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Cochlear Implantation as a Treatment Option for Adults with Post-lingual Single Sided Deafness: A Systematic Review of the Literature

Elvera Bader
Graduate Center, City University of New York

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By:

Elvera Bader

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John P. Preece, Ph. D.

_________ _______________________________

Date Faculty Mentor

John P. Preece, Ph. D.

_________ _______________________________

Date Executive Officer

THE CITY UNIVERSITY OF NEW YORK

ABSTRACT

COCHLEAR IMPLANTATION AS A TREATMENT OPTION FOR ADULTS WITH POST-LINGUAL SINGLE SIDED DEAFNESS: A SYSTEMATIC REVIEW OF THE LITERATURE

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Elvera Bader

Advisor: John P. Preece, Ph.D.

Adults with post lingual single sided deafness experience a myriad of issues as a result of their condition. Speech perception in noise and localization are well documented as being compromised in this population due to the loss of binaural auditory input. Cochlear implantation was introduced in the 2000s as an experimental treatment option for suppression/abatement of tinnitus in individuals with SSD, with consistent demonstration in reduction of tinnitus severity. Most recently, the focus has shifted to the potential reintroduction of binaural effects, and subsequently, improvements in speech in noise and localization performance through this treatment modality. The present systematic review provides overwhelming evidence that indicates cochlear implantation is a viable and effective treatment method for this population in terms of suppression/abatement of ipsilateral tinnitus, restoration of localization ability and for speech performance in various speech/noise configurations.

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Single-sided deafness (SSD) or unilateral deafness is a term used to describe individuals with severe to profound hearing loss in one ear. The term however, can render various audiologic profiles for the contralateral ear, with a universal trend of having preserved or aidable audiometric thresholds in the unaffected ear (Giardina, Formeister & Adunka 2014). For the purpose of this systematic review, the term SSD will refer to individuals with severe to profound hearing loss in one ear, with normal to near normal hearing in the contralateral ear (PTA 0.5, 1, 2, & 4 kHz $\leq$ 30 dB HL). Acquired post-lingual SSD can be caused by a variety of different conditions and present with various co-morbid features, dependent upon the underlying etiology. According to Giardina et al. (2014) sudden sensorineural hearing loss is the most common cause of SSD, though other etiologies are well documented including Meniere's disease, unilateral vestibular schwannoma, temporal bone fracture, labryinthitis, unilateral noise damage and ototoxic drug exposure. Many of the conditions resulting in SSD may also present with concomitant ipsilateral tinnitus. For many individuals, the presence of tinnitus may be more disconcerting than the loss of auditory perception in that ear. Due to the degree of hearing impairment in individuals with SSD, traditional treatment options such as acoustic sound therapy are not viable for this population. Though current literature on cochlear implantation for patients with SSD focuses on the ability to restore binaural input, this approach began in the 2000s as an experimental treatment option for suppression/abatement of incapacitating tinnitus (Giardina et al., 2014; Tokita, Dunn & Hansen 2014). Research in this short time has demonstrated consistent success in reduction of tinnitus severity and has resulted in the evaluation of this treatment option for restoring binaural functions lost by this condition in appropriate candidates (Gartrell et al., 2014)

Binaural hearing has been demonstrated throughout the literature to be superior to unilateral hearing in regards to speech perception in noise and sound localization (Buss et al. 2008; Dubno, Ahlstrom & Horwitz, 2008). This superiority is based on advantages derived from three principles of binaural hearing. These include the binaural squelch effect, the binaural summation effect and the head shadow effect. The first two principles rely on true binaural sound processing, whereas the head-shadow effect is a physical phenomenon reliant upon hearing in both ears. The head-shadow effect occurs when the head obstructs sounds arriving at the ears from different locations. This phenomenon allows the listener to always be able to utilize the ear with the more favorable signal to noise ratio. Binaural summation, resulting from the stimulation of both ears causes an increase in the perception of the loudness of the signal. Additionally, redundancies in the auditory signal which may result in greater frequency and intensity discrimination are available with binaural stimulation. Finally, the binaural squelch effect refers to the advantage gained through the addition of the ear with the poorer SNR as compared to listening monaurally with the better SNR ear alone. This allows for comparison of timing, amplitude and spectral differences in the signals arriving from each ear which provides a greater representation of the signal (Tyler et al., 2002). The combination of these effects provided by binaural stimulation translate to improvements in speech recognition ability for separated sound sources, listening in noise, and better sound localization (Buss et al., 2008; Dirks & Wilson, 1969; Dubno, Ahlstrom & Horwitz, 2008).

Speech perception is vastly affected in individuals with SSD, as they cannot benefit from having two separately processed sound inputs and must solely rely on the input provided to their hearing ear. The benefits of binaural stimulation for speech comprehension are specifically attributed to the effects of binaural squelch and binaural summation. For speech perception in noise, binaural squelch allows for the brain to selectively filter noise from an incoming sound, particularly when noise and speech have different azimuthal locations. The result are differences in inter-aural level, phase and timing that allow for the speech to be “unmasked” (Dirks & Wilson, 1969). Kamal et al. (2012) & Vermeire and Van de Heyning (2009) reported advantages of the binaural squelch effect in gains of 2-5 dB in SNRs for speech in noise testing. Binaural summation is a psychoacoustic phenomenon that results in an additive effect of perceived intensity of approximately 2-6 dB in SRT compared to a monaural listening condition (Giardina et al., 2014; Tokita et al., 2014). Finally, the head shadow effect can attenuate signals directed towards the affected ear anywhere from 10-16 dB by the time they reach the contralateral ear. The combined effect of these lost cues translate to difficulties in speech recognition ability for separated sound sources and listening in noise.

Localization is another function that is greatly compromised in individuals with SSD. According to Tokita et al. (2014) sound localization is dependent upon accurate calculation of three spatial coordinates. These include azimuth, elevation, and distance of the sound source. Directional hearing for determining the azimuth of a signal depends on binaural differences in sound arrival time (inter-aural time differences) for lower frequencies (<1500 Hz) and inter-aural level differences caused by the head shadow effect for higher frequencies (>3000 Hz). Monaural listeners lack these cues, as no inter-aural comparisons between sound level and timing can be made (Wanrooij & Opstal, 2007). Monaural cues for sound localization are limited to acoustic changes caused by the outer ear structures including the pinna and external auditory canal (Tokita et al., 2004). For monaural listening, the limited acoustic cues derived from the modifications in the spectral composition of the signal are ineffective in aiding in horizontal localization (Giardina et al., 2014).

Traditional treatment options for SSD include the contralateral routing of the signal (CROS) systems, and more recently osseo-integrated (BAHA, PONTO, SOPHONO) and bone conduction hearing devices (e.g. SoundBite). All these pseudo-binaural treatment options have the same end goal, routing of the signal from the "dead" ear to the better, contralateral ear. The CROS device achieves this via wireless transmission and presentation to the good ear through air conduction, while osseo-integrated devices and other bone conduction devices achieve this via bone conduction transmission. According to Bishop and Eby (2010) literature on CROS hearing technology suggests limited efficacy in addressing the myriad of issues associated with SSD. These limited benefits are thought to be a result of restoration of sound awareness on the affected side and reducing the negative effects of the head-shadow for monaural listeners. Despite reports of subjective benefit by some users, Giardina et al. (2014) reported that overall, the CROS device is ineffective in improving listeners' experience in noise and in regards to localization performance. In addition, in those patients with normal hearing in the contralateral ear, use of the CROS device may result in an occlusion effect in the better ear.

The introduction of bone conduction devices as a treatment option in this population resulted in a re-visitation of CROS efficacy through the comparison to bone conduction devices. Various studies that compared CROS and bone conduction devices reported results that indicated superiority on both subjective and objective outcome measures for bone conduction options (Bishop & Eby, 2010; Niparko, Cox & Lustig, 2003). Giardina et al. (2014) noted that studies on efficacy of BAHA consistently demonstrated increased speech perception in noise, moderate improvements in sound localization and overall patient satisfaction. However, a recent systematic review of the literature by Peters et al. (2015) comparing CROS and BAHA devices found no benefit with the addition of either treatment option for performance on sound localization tasks. In addition, Bishop and Eby (2010) noted that both CROS and bone conduction treatment options fell short in terms of patient satisfaction and sound localization.

Most recently, cochlear implantation has been explored as a treatment option for individuals with SSD with or without the presence of ipsilateral tinnitus. The research over this short time has demonstrated great success in reduction of tinnitus severity (in those individuals with pre-operative tinnitus) and self-perceived functioning (Gartrell et al., 2014; Vlastarakos et al. 2014). This growing trend of implanting individuals who present with normal/near normal hearing in the contralateral ear has created the opportunity to assess integration of electrical and acoustic input, and measure the effects restored through the re-introduction of binaural stimulation. The implementation of CI as a treatment for individuals with SSD provides the opportunity to overcome the limitations of pseudo-binaural forms of intervention. In addition to being the only treatment option that can truly restore binaural function, it is also the only feasible intervention for those who present with ipsilateral tinnitus.

Statement of Purpose

Since their acceptance by the FDA in 1984, cochlear implants have become the predominant treatment option for adults with bilateral severe to profound hearing impairment in developed nations. Over this short time, technological advancements, identification of post-operative success factors and the benefits of binaural stimulation for traditional cochlear implant recipients has caused a shift from unilateral to bilateral cochlear implantation and has resulted in expansion of candidacy criteria to include those with a variety of audiological profiles. Once again, a new frontier is being approached and the candidacy for CI indication is being revisited. It is for this reason that the present systematic review was conducted, so that the current literature on CI for SSD may be evaluated and the efficacy of this treatment option on various outcomes could be critically reviewed.

