
BiCI07	23.7	30.5	34.7	0.83	-0.3	0.777	28.1	<0	<0	0
BiCI06	25.0	30.3	25.5	0.83	-8.9	0.517	31.6	0	<0	0
BiCI02	28.7	38.2	60.4	0.92	-0.4	0.671	41.0	-3	<-3	0
BiCI01	21.0	26.0	29.1	0.82	8.5	0.689	41.8	-3	-3	7
BiCI08	41.9	44.8	58.8	0.97	3.9	0.933	43.6	<-3	-3	0

^a Absolute error: Median across the 11 directions of the averaged absolute difference between target location and perceived direction.

^b Root-Mean-Squared Error: Median across the 11 directions of the square-root of the averaged squared differences between target location and perceived direction.

^cMedian across the 11 directions of the range including 50% of individual localization responses symmetrically around the individual median response.

^dLeast-squares linear regression fit to the individual localization responses.

^eSpatial Resolvability: Averaged standard deviation divided by the slope of the regression fit. Results $>180^\circ$ denote insufficient localisation ability and are omitted.

^fHighest SNR at which side discrimination is still not significant (Sign test, $p > 0.05$). For SNRs at or below the given value side discrimination was not possible. The analysis was done over all localisation responses (“All”), only for localisation responses at high roving level (“High”, pooled results of +3 and +6 dB) and only for responses at low roving levels (“Low”, −3 and −6 dB). Values for UnCI01 and UnCI03 were omitted because these participants did not show significant side discrimination ability in quiet. The “<” sign in the cells marks conditions where side discrimination was still significant at the lowest SNR tested with the participant.

^gcould not determine: The roving level of +6 dB was not tested with participant BiCI09.