Materials and Methods

Literature Search

A comprehensive review of the literature was performed using MEDLINE, Scopus, Cochrane and other database sources available through the CUNY library system looking for three primary endpoints: (1) assessment of cochlear implantation for speech comprehension in noise for unilaterally deafened patients (2) assessment of cochlear implantation in sound localization for unilaterally deafened patients and (3) assessment of cochlear implantation as a treatment option in unilateral tinnitus. The search strategy used the keywords *unilateral deafness, unilateral hearing loss, single sided deafness, single sided hearing loss, cochlear implantation, cochlear implants*, and *asymmetric deafness* to identify articles and reviews published from database inception to January of 2015.

Abstracts were reviewed to identify articles which met one or more of the study endpoints, and would therefore be appropriate for analysis. Reference lists from retrieved articles were manually searched to identify additional articles that would be appropriate for analysis. Extended abstracts and unpublished data were excluded, as were articles published in languages other than English.

Data Extraction

After identification of articles that were appropriate for analysis, full text articles were reviewed to identify individual patients who met inclusion criteria for the present systematic review. Inclusion criteria for individual participants were adults (18+) with unilateral, post lingual deafness with normal to near normal hearing (PTA 0.5,1, 2 & 4 kHz $\leq$ 30 dB) in the contralateral ear. Etiologies for the unilateral severe to profound hearing loss included idiopathic sudden sensorineural hearing loss (ISSNHL), acute traumatic or postoperative hearing loss, Meniere’s disease/labryinthectomy and labyrinthitis. A comprehensive list of all participants from each of the twelve studies can be seen in Table 2.

Data measures post cochlear implantation that were extracted for review included the following: (1) objective test performance for speech in noise measures (2) objective test performance for speech and sound localization (3) scoring on standardized questionnaires (4) subjective tinnitus (5) subjective speech comprehension (6) subjective speech/sound localization.

Assessing Quality of Studies

Assessment of quality of the included studies was adapted from a recent review of the literature conducted by Zon, Peters, Stegeman, Smit and Grolman (2014). Their strategy included assessing the articles on directness of evidence and risk of bias. Studies were classified as having high directness of evidence if they complied with three or more of the indicated criteria, moderate if they complied with two, and low directness of evidence if they only complied with one of the indicated criteria. Articles were classified as having low, mid or high risk of bias based on treatment allocation, blinding and standardization of treatments and outcomes. The comprehensive assessment of quality of included studies can be viewed in Table 3.

Results

Systematic Review

Literature search and Data Extraction

Comprehensive review of the literature produced twelve studies with patient populations that were appropriate for analysis. A list of included studies and their respective outcome measures can be seen in Table 1. Data extraction yielded 91 participants that met the specific individual patient criteria. Eight participants that were selected for analysis from the Vermeire and Van de Heyning (2009) trial were also included in the Van de Heyning et al. (2008) trial and were therefore only counted once. In addition, six participants from the Tavora-Vieira, Ceulaer, Govaerts and Rajan (2014) study were participants in the Tavora-Vieira, Marino, Krishnaswamy, Kuthbutheen and Rajan (2013) study and were only counted once. A comprehensive list of all participants that met the inclusion criteria for the present systematic review can be viewed in Table 2. Due to the large degree of clinical heterogeneity throughout the studies in terms of classification of SSD (audiological profile of the contralateral ear), outcome measurements, test materials, testing configurations, test conditions (unaided, CI, CROS, BAHA), durations of deafness and follow-up durations, polling of data for meta-analysis was not possible.

Speech Perception in Noise

Speech perception in noise for individuals with SSD was examined by six of the twelve studies in the present systematic review. While all six studies evaluated and compared speech perception in noise in the monaural condition to the CI-aided condition, two studies (Arndt et al. 2010; Hassepass et al. 2013) also examined performance with use of pseudo-binaural forms of SSD intervention including CROS and BAHA devices. In addition, two of the studies (Firszt et al. 2012; Stelzig et al. 2011) evaluated participant performance in a CI- alone condition on certain tasks, with the contralateral un-implanted ear plugged and muffed or masked. Speech perception in noise was measured using various configurations of spatially separated loudspeakers that were labeled in slightly different manners in each of the studies. For the purpose of continuity in this review, spatial configurations will be indicated by the terms S (Sound), N (Noise) followed by the direction CI (cochlear implant ear) and NH (normal hearing ear) and 0 (Front, 0 degree azimuth). For example, a condition with speech towards the front and noise towards the implanted ear would be labeled as S0/NCI. A detailed table including test conditions, spatial configurations, test materials and extracted data for speech in noise testing can be viewed in Table 4**.** Though test methods, materials, conditions and time intervals post CI-activation varied between studies, two outcome measures were pervasive throughout the literature. They included assessment of speech comprehension in noise as the total percentage of correctly repeated words and identification of the signal to noise ratio (SNR) where participants could correctly identify 50% of the sentence, or their critical SNR.

Arndt et al. (2010) evaluated performance of speech perception in noise in three different presentation setups; S0/N0, SNH/NCI and SCI/NNH. Testing was completed pre-operatively in a monaural unaided condition, with a CROS Phonak Una M device and with a BAHA Intenso via a soft band. CI-aided testing was performed six months post-activation. Materials used for speech comprehension in noise testing included the Hochmair-Schulz-Moser (HSM) sentence test and the Oldenburg Sentence Test (OLSA). The HSM sentence test consists of 30 lists of 20 everyday sentences in German. It was developed as a tool to assess CI recipients' speech comprehension in noise performance. The OLSA sentence test is another German speech intelligibility task that uses an adaptive measurement to obtain individuals' critical SNR. Speech and background noise were presented at a level of 65 dB SPL with a fixedsignal to noise ratio (SNR) of 0 dB for the HSM test. Speech comprehension for the HSM test was scored as a percentage correct word score. The OLSA speech comprehension task used an adaptive procedure with background noise presented at a level of 65 dB SPL and the speech signal adjusted adaptively based on the participants' response to the test items to obtain the SNR at which the percent correct word score was 50% (critical SNR). Speech perception in noise using the same test setup, materials and test conditions as Arndt et al. (2010) was performed by Hassepass et al. (2013) in two participants with SSD. Post-operative data on a third participant was not obtained due to discontinued use of the CI six months post-surgery.

Stelzig, Jacob and Mueller (2011) examined speech understanding in noise in four participants with single sided deafness. Test materials included OLSA sentence test, the HSM sentence test and the Freiburg monosyllable test. Test conditions included monaural unaided, CI-aided and CI-only, in which the contralateral un-implanted ear was plugged and masked with 80 dB of wideband noise. Test setup included 11 loudspeakers mounted on a steel ring 2 meters in diameter at a height of 1.2 meters in the frontal plane from 90 degrees to the right and -90 degrees to the left, with 18 degrees between each speaker. Participants were positioned on an adjustable chair in the center of the semicircle of loudspeakers. The Freiburg monosyllable test and HSM sentence test were both administered with target stimuli presented at 65 dB SPL in a S0/N0 condition. The Freiburg monosyllable test was administered at SNRs of 15 dB, 5 dB and 0 dB with speech simulating CCITT noise. The HSM sentence test was administered at SNRs of 10 dB, 0 dB and -5 dB. The OLSA Sentence Test was administered with speech constantly presented from the front with an adaptively varying presentation level, and noise emanating from either the front, CI side or the contralateral un-implanted side at a constant level of 60 dB SPL. Speech in noise testing for the HSM and OLSA sentence tests were only administered in the monaural unaided and CI-aided condition. Firszt et al. (2012) assessed speech understanding in noise using the Bamford–Kowal-Bench Speech in Noise test (BKB-SIN) and the Hearing in Noise Test (HINT). Testing for the BKB-SIN test was administered in the sound-field with a three speaker test setup (front, -90 degrees, +90 degrees) at a level of 65 dB SPL with four talker babble coming from one of the three speakers. Signal to noise ratios varied from +21 dB SNR to -6 dB SNR and were decreased until a critical-SNR was obtained. HINT testing was administered in the R-SPACE, which is a speaker setup that attempts to simulate real world listening conditions. Participants were seated in the center of 8 loudspeakers with diffuse restaurant noise presented at a level of 60 dB SPL from each loudspeaker. Sentence intensity was varied adaptively by 2 dB based on whether the participants' response was correct or incorrect. A total of 17 responses per list were averaged and a critical SNR was obtained. Both the BKB-SIN and HINT tests were administered in three listening conditions including monaural unaided, CI-only (contralateral ear plugged and muffed), and binaurally. Tavora-Vieira et al. (2013) also assessed speech understanding in noise in nine participants with SSD using the BKB-SIN test. The same three spatial configurations described in the Firszt et al. (2012) study were used, with the addition of a SCI/NNH configuration. Performance in all four spatial configurations was obtained pre-operatively, and binaurally, three months post activation. It should be noted that the participants in this study were asked to dedicate 60 minutes a day to aural rehabilitation using direct audio input to their cochlear implant and increasing the speech rate of audio books as their understanding improved. Vermeire and Van de Heyning (2009) evaluated speech performance in noise in ten participants with SSD. Testing was conducted 12 months post CI-activation in a monaural unaided condition and CI-aided condition. Test materials used were the Leuven Intelligibility Sentence Test (LIST) which includes 35 lists of 10 sentences spoken by a female speaker. Noise used was a speech-weighted stationary noise that was based on the long-term average speech spectrum of the LIST sentences. The noise was presented at a constant level of 65 dB SPL with the level of the speech signal beginning at 55 dB SPL and varying adaptively (in steps of 2 dB) based on the participants' response. Spatial configurations included S0/N0, S0/NCI and N0/SCI.

All six studies assessed speech comprehension in noise for the spatial configuration S0/N0. Stelzig et al. (2011) reported performance on the Freiburg monosyllable test demonstrated consistent increases in speech understanding in the binaural condition compared to the monaural unaided condition at all three SNR levels. It should be noted that improvements in speech understanding in noise were greatest in the most difficult SNR condition of 0 dB, with mean benefit of 11.9 percentage points (3.8 pp at 15 dB SNR, 7.5 pp at 5 dB SNR). Similarly, scores on the HSM sentence test were higher in the binaural condition versus the monaural unaided condition for both the 0 and -5 dB SNR conditions. Once again, mean increase in understanding with the use of the CI was greater for the more difficult test condition of – 5 dB SNR. Stelzig et al. (2011) also reported slightly improved critical SNRs on the OLSA sentence test for the S0/N0 spatial configuration in the CI–aided versus monaural condition (-5.0 dB w/CI versus -4.8 dB w/out CI). Tavora-Vieira et al. (2013) also reported improved critical SNR values on BKB-SIN testing with the use of the CI in the S0/N0 configuration. Individual critical SNRs demonstrated improved performance in noise in eight of the nine participants, with a group mean SNR improvement of 3 dB. Data on the two participants in the Hassepass et al. (2013) study also demonstrated improvement in speech perception in noise in the binaural CI condition. Participants obtained the highest HSM sentence scores in the CI aided condition as compared to the unaided, CROS and BAHA listening conditions. The remaining three studies (Arndt et al.

2010, Firszt et al. 2012, &Vermeire and Van de Heyning 2009) reported no significant improvements in speech in noise performance in the CI-aided condition versus the monaural unaided condition. It is important to note that overall, participant performance in the S0/N0 configuration was not negatively affected in any of the studies with the addition of the CI.

Three of the six studies assessed speech comprehension in noise in the spatial configuration SCI/NNH, with all three reporting improvements in performance in the CI-aided condition compared to the monaural unaided. Performance in noise with the CI was demonstrated by both the Arndt et al. (2010) and Hassepass et al. (2013) to be significantly improved as compared to pseudo-binaural forms of SSD intervention. Arndt et al. (2010) reported statistically significant results in performance for the spatial configuration SCI/NNH in the CI-aided condition as compared to the unaided, BAHA and CROS conditions. The two participants in the Hassepass et al. (2013) study demonstrated improvements from 21% and 0% on HSM sentence scores in the monaural unaided condition, to 80.7% and 19.8% in the binaural condition 12 months post CI activation. Additionally, Tavora-Vieira et al. (2013) found mean improvements of 5 dB in the critical SNR in the SCI/NNH configuration for the CI-aided versus monaural unaided condition. Two studies assessed participant performance in a similar spatial configuration with speech presented towards the front instead of towards the CI ear; S0/NNH (Firszt et al. 2012; Stelzig et al. 2011). Three of the four participants in the Stelzig et al. (2011) study obtained lower SRTs on the OLSA sentence test in the binaural condition versus the monaural unaided condition, with one participant obtaining a higher SRT in the binaural condition. Firszt et al. (2012) reported no significant difference in speech in noise performance in the CI aided versus monaural unaided condition in this spatial configuration.

Three studies assessed speech performance in noise for the spatial configuration

SNH/NCI. Arndt et al. (2010) reported significant improvement in performance in the aided CI-condition as compared to the BAHA and CROS conditions, though no improvement as compared to the monaural unaided condition was demonstrated. These findings were not replicated in the two participants in the Hassepass et al. (2013) study, with comparable HSM sentence scores demonstrated in all four listening conditions. It should be noted however that ceiling effects for the SNH/NCI condition might have prevented any demonstration of benefit from the addition of the CI, with excellent scores obtained for all four listening conditions.

Four studies reported on speech performance in noise in the S0/NCI spatial configuration. Of the nine participants in the Tavora-Vieira et al. (2013) study, five demonstrated improved critical SNR values on the BKB-SIN test in the CI-aided versus the monaural unaided condition. Two participants demonstrated equal SNR values in both conditions, and the remaining two showed minimal declines (-0.5 dB) in critical SNRs when noise was presented to the CI side. The remaining three studies (Firszt et al., 2012; Stelzig et al., 2011; Vermeire and Van de Heyning, 2009) reported similar findings, with no significant improvement in the critical SNR for the CI-aided condition as compared to the monaural unaided condition for the S0/NCI configuration. Despite not demonstrating any benefit for speech performance in noise with use of a CI in this spatial configuration, the addition of the CI did not result in any significant decline in speech understanding with noise presented to the CI ear.

Vermeire and Van de Heyning (2009) evaluated performance in noise in a SCI/N0 spatial configuration. Of the ten participants, nine demonstrated improvements in their SRT in the CI-aided condition when compared to the monaural unaided condition, with one participant obtaining the same SRT in both conditions. Overall, the group mean SRT improved significantly for the CI-aided condition by 1.7 dB (0.2 dB monaural unaided, -1.5 dB CI-aided).

Sound Localization

Speech/sound localization was assessed in six of the 12 studies that were included the present systematic review. A total of 46 participants from the six studies met the audiological criteria for normal/near normal hearing (PTA at 0.5,1,2 & 4 $\leq$ 30 dB) in the contralateral un-implanted ear and were therefore included in the data analysis. All six studies obtained localization data in the monaural unaided condition (either pre-operatively or post-operatively) and post-operatively with the addition of the CI. In addition, three studies (Arndt et al, 2010; Erbele et al. 2014; Hassepass et al. 2011) obtained localization data with pseudo-binaural forms of SSD intervention including BAHA and/or CROS devices. Data from each of the individual studies are presented in Table 5. Despite variability in test setup and stimuli used, all tests measured participants' performance in terms of localization error or root mean square error. Localization error or root mean square error refers to the mean difference in degrees between the location of the sound source and the sound source indicated by the participant, with lower scores indicating better localization performance.

Arndt et al. (2010) compared localization performance of 11 participants with SSD in four test conditions including monaural unaided, CROS, BAHA with soft-band, and six months post-operatively in a CI-aided condition. Localization testing was completed in a sound-treated booth with a setup array of 7 loudspeakers located at 30-degree intervals from -90 to 90 degrees in a frontal semicircle. Stimulus materials used were OLSA sentences presented at 5 different intensity levels between 59 and 71 dB SPL in each of the four different test conditions, for a total of 70 stimulus presentations. Localization ability was measured two ways, the first as the percentage of the 70 presenting speakers correctly indicated by the participants as the sound delivering speaker, the chance level of accurate speaker localization is 14.3% (100% divided by the number of speakers). Localization ability for each subject was also measured as localization error. Localization ability in the same four test conditions (unaided, CROS, BAHA and CI 6 months) was also evaluated by Hassepass et al. (2013) in three unilaterally deafened patients. An additional 12 month post CI activation test condition was added, with testing completed using the same methodology and outcome measurements as described by Arndt et al. (2010). Localization data in the CI condition for one of the participants was not obtained as patient discontinued use six months post-operatively with reports of no sound detection with use of the device. Erbele et al. (2014) also compared sound localization ability in participants with unilateral/single sided deafness who were previous, dissatisfied osseo-integrated device users. Sound localization data was collected pre-operatively unaided, and with patients' osseo-integrated hearing device. Post-operative data was obtained unaided, with participants' osseo-integrated hearing device, and in the CI-aided condition 3 months post activation. Testing was performed in a sound treated booth with a 26-loudspeaker array that covered a range of +/- 135 degrees horizontally around the patient's head, and +/- 30 degrees relative to the horizontal plane. Test stimuli consisted of various environmental sounds (teeth brushing, soda pouring) and were presented in three different localization conditions including a single-source condition, multi-source "add" and a multi-source "remove" condition. In the single source condition, patients were required to identify the source loudspeaker from which a two second stimulus was presented. In the multi-source "add" condition, patients were asked to localize the source speaker of a four second stimulus which was added to a mixture of 1-3 pre-existing sounds. Finally, for the multi-source "remove" condition, patients were required to identify the source speaker for a stimulus that was removed from a mixture of 2-4 existing sounds.

The remaining three studies (Firszt et al. 2012; Hansen et al. 2013; Tavora-Vieira et al.

2014) assessed localization ability in the monaural unaided condition and post-operatively in the binaural condition with the use of the CI. In addition, Firszt et al. (2012) examined localization ability in a CI alone (contralateral un-implanted ear, plugged and muffed) test condition. Testing was completed with participants facing a 15 loudspeaker array with each speaker located 10 degrees apart. Test stimuli used were 100 monosyllabic CNC words presented pseudo randomly through 10 active loudspeakers at a level of 60 dB SPL. Localization ability was measured as a root mean square error for each of the three test conditions. Hansen et al. (2013) evaluated localization ability in 17 patients with SSD. Testing was completed using an 8-array loudspeaker setup which spanned 108 degrees horizontally with the outermost speakers located at 54 degrees to the right and left of the zero degree azimuth. Each of the16 different everyday sound items was presented randomly a total of 6 times, for a total of 96 presentations. Target stimuli were presented randomly at 60 dB A from each of the 8 loudspeakers and participants were required to identify the source speaker. All data was collected pre-operatively, and post-operatively at 3, 6 and 12 month intervals. Tavora-Vieira et al. (2014) assessed localization ability in sixteen adult subjects with post-lingual unilateral deafness. All of the participants had opted for a cochlear implant after a wireless CROS and BAHA trial. All 16 participants received 3-6 months of intensive auditory training and had 6-18 months of experience with their cochlear implant at the time of data collection. Localization ability was assessed with the auditory speech sounds (ASE) evaluation localization test software. This test presents a narrow band noise of 1/3rd octave centered around 4000 Hz simultaneously from two loudspeakers placed at -60 and 60 degrees from the listener, with the noise from the speakers correlating with an inter-aural time difference of zero. The presentation level of the noise from the two speakers varies, simulating an inter-aural level difference and creating the illusion of a sound source being localized somewhere on the azimuth between the two speakers (Tavora-Vieira et al. 2014). Testing was administered in a soundproof booth with a 24-loudspeaker array with 13 active loudspeakers, and 11 “sham” loudspeakers placed in between each of the active speakers. Participants sat facing a zero degree azimuth and were not permitted to move their head. A total of 33 test items at varying inter-aural level differences including -30, -20, -10, -4, 0, +4, +10, +20 and +30 dB were presented. Participants were required to identify the speaker they thought the sound was coming from, with a root mean square error calculated to measure localization performance. In addition, RMS error was compared to normative data, which was based on 30 normal hearing adults.

Three studies reported on sound localization in unaided monaural, CROS, BAHA and CI-aided test conditions (Arndt et al. 2010; Erbele et al. 2014; Hassepass et al. 2013). Arndt et al. (2010) found localization error was significantly reduced in the binaural CI-aided condition compared to the monaural unaided condition, the CROS condition and the BAHA condition. Median group localization errors were 15.0 degrees in CI-aided, 30.4 degrees in the BAHA condition, 33.9 degrees in the unaided condition, and 39.9 degrees in the CROS condition, with a lower degree reflecting improved sound localization. Localization performance from the two participants in the Hassepass et al. (2013) study demonstrated improved performance in localization in the binaural CI-aided condition at both the 6 and 12 month post activation tests, as compared to the pre-operative unaided, CROS and BAHA conditions. Localization accuracy for both participants improved from 27.1% and 25.7% in the pre-operative unaided condition to 57.1% and 51.4% in the post-operative CI-aided condition. Hassepass et al. (2013) reported their localization data as a function of accuracy (not error) and therefore higher percentages reflect improved localization performance. Of the three participants in the Erbele et al. (2014) study, two demonstrated significant localization benefit in the CI-aided condition as compared to the unaided monaural condition. For one of the participants, the CI-aided condition did not provide significant benefit in localization as compared to the unaided condition, however it should be noted that performance was not negatively affected with the addition of the CI. One of the three participants in this study was a previous CROS user and therefore no data on localization performance with an osseo-integrated hearing device was obtained. Of the remaining two participants in this study who were previous osseo-integrated hearing device users, one showed significant improvement with the CI as compared to the BAHA condition while one demonstrated no change in performance.

The remaining three studies reported on localization pre-operatively unaided and post-operatively with use of the CI, with one study also providing data in a CI alone condition. Firszt et al. (2012) found that all three participants had significantly improved localization ability in the binaural CI-aided condition as compared with the monaural unaided condition. In addition, root mean square/localization error was lowest for all three participants in the binaural condition as compared to the monaural unaided and monaural CI condition, suggesting better localization with the use of the cochlear implant in conjunction with the contralateral un-implanted ear. The authors also reported that inspection of participant responses showed that binaurally, the majority of responses were lateralized to the correct side, even when there was an error identifying the source speaker. A study conducted by Hansen et al. (2013) found similar results with regards to localization with the addition of the CI. Of the 17 participants who met the inclusion criteria for the present systematic review, both pre and post-operative localization data are available for only 11 eleven of the participants. In most, but not all of the participants, localization error was reduced post-operatively with the addition of the CI. It should be noted however that those participants who did not demonstrate improved localization benefits post CI, had greater amounts of residual hearing in the implanted ear pre-operatively than the other participants. In addition, localization data at the 12 month post-operative interval, was obtained in only 6 participants; however those with 3 and 12 month post-operative localization data demonstrated a trend of improvement over time, suggesting experience as a factor in localization performance.

Tavora-Vieira et al. (2014) assessed localization performance in 16 participants with single sided deafness. Data analysis was completed using paired sample t-tests to examine the differences between the monaural unaided condition and the CI-aided condition. Localization ability as determined by the ASE software was significantly improved in the CI-aided condition as compared to the monaural unaided condition with group root mean square errors of 22.8 and 48.9 respectively. Of the 16 participants, only two did not demonstrate significant improvement in localization ability with the addition of the CI to the contralateral un-implanted ear. Tavora-Vieira et al. (2014) also examined the effects of gender, age at implantation and duration of deafness on localization performance. Statistical analysis revealed improved localization performance in the CI-aided conditions compared to the unaided condition in both female and male participants, those <55 and >55 years of age, and in those with a duration of deafness <10 years and > than 10 years. In addition, no effect of gender, duration of deafness and age at implantation was found on performance in the unaided monaural condition versus the CI-aided condition.

Psychoacoustic Measures

Two of the twelve studies included in the systematic review administered psycho-acoustic tasks to measure the effects of CI activation on spectral and temporal resolution and the head shadow effect in patients with SSD. Firszt et al. (2012) administered two different tasks that assessed participants' temporal and spectral discrimination in a monaural condition and binaurally with the CI-activated. The first task used noise-like random spectrogram sounds (RSS) that had no resemblance to either speech or music. An "odd man" out, 3 interval, 3 alternative, forced choice adaptive paradigm was used to determine the minimum detectable changes in complexity. The second task was an adaptive speech reception threshold measure. Testing consisted of 25 spondees spoken by a male talker in a 4 alternative forced choice paradigm. Target stimuli were always presented from the front loudspeaker with noise coming from either the front, 90 degrees to the right or 90 degrees to the left. Three different types of competing noise were randomly presented including male talker Harvard IEEE sentences, female talker IEEE Harvard, and multi-talker babble (Firszt et al. 2012). Presentation level of the target stimuli began at 60 dB SPL and varied adaptively based on participants' responses. Stelzig et al. (2011) administered a dichotic listening test that was designed to emphasize the impact of the head shadow effect on binaural hearing. The test included 10 number groups that each contained 10 two-digit number pairs presented simultaneously at 80 dB SPL via loudspeakers. The test was administered in a monaural unaided condition, CI-aided condition and CI-alone condition (contralateral ear plugged and masked).

Firszt et al. (2012) compared unilateral/single sided deaf participants' JND scores on the RSS stimuli tasks to normative data obtained on 20 normal hearing peers. Performance in all three test conditions was compared to the mean JNDs obtained from the normal hearing group. For most participants in the binaural condition and some in the CI alone condition, spectral and temporal JNDs were at least 1 standard deviation better than the mean. Additionally, two of the three participants' obtained their best JND scores in the binaural condition. Results for the adaptive SRT test were compared to results obtained from 24 normal hearing adults. With noise, participants' SRTs in the binaural condition were equal to or lower than the monaural condition, suggesting the CI did not provide and significant improvement in speech perception, but also that it did not hinder performance. It should be noted however, that SRTs in noise as compared to the normal hearing group were significantly poorer than 1 standard deviation of the mean in all three of the participants, suggesting that noise has a significant impact on speech perception in this population. Stelzig et al. (2011) reported significant improvements in performance on the dichotic digits listening tasks with the addition of the CI. Group mean score improved from 71.3% in the monaural unaided condition to 90% in the binaural condition, with a mean benefit of 18 percentage points in the binaural condition.

Subjective Measures

Nine of the twelve studies included in the present systematic review evaluated participants' subjective perceptions of CI use on several different outcomes. These included speech performance, spatial hearing, tinnitus suppression/distress, and quality of life measures. Materials used included the Speech, Spatial and Qualities of Hearing scale, Visual Analogue Scale for both CI acceptance and for tinnitus loudness/distress, the Tinnitus Reaction Questionnaire, Tinnitus Handicap Inventory, Tinnitus Questionnaire, Health Utilities Index-3 (HUI-3), and International Outcome Inventory for Hearing Aids (IOI-HA).

Five of the nine studies administered the SSQ, which is a three section questionnaire that assesses speech understanding, spatial hearing, and hearing quality. The scoring system allows for the participant to choose a number between 0-10 for each item, with 0 representing an inability to hear and 10 indicating perfect hearing. All five studies administered the questionnaire for the unaided monaural condition either pre-operatively or retrospectively and at varying times post-CI activation. Four studies administered the SSQ pre-operatively, with one study re-administering the SSQ 12 months post implantation, and asked participants to fill it out based on their pre-implantation hearing. They found no significant differences in the results between participants' pre-op and retrospective SSQ scores. Based off these findings, Firszt et al. (2012) administered the SSQ to two of its participants at 12 months post-op and asked them to base their responses off their pre-implant hearing ability. Post-operative SSQs for assessment of function with the addition of the CI were administered at 3 months post implantation by Tavora-Vieira et al. (2013), 6 months post implantation by Arndt et al. (2011), and 12 months post-op by Vermeire and Van de Heyning (2009) & Hassepass et al. (2013). In addition, Arndt et al. (2010) administered the SSQ post CROS and BAHA trials.

Arndt et al. (2010) reported significant improvement in SSQ scores with the addition of the CI as compared to the monaural unaided, CROS and BAHA conditions for the speech section. Median scores for the speech section were 5.76 for the CI condition, 3.13 for the CROS, 2.93 for the BAHA condition and 2.55 for the unaided condition. Similarly, significant improvement in SSQ scores for the spatial section were demonstrated for the CI condition as compared to the unaided, CROS and BAHA conditions, with respective median scores of 5.71, 2.59, 2.36, and 2.29. No statistically significant difference was found on SSQ scores for the quality of life section when comparing the CI condition to the other three listening conditions. Hassepass et al. (2013) reported similar findings in its two participants, with significant improvements noted on the speech and spatial sections when comparing performance with the CI versus the monaural unaided listening condition. Firszt et al. (2012) reported SSQ scores for both pre-implant hearing and post-implant hearing in only two of the three participants. Scores for both participants on the spatial subscale were judged to be significantly better, while only one participant reported improvement on the speech section with use of the CI. Additionally, one participant reported a decrease in the quality section, related to music sounding unnatural and difficulty ignoring unwanted sounds. The remaining two studies (Tavora-Vieira et al. 2013; Vermeire and Van de Heyning 2009) reported significant improvement in participants' SSQ scores for all three sections with use of the CI as compared to their pre-implant hearing.

Stelzig et al. (2011) administered a Visual Analogue Scale ranging from 0 (low) to 10 (very high) to measure subjective perception of performance with the CI. Overall, participants reported a high level of CI acceptance, integration of CI hearing, increased ease of listening especially in noise, and regaining acoustic orientation abilities. Arndt et al. (2010) administered two additional subjective measures to assess quality of life and effectiveness of auditory treatment which included the HUI-3 and IOI-HA. The HUI-3 is a generic, multi-attribute, preference based classification system administered as a measure of general health status. Responses from the HUI-3 are computed to a health utility index score ranging from 0(dead) to 1(perfect health) with single attribute utility scores ranging from 0 (lack of function) to 1 (full function). The HUI-3 was administered pre-operatively, post CROS and BAHA trials, and 6 months post CI fitting. The IOI-HA is a self-report measure that attempts to assess effectiveness of hearing aid treatments. The IOI-HA was administered post CROS and BAHA trials and 6 months post CI-activation. Overall, group scores for the HUI-3 demonstrated significant improvement with the CI as compared to the CROS and BAHA, although no significant improvements were noted individually for the hearing and speech subdomains. Results from the IOI-HA rendered the highest scores on all seven sub-domains with the use of the CI. Participants reported longer daily use of the CI, greater benefit, satisfaction and quality of life as compared to the CROS and BAHA treatments. In addition, improvement in residual activity limitation and residual participation restrictions were demonstrated with the CI as compared to the BAHA device.

Tinnitus

Of the twelve studies included in the present systematic review, five reported on the efficacy of suppression/abatement of tinnitus with cochlear implantation in individuals with SSD. The studies utilized several subjective measures/scales to assess tinnitus loudness and distress, which were administered at varying times post-implantation. Four of the five studies included utilized a Visual Analogue Scale (VAS) to measure tinnitus loudness and/or distress. Other subjective measures used included the Tinnitus Handicap Inventory the Tinnitus Questionnaire (TQ). Tavora-Vieira et al. (2013) utilized the Tinnitus Reaction Questionnaire for their subjective measure on tinnitus treatment with cochlear implantation.

Tinnitus loudness/distress is often subjectively measured using the VAS, with patients placing an X on a scale between 0 and 10, with zero indicating no tinnitus and 10 indicating severe, disabling tinnitus. Arndt et al. (2010) obtained pre and 6 month post-operative data on tinnitus distress using the VAS. Of the 11 participants, one patient reported no tinnitus prior to or after surgery. Five out of the ten participants with pre-operative tinnitus reported complete abatement of their tinnitus with the CI activated. Three patients reported a reduction in their tinnitus post-operatively with use of the speech processor. In one of the participants, tinnitus remained stable post-operatively, independent of CI use, and one patient reported stable post-operative tinnitus with the CI activated, with an increase in tinnitus when the processor was not active. Ramos et al. (2014) evaluated tinnitus severity in four participants with unilateral/single sided deafness using the VAS, with all four patients demonstrating reduced tinnitus severity 3 months post-operatively. In addition, Ramos et al. (2012) reported improvements in tinnitus perception remained even when the implant was switched off. Subjective assessment of tinnitus handicap was also completed via the Tinnitus Handicap Inventory pre-operatively, and at 1 and 3 months post-operatively. Results from all four participants demonstrated reduced degrees of tinnitus perception and subsequently reduced degrees of disability associated with their tinnitus, with one participant reporting complete suppression of tinnitus. Van de Heyning et al. (2008) reported reduced tinnitus loudness via the VAS in all participants 12 months post-operatively, with the CI-activated, and with it deactivated for more than 1 hour. Additionally, 3 of the 11 participants reported complete inhibition of the tinnitus after deactivation of the device for at least 12 hours. Subjective assessment of tinnitus distress was also measured pre and post-operatively with use of the Tinnitus Questionnaire, with scores reflecting significantly reduced tinnitus degree with CI use. Tavora-Vieira et al. (2013) administered the Tinnitus Reaction Questionnaire to assess efficacy of cochlear implantation on tinnitus. Of the 9 participants, seven particiapnts reported pre-operative tinnitus. All seven participants reported reductions in tinnitus distress when the CI was activated with reductions varying from 77% to 100%. In addition, no reports of increased tinnitus perception were reported in this study.

Mertens et al. (2013) conducted a study on the effects of tinnitus on the SRT in noise of the contralateral un-implanted ear. Although tinnitus suppression was not a main outcome measure, but a pre-requisite for participation in the study, it demonstrated the efficacy of CI on treatment of tinnitus. In addition, the main outcome measures, though unique, are of particular interest in a review on CI efficacy as a treatment option for SSD. A VAS for tinnitus loudness was administered in a CI-off and CI-on condition to ensure suppression of tinnitus with the addition of the CI. All 15 participants in the study reported significant reductions in their tinnitus, with mean VAS scores of 7.2 in the CI-off condition and 3.4 in the CI-on condition. Assessment of SRT in noise for the contralateral un-implanted ear demonstrated a mean improvement of 1.98 dB with the CI-on condition, with 13 out of 15 participants demonstrating improvement.

Discussion

The present systematic review was designed to assess the efficacy of cochlear implantation as a treatment option in adults with post lingual SSD. Specifically, this review assessed subjective and objective outcomes on speech performance in noise and localization ability with cochlear implantation, in addition to subjective improvements in tinnitus and perceived quality of life. With cochlear implantation becoming a more accepted treatment option for SSD and the candidacy criteria once again being broadened, the need arises for critical and systematic review of the current evidence on its' efficacy. In addition, as the only treatment option that can restore true binaural input and provide relief from tinnitus, it is important to critically assess the effects of the CI on these outcomes.

Speech Perception in Noise

Overall, five out of the six studies in the present systematic review reported that use of the CI in patients with SSD rendered benefits in speech in noise when compared to the unaided condition for at least one spatial configuration. Additionally, Arndt et al. (2010) and Hassepass et al. (2010) found that the CI-aided condition was superior to pseudo-binaural forms of SSD intervention. There were a variety of spatial configurations utilized by the different studies, with certain spatial setups aimed at measuring certain effects of binaural hearing including the head shadow, binaural squelch and binaural summation. For example, the S0/N0 spatial configuration assesses the effect of binaural summation. Stelzig et al. (2011) reported significant improvement on the Freiburg monosyllabic word test and HSM sentence test in this spatial configuration, with greater improvements with the CI as compared to the monaural condition noted at more challenging SNRs. Additionally, performance in this spatial configuration demonstrated improvement in eight of the nine participants in the Tavora-Vieira et al. (2013) study. The two participants in the Hassepass et al. (2010) study obtained the highest scores on HSM sentence testing with the use of the CI when compared to the unaided, CROS and BAHA conditions. Though no significant improvements were demonstrated in the remaining studies (Vermeire and Van de Heyning 2009, Arndt et al. 2010, Firszt et al. 2012) for this spatial configuration, it is important to note the CI did not hinder performance.

Binaural squelch was assessed by several studies through administration of speech in noise testing in the S0/NCI spatial configuration. Individual data from the Tavora-Vieira et al. (2013) study demonstrated reduced critical SNRs in five out of nine participants. Two of the four participants in the Stelzig et al. (2011) study demonstrated slight improvements in their SRTs for OLSA sentence testing. Vermeire and Van de Heyning (2009) also administered speech in noise testing in the spatial configuration S0/NCI. Results from testing were judged to be non-significant, with performance in the aided condition not demonstrating any improvement to the monaural condition. They did note that these findings might have been due to the fact that mean SRT for the monaural condition was already -7.4 dB and the addition of the CI was unlikely to provide any improvement to that (Schleich, Nopp & D'Haese, 2004). Similar results were rendered by Firszt et al. (2012) with no improvements in critical SNR when comparing the CI-aided to the monaural condition.

Speech in noise testing was administered in the SCI/N0 configuration with the purpose of evaluating the combined effect of head shadow effect and binaural squelch on speech in noise performance. Results from the Vermeire and Van de Heyning (2009) study rendered significant improvements in participants' SRT, with mean improvements of -1.7 dB in the CI aided condition as compared to the monaural condition. The findings suggest a significant binaural effect introduced by use of the CI, though it is unclear as to what extent the head shadow effect contributed. Arndt et al. (2010) attempted measuring the binaural squelch in their participants by calculating the difference between performance in the aided condition with the CI and the unaided condition for the spatial configuration SCI/NNH. In addition to evaluating the effects of binaural squelch and summation with the addition of the cochlear implant, the spatial configuration SCI/NNH simulates a real world condition that is most challenging for people with SSD. It is well documented that individuals with SSD struggle when speech is located on the side of their poor ear, especially with noise on the side of the contralateral good ear (Arndt et al. 2010). Arndt et al. (2010) reported an overall combined effect of -4.9 dB improvement in critical SNR with the use of the CI, though the contribution of the head shadow effect remains unclear. These binaural effects were replicated in the Tavora-Vieira et al. (2013) study, with mean improvement of -5 dB on critical SNR for BKB-SIN testing in the CI condition as compared to the unaided condition for the SCI/NNH spatial configuration. The two participants in the Hassepass et al. (2013) study also demonstrated improved performance in this spatial configuration with use of the CI.

Despite significant heterogeneity between methodologies for assessing performance, the benefits provided by a cochlear implant for speech perception in noise in individuals with SSD are evident on both objective and subjective measures. Combined, objective results from the included studies provide substantial evidence to suggest that cochlear implantation allows for the reintroduction of binaural effects through electrical stimulation, though it is unclear as to which binaural effects are truly responsible for the improvements in performance. In addition, findings from the two studies (Arndt et al. 2010; Stelzig et al. 2011) that administered psychoacoustic tasks suggest improvements in spectral and temporal resolution with use of the CI and possible benefits of the head shadow, as well as other binaural effects. Furthermore, Tavora-Vieira et al. (2013) found that these improvements were not unique to patients with short durations of deafness. Benefits in speech perception in noise were demonstrated by patients with long durations of deafness, who lost their hearing post-lingually. They postulated that these patients were able to rapidly integrate the electrical stimulation and acoustic stimulation due to normal auditory input during a critical period of bilateral auditory development. These findings are promising for individuals with long durations of deafness that are still dissatisfied with current treatment options for SSD. At the very least, these findings warrant further studies to assess the benefits in this unique patient population. In addition to objective test measures, subjective improvements of speech perception were measured through administration of the SSQ. In all five studies (Arndt et al. 2010; Firszt et al. 2012; Hassepass et al. 2013; Tavora-Vieira et al. 2013; Vermeire and Van de Heyning 2009) significant improvements in the speech subsection were noted when comparing the monaural condition to the CI-aided condition. Most importantly, the findings from the present systematic review clearly demonstrate how cochlear implantation provides significant improvement for the most difficult real world listening condition for patients with SSD on both objective performance and in patient perception of functioning.

Localization

All six studies that assessed localization ability indicated significantly improved performance with the cochlear implant as compared to the monaural unaided condition. In addition, Arndt et al. (2010) and Hassepass et al. (2013) reported improvements in localization when compared to the BAHA and CROS conditions. Erbele et al. (2014) demonstrated this in one of the two participants who were previous osseo-integrated hearing device users, with one participant demonstrating no change in performance. Firszt et al. (2012) reported improved localization ability and reduced variability in responses in all three participants. Similarly, Tavora-Vieira et al. (2014) reported significant decline in localization error with the use of the CI compared to the monaural unaided condition. In addition to comparing performance in the monaural and CI-aided condition, stratified analyses was conducted to assess influence of gender, age at implantation and duration of deafness on localization performance. The findings from the study indicated no effect of gender, age at implantation and duration of deafness on localization performance. Hansen et al. (2013) reported limited post-operative data for 12 month follow up, but did note that overall, data from their cohort appeared to support the idea that the CI allows for improved sound localization in individuals with SSD. In addition, post-operative data that was available at 12 month and 24 month follow up suggested that localization ability improves with time and experience, as the brain adapts to integrating the acoustic signal from the good ear with the electrical signal from the affected ear.

The included studies, though varied in test methodology, all clearly demonstrate improvements in localization with a cochlear implant for adults with post-lingual SSD. In addition, two studies (Arndt et al 2010, Hassepass et al. 2013) demonstrated improvements as compared with pseudo-binaural forms of intervention. Tavora-Vieira et al. (2014) rendered significant findings which suggest that age at implantation and duration of deafness do not influence performance in individuals with post-lingual SSD. This study was unique in nature, as previous literature reporting on localization performance included patient populations with <10 years of deafness. Tavora-Vieira et al. (2014) stratified their participants into two groups of >10 years (n=6) and <10 (n=10) years of deafness, with no significant difference between the two groups for either listening condition. They did note that four of the six participants with duration of deafness > 10 years, four lost their hearing after age 12. They postulated that this group was able to benefit in terms of localization, despite prolonged periods of auditory deprivation, due to the fact that they had normal binaural stimulation during the development of their auditory pathways, (Grothe, Pecka, & McAlpine, 2010; Litovsky, Jones, & Agrawal, 2010; Keating and King, 2013). A study by Langers, van Dijk, and Backes (2005) conducted electrophysiological testing which demonstrated that individuals who sustain unilateral deafness after maturation of bilateral pathways, lateralization of contralateral activation is not altered. These findings, in conjunction with the localization data obtained by Tavora-Vieira et al. (2014) suggest that even patients with long durations of deafness may derive benefit for speech/sound localization with use of a cochlear implant.

In addition to objective test measures, speech/sound localization was subjectively assessed through administration of the SSQ in five studies (Arndt et al. 2010; Hassepass et al., 2013; Firszt et al., 2012; Tavora-Vieira et al., 2013; Vermeire & Van de Heyning, 2013). Subjective improvement in localization for the CI condition as compared to the monaural unaided condition was reported by all five studies with significantly improved scores for the spatial subsection. It should be noted that in several of the studies, this subsection rendered the greatest difference in subjective improvement with the use of the CI as compared to the unaided condition.

Collectively, the data produced from the included studies provides robust evidence that suggests cochlear implantation is effective in improving speech/sound localization, which is a well-documented difficulty in this population (Giardina et al. 2014; Blasco et al. 2014; Tokita et al. 2014; Vlastarakos et al. 2014; Zon et al. 2014). Improvements in performance were demonstrated objectively, with significantly reduced localization or root mean square error in the CI-aided condition, and subjectively, with improved scores on the spatial subsection of the SSQ questionnaire. Furthermore, though limited in number, the three studies that did compare localization performance with the CI to pseudo-binaural forms of treatment strongly suggest that cochlear implantation is a superior treatment option for restoring localization ability in this population.

Tinnitus

Suppression/abatement of tinnitus was assessed by five of the included studies, predominantly through administration of a VAS for tinnitus loudness/distress. All four studies which compared tinnitus loudness/distress through administration of the VAS reported reductions in tinnitus with activation of the CI. Arndt et al. (2010) reported significant reduction and complete suppression in eight out of ten participants with pre-operative tinnitus. Ramos et al. (2012) also reported reductions in tinnitus in all four participants with CI-activation. These results were further substantiated by improvements in one and three month post-operative scores on the Tinnitus Handicap Inventory, in all four participants. Van de Heyning et al. (2008) reported reductions in tinnitus loudness in all 11 participants, with two reporting complete residual inhibition 12 hours post deactivation of the CI. In addition, subjective benefit was measured through administration of the Tinnitus Questionnaire, with mean total scores significantly reduced at 1 month, 3 month, 6 month, 12 month, 18 month and 24 month follow up as compared to pre-op scores. A significant finding from the long term follow up in this study was that over a two year period, the tinnitus did not recur and therefore no adaptation to the electrical stimulation was demonstrated. This is of critical clinical value, as cochlear implantation in SSD originated as a treatment option for those with ipsilateral tinnitus. These findings indicate that cochlear implantation is an effective long-term method in managing tinnitus in the ipsilateral ear. Mertens et al. (2013) used statistically significant reductions in tinnitus loudness on the VAS as an inclusion criterion for their study. Therefore, all 15 participants demonstrated improvement in tinnitus loudness with the use of the CI. Participants also demonstrated significant reductions on the Tinnitus Questionnaire when comparing their pre-op scores to their 1 year and 3 year scores. Additionally, Mertens et al. (2013) found that SRT in noise for the contralateral un-implanted ear was significantly improved when the CI was activated in 13 of the 15 participants. These findings were unique as previous research demonstrated the effects of tinnitus on speech reception in the ipsilateral ear. These findings add to the clinical picture by suggesting that SSD patients with ipsilateral tinnitus not only lose the benefits of binaural stimulation, but their understanding in noise can also be adversely affected by the presence of tinnitus in the affected ear. The remaining study by Tavora-Vieira et al. (2013) assessed tinnitus distress through administration of the Tinnitus Reaction Questionnaire. Of the seven participants who reported pre-operative tinnitus, all seven demonstrated reductions in tinnitus distress post-operatively with the CI activated.

Overall, the combined data from all five studies demonstrates significant and consistent reductions in tinnitus loudness and distress. Studies which administered subjective outcomes in conjunction with a VAS further substantiated their findings by demonstrating CI activation had a positive effect on reducing handicap associated with the ipsilateral tinnitus. Mertens et al. (2013) provided data that illustrates how incapacitating tinnitus not only results in psychological distress and perceived handicap, but also adversely effects speech in noise performance in the contralateral ear. Finally, Van de Heyning et al. (2008) provided critical data that indicates cochlear implantation is an effective long-term treatment option for patients with SSD and ipsilateral tinnitus. These findings suggest that cochlear implantation is not only a viable long-term treatment option for tinnitus suppression, but also in prevention of further deterioration of speech in noise performance for SSD patients with ipsilateral tinnitus.

Adults with post lingual single sided deafness experience a myriad of issues as a result of their condition. Speech perception in noise and localization are well documented as being compromised in this population due to the loss of binaural auditory input and its subsequent effects (Giardina et al. 2014; Blasco et al. 2014; Tokita et al. 2014; Vlastarakos et al. 2014; Zon et al. 2014). Cochlear implantation in this population provides the potential to restore the effects through the re-introduction of binaural electro-acoustic stimulation. In addition, for those patients who also experience ipsilateral tinnitus, cochlear implantation has been proven to be an effective long-term treatment option. The present systematic review provides overwhelming evidence that indicates cochlear implantation is a viable and effective treatment method for this population in terms of restoration of localization ability and for speech performance in various speech/noise configurations, especially those which present monaural listeners with the greatest difficulty. Additionally, post-operative subjective reports on perceived performance and tinnitus suppression, in addition to a high rate of continued use are promising that CI is a viable option for restoration of many functions lost in this population.

Limitations of included studies

An important finding of this systematic review is that the majority of studies on this topic are of low or moderate levels of evidence. There are no randomized studies and actual numbers of participants in each study remain very low. In addition, there is a large degree of inter-study variability in terms of the classification of single sided deafness (varying degrees of hearing in the contralateral un-implanted ear), duration of deafness of included participants, age at implantation, test conditions, test materials and methodology. Differences between test methodology and spatial configurations for speech in noise testing may have led to the variable results on this outcome measure. Follow-up duration post implantation is another critical limitation for many of the included studies. It is well known that performance with cochlear implants often improves with time and experience, with some research suggesting continued improvements up to 30 months post implantation. This trend was demonstrated by the few participants in the Hansen et al. (2012) study in which post-operative data were available at 3 and12 month intervals on localization, with improvements in performance noted at the 12 month data collection. In addition, Gartrell et al. (2014) recommended follow-up periods greater than 18 months, based on data that measurement of binaural benefits requires longer follow-up periods post-operatively. Finally, the three studies which compared performance with the CI on various outcomes to those of pseudo-binaural forms of intervention, did so with patients who reported dissatisfaction with the latter forms of intervention. Therefore, subjective outcome measures may reflect their bias towards the more conventional treatment options. Future studies should include larger numbers of participants with control for various factors including duration of deafness, degree of hearing loss in the contralateral ear and time intervals for testing post-implantation. In addition test methods and spatial configurations for assessment of speech in noise performance should be standardized.

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Table 1- Studies Meeting Inclusion Criteria for Systematic Review

Study	Total N	N selected for analysis	Objec. (O)	Subj. (O)
Arndt et al. (2010)	11	11	OLSA, HSM, localization	SSQ, HUI-3, IOI-HA, Tinnitus (VAS)
Erbele et al. (2014)	5	3	Localization	None
Firszt et al. (2012)	3	3	BKB-SIN, HINT, Localization, Psychoacoustics	SSQ
Hansen et al. (2013)	29	17	Localization	None
Hassepass et al. (2013)	3	2	HSM, Localization	SSQ
Mertens et al. (2013)	15	15	LIST sentences (SRT in noise)-contralateral ear	Tinnitus (VAS),
Ramos et al. (2012)	10	4	None	Tinnitus (VAS), THI
Stelzig et al. (2011)	4	4	OLSA,HSM, Freiburg monosyllabic, Psychoacoustics	CI acceptance (VAS)
Tavora-Vieira et al. (2013)	9	9	BKB-SIN	SSQ, TRQ
Tavora-Vieira et al. (2014)*	16	16	Localization	None
Van de Heyning et al. (2008)	21	11	None	Tinnitus (VAS), TQ
Vermeire & Van de Heyning (2009)**	20	10	LIST sentences	SSQ

*6 participants from the Tavora-Vieira et al. (2013) study were included in the Tavora-Vieira (2014) study and were only included once

**8 participants from the Vermeire & Van de Heyning (2009) trial were also included in the Van de Heyning et al. (2008) trial and were only included once

Table 2 -Overview of Participants Included in Systematic Review

Study	Patient no.	Gender	Etiology of hearing loss	Deaf ear	PTA contra	Age at imp.	DoD (months)	Device
Arndt et al. (2010)	***1***	**-**	**Sudden hearing loss**	**L**	**13**	**47**	**43**	**CI24RE**
	2	-	Sudden hearing loss	L	18	68	31	CI24RE
	3	-	Temporal bone fracture	L	8	23	4	CI24RE
	4	-	Sudden hearing loss	L	8	38	34	CI24RE
	5	-	Sudden hearing loss	R	9	39	6	CI24RE
	6	-	Labryinthitis	L	9	41	10	CI24RE
	7	-	Labryinthitis	R	8	41	11	CI24RE
	8	-	Meniere's disease	L	7	46	110	CI24RE
	9	-	Sudden hearing loss	L	16	54	10	CI24RE
	10	-	Sudden hearing loss	L	30	51	9	CI24RE
	11	-	Post ear surgery	R	16	31	4	CI24RE
Erbele et al. (2014)	***12(2)***	**-**	**Sudden hearing loss**	**L**	**10**	**42**	**108**	**Concert**
	13(4)	-	Perilymphatic fistula	R	12	27	7	Concert
	14(5)	-	Sudden hearing loss	L	30	46	120	Concert
Firszt et al. (2012)	**15(1)**	**-**	**Sudden hearing loss**	**R**	**21**	**62**	**9**	**Nucleus 5**
	16(2)	-	Sudden hearing loss	R	28	57	54	Nucleus 5
	17(3)	-	Post ear surgery	R	23	56	30	Nucleus 5
Hansen et al. (2013)	***18(1)***	**-**	**Sudden hearing loss**	**L**	**15**	**58**	**24**	**NUCI512**
	19(2)	-	Meniere's/Labryinthectomy	L	16	50	24	NUCI512
	20(3)	-	Meniere's/Labryinthectomy	R	21	55	12	NU Freedom
	21(4)	-	Meniere's/Labryinthectomy	L	28	57	24	NU Freedom
	22(5)	-	Sudden hearing loss	L	13	58	47	AB 90K
	23(7)	-	Sudden hearing loss	R	13	48	7	AB 90K
	24(8)	-	Vestibulopathy/Labryinthectomy	L	15	52	36	NUCI422
	25(11)	-	Sudden hearing loss	R	9	55	7	AB 90K
	26(16)	-	Meniere's/Labryinthectomy	L	30	61	19	NUCI422
	27(18)	-	Sudden hearing loss	L	10	64	36	NUCI422
	28(19)	-	Sudden hearing loss	L	15	53	6	AB 90K
	29(21)	-	Head trauma	L	19	63	120	NUCI422
	30(22)	-	Meniere's/Labryinthectomy	R	16	63	96	NUCI422
	33(23)	-	Sudden hearing loss	R	28	64	4	AB 90K
	34(26)	-	Meniere's/Labryinthectomy	R	14	63	10	NUCI422
	35(28)	-	Sudden hearing loss	L	15	36	60	NUCI422
	36(C1)	-	Sudden hearing loss	L	14	59	10	NU Freedom
Hassepass et al. (2013)	***37(1)***	**F**	**Progressive**	**L**	**10**	**40**	**1.5**	**CI24RE**
	38(2)	M	Progressive	R	22.5	54	120	CI24RE
Mertens et al. (2013)	**39(1)**	**F**	**Not reported**	**L**	**-**	**58**	-	MED-EL SONATATI
	40(2)	F	Not reported	R	-	61	-	MED-EL SONATATI
	41(3)	F	Not reported	R	-	44	-	MED-EL SONATATI
	42(4)	F	Not reported	L	-	46	-	MED-EL SONATATI
	43(5)	M	Not reported	L	-	63	-	MED-EL SONATATI
	44(6)	F	Not reported	L	-	59	-	MED-EL SONATATI
	45(7)	M	Not reported	R	-	41	-	MED-EL SONATATI
	46(8)	M	Not reported	L	-	58	-	MED-EL SONATATI
	47(9)	M	Not reported	R	-	22	-	MED-EL SONATATI
	48(10)	F	Not reported	L	-	59	-	MED-EL SONATATI
	49(11)	M	Not reported	R	-	55	-	MED-EL SONATATI
	50(12)	M	Not reported	L	-	49	-	MED-EL COMBI 40+
	51(13)	F	Not reported	L	-	38	-	MED-EL COMBI 40+
	52(14)	F	Not reported	R	-	53	-	MED-EL PULSARCI
	53(15)	F	Not reported	L	-	59	-	MED-EL PULSARCI
Ramos et al. (2012)	54(6)	-	Profound unilateral SNHL	L	16	34-62	<10 years	CI24REH
	55(7)	-	Profound unilateral SNHL	L	13	34-62	<10 years	CI512
	56(8)	-	Profound unilateral SNHL	L	25	34-62	<10 years	CI24REH
	57(10)	-	Profound unilateral SNHL	R	25	34-62	<10 years	CI24RE

Table 2 -Overview of Participants Included in Systematic Review con't

Study	Patient no.	Gender	Etiology of hearing loss	Deaf ear	PTA contra	Age at imp.	DoD (months)	Device
Stelzig et al. (2011)	58(1)	M	Unknown etiology	-	<30 dB	48	11	MED-EL PULSARCI
	59(2)	M	Acoustic trauma	-	<30 dB	51	45	MED-EL PULSARCI
	60(3)	M	Post stapedectomy surgery	-	<30 dB	48	96	MED-EL PULSARCI
	61(4)	M	Borellia infection	-	<30 dB	57	33	MED-EL PULSARCI
Tavora-Vieira et al. (2013)	**62(1)**	**-**	**Sudden hearing loss**	**R**	**10**	**45**	**36**	**MED-EL FLEXSOFT**
	63(2)	-	Head Trauma	L	18	56	24	MED-EL FLEXSOFT
	64(3)	-	Unknown	L	13	55	480	MED-EL FLEXSOFT
	65(4)	-	Sudden hearing loss	R	25	70	7	MED-EL FLEXSOFT
	66(5)	-	Meniere's disease	L	18	55	240	MED-EL FLEXSOFT
	67(6)	-	Traumatic surgery	R	28	68	420	MED-EL FLEXSOFT
	68(7)	-	Unknown	L	18	60	12	MED-EL FLEXSOFT
	69(8)	-	Sudden hearing loss	R	13	53	7	MED-EL FLEXSOFT
	70(9)	-	Mumps	R	3	51	468	MED-EL FLEXSOFT
Tavora-Vieira et al. (2014)*	71(2)	-	Unknown	L	7	40	420	MED-EL FLEX
	72(5)	-	Unknown	L	8	36	360	MED-EL FLEX
	73(7)	-	Unknown	L	8	48	11	MED-EL FLEX
	74(9)	-	Unknown	L	5	41	144	MED-EL FLEX
	75(10)	-	Sudden hearing loss	R	7	62	4	MED-EL FLEX
	76(11)	-	Sudden hearing loss	L	24	72	5	MED-EL FLEX
	77(13)	-	Unknown	R	30	71	60	MED-EL FLEX
	78(14)	-	Unknown	L	21	73	19	MED-EL FLEX
	79(15)	-	Sudden hearing loss	L	25	57	12	MED-EL FLEX
	80(16)	-	Fistula	R	27	39	4	MED-EL FLEX
Van de Heyning et al. (2008)	81(1)	-	Temporal bone fracture	R	27	36	102	MED-EL COMBI 40+
Vermiere & Van de Heyning (2009)**	82(5)	-	Labryinthitis	L	17	38	30	MED-EL COMBI 40+
	83(11)	-	Sudden hearing loss	R	10	54	162	MED-EL PULSARCI
	84(12)	-	Sudden hearing loss	R	10	63	24	MED-EL PULSARCI
	85(13)	-	Endolymphatic hydrops	L	17	59	66	MED-EL PULSARCI
	86(14)	-	Posttraumatic	R	12	55	78	MED-EL PULSARCI
	87(15)	-	Sudden hearing loss	R	13	23	30	MED-EL PULSARCI
	88(16)	-	Labryinthitis	R	10	41	102	MED-EL PULSARCI
	89(18)	-	Viral cochleitis	L	15	47	126	MED-EL PULSARCI
	90(19)	-	Herpes zoster	L	13	59	42	MED-EL PULSARCI
	91(21)	-	Posttraumatic	L	20	45	30	MED-EL PULSARCI

6 participants from the Tavora-Vieira et al. (2013) study were included in the Tavora-Vieira (2014) study and were only included once.

*****8 participants from the Vermeire & Van de Heyning (2009) trial were also included in the Van de Heyning et al. (2008) trial and were only included once.***

Table 3 - Assessment of Quality of Included Studies (adapted from Zon et al. 2014)

			Directness of Evidence (DoE)							Risk of Bias (RoB)					
				Outcomes											
Study	**Design**	**N**	**Tx**	**Sp. In Noise**	**Loc.**	**Tinnitus**	**QofL**	**Follow-up**	**DoE**	**Tx Allocation**	**Blinding**	**Standard (T)**	**Standard(O)**	**Comp. Data**	**RoB**
Arndt et al. (2010)	PCS	11	CI	X	X	X	X	6 months	High	●	●	○	○	●	Mid
Erbele et al. (2014)	PCS	5	CI		X			4-17 months	Mid	●	●	○	○	●	Mid
Firszt et al. (2012)	PCS	10	CI	X	X		X	4-17 months	Mid	●	●	○	○	●	Mid
Hansen et al. (2013)	PCS	29	CI		X			3-12 months	Mid	●	●	○	○	○	High
Hassepass et al. (2013)	PCS	3	CI	X	X		X	6/12 months	High	●	●	○	○	○	High
Mertens et al. (2013)	PCS	15	CI			X		12 month	Mid	●	●	○	○	●	Mid
Ramos et al. (2012)	PCS	10	CI			X		6 months	Low	●	●	○	○	●	Mid
Stelzig et al. (2011)	RCS	4	CI	X			X	6 months	Mid	●	●	○	○	●	Mid
Tavora-Vieira et al. (2013)	PCS	9	CI	X		X	X	3 months	Mid	●	●	○	○	●	Mid
Tavora-Vieira et al. (2014)	PCS	16	CI		X			6-18 months	Mid	●	●	○	○	●	Mid
Van de Heyning et al. (2008)	PCS	22	CI			X		12 month	Mid	●	●	○	○	●	Mid
Vermeire et al. (2009)	PCS	20	CI	X			X	12 month	Mid	●	●	○	○	●	Mid

Risk of Bias Bias

Treatment allocation: ●-neither randomized nor concealed
Blinding: ●-no blinding
Standardization (T) of cochlear implantation(implant type and processor mentioned): ○ - yes
Standardization (O) of outcome measure: ○- yes
Completeness of outcome data for primary outcome: •- below 15% missing data ○- 15% or more missing data

Table 4 - Speech Perception in Noise Data

Condition	Study/Individual participants	S0/N0	SCI/NNH	SNH/NCI	S0/NNH	S0/NCI	SCI/N0	R-SPACE
	Arndt et al. (2010)*							
Unaided		**HSM**-74.06% **OLSA-** <-5 dB SNR	**HSM**-14.62% **OLSA-** -0.6 dB SNR*	**HSM**-99.53% **OLSA-** -15 dB SNR				
CROS		**HSM**-76.89	**HSM-** 24.53%	**HSM**-98.58% *				
BAHA		**HSM**-74.06%	**HSM**-10.38%	**HSM**-98.58% *				
CI		**HSM**-76.42% **OLSA-** <-5 dB SNR	**HSM**-42.45% **OLSA-** -6.2 dB SNR*	**HSM**-100%* **OLSA-** -15 dB SNR				
	Firszt et al. (2012)*							
Unaided	**15(1)**	**BKB-SIN-** < 0 dB SNR			**BKB-SIN-** < 5dB SNR	**BKB-SIN-** < 0dB SNR		**HINT-** < 0dB SNR
	16(2)	**BKB-SIN-** < 5 dB SNR			**BKB-SIN-** < 5dB SNR	**BKB-SIN-** < 0dB SNR		**HINT-** < 5dB SNR
	17(3)	**BKB-SIN-** < 0 dB SNR			**BKB-SIN-** < 5dB SNR	**BKB-SIN-** < 0dB SNR		**HINT-** < 0dB SNR
CI-aided	**15(1)**	**BKB-SIN-** < 5 dB SNR			**BKB-SIN-** < 5dB SNR	**BKB-SIN-** < 0dB SNR		**HINT-** ≤ 5dB SNR
	16(2)	**BKB-SIN-** < 5 dB SNR			**BKB-SIN-** < 5dB SNR	**BKB-SIN-** < 0dB SNR		**HINT-** < 25dB SNR
	17(3)	**BKB-SIN-** < 5 dB SNR			**BKB-SIN-** < 5dB SNR	**BKB-SIN-** < 0dB SNR		**HINT-** < 15dB SNR
CI-only	**15(1)**	**BKB-SIN-** <10 dB SNR			**BKB-SIN-** < 5dB SNR	**BKB-SIN-** ≥ 10dB SNR		**HINT-** < 0dB SNR
	16(2)	**BKB-SIN-** <15 dB SNR			**BKB-SIN-** < 10dB SNR	**BKB-SIN-** < 20dB SNR		**HINT-** < 0dB SNR
	17(3)	**BKB-SIN-** <15 dB SNR			**BKB-SIN-** < 5dB SNR	**BKB-SIN-** < 15dB SNR		**HINT-** < 0dB SNR
	Hassepass et al. (2013)*							
Unaided	***37(1)***	70%**<HSM**<80%	20%<**HSM**<40%*	80% < **HSM**<100%				
	38(2)	40%<**HSM<**50%	**HSM-** 0%*	80% < **HSM-** <100%				
CROS	***37(1)***	**HSM-** ≤80%	40%<**HSM<**60%	80% < **HSM-** <100%				
	38(2)	30%**<HSM-** <40%	**HSM-** 0%	80% < **HSM-** <100%				
BAHA	***37(1)***	60%**<HSM**<80%	20%<**HSM**<40%	80% < **HSM-** <100%				
	38(2)	**HSM-** <40%	**HSM-** 0%	80% < **HSM-** <100%				
CI	***37(1)***	**HSM-** ≤80%	80%<**HSM**<100%*	80% < **HSM-** <100%				
	38(2)	40% **<HSM-** ≤50%	**HSM-** 19.8%*	80% < **HSM-** <100%				
	Stelzig et al. (2011)*							
Unaided		**FMS-**> 15,5, 0 dB SNR* **OLSA-** -4.8 dB **HSM**-0,-5 dB *			**OLSA-**-4.3 dB	**OLSA-**-9.2 dB		
CI-aided		**FMS-**> 15,5, 0 dB SNR* **OLSA-** -5.0 dB **HSM**-0,-5 dB *			**OLSA-**-4.7 dB	**OLSA-**-9.3 dB		

Table 4 (Con't) - Speech Perception in Noise Data

Condition	Study/Individual participants	S0/N0	SCI/NNH	SNH/NCI	S0/NNH	S0/NCI	SCI/N0	R-SPACE
	Tavora-Vieira et al. (2013)*							
Unaided		**BKB-SIN-** 6 dB SNR	**BKB-SIN-** 2 dB SNR		**BKB-SIN-** 1 dB SNR	**BKB-SIN-** -3 dB SNR		
CI		**BKB-SIN-** 3 dB SNR*	**BKB-SIN-** -3 dB SNR*		**BKB-SIN-** -2 dB SNR*	**BKB-SIN-** -3 dB SNR		
	Vermeire & Van de Heyning (2008)*							
Unaided		**LIST-**-2.7 SRT				**LIST-** -6.7 SRT	**LIST-** 0.2 SRT	
CI		**LIST-**-3.0 SRT				**LIST-** -5.5 SRT	**LIST-** -1.5 SRT *	

Arndt et al. (2010)* - Results reported were median percent correct scores and critical SNR values. *Indicate conditions that dem. Sig difference to the CI condition.
Firszt et al. (2012)*- Results reported were indiv. scores derived from graphs in the study as no quantitative data was reported. No sig improvements for CI condition found.
Hassepass et al. (2013)*- Results reported were indiv. scores derived from graphs in the study. *Indicates conditions where performance was sig. improved in the CI condition.
Stelzig et al. (2011)* FMS*-Indicates SNR ratios where improvement with CI was noted. *HSM-improvement noted in CI condition for 0 and -5 dB SNR.

Tavora-Vieira et al. (2013)*-Indicates mean BKB-SIN critical SNRs that were sig. improved in CI condition.

Vermeire & Van de Heyning (2008)*-Sig. improvement in CI condition.

Table 5- Localization Data

			Pre-operative				Post-operative		
Study	Test Setup	Materials/Pres. Level	Unaided	BCD	CROS		Unaided	Binaural-CI	CI-alone
Arndt et al. (2010)*	7 loudspeakers, 180° arc, 30° intervals	OLSA sentences, 59-71 dBSPL	33.9° (p=0.003)	30.4° (p=0.002)	39.9° (p=.0.001)			15.0°	
Erbele et al. (2014) **	26 loudspeakers, +/- 135° , single source, multisource "add", multisource "remove"	Environmental sounds, 58, 64, or 70 dB SPL	**12(2)**-70° **13(4)**-35° **14(5)**-50°	No data **13(4)**-40° **14(5)**- 50°			**12(2)**-60° **13(4)**-25° **14(5)**-55°	**12(2)**- 45° **13(4)**-25° **14(5)**- 47°	
Firszt et al. (2012) ***	15 loudspeakers, 140° arch, 10° intervals	CNC monosyllabic words, 60 dB SPL					**15(1)**- 36° **16(2)**- 20° **17(3)**- 60°	**15(1)**- 19° **16(2)**- 18° **17(3)**- 25°	**15(1)**- 44° * **16(2)**- 52° * **17(3)**- 38° * (p <.001)
Hansen et al. (2013)	8 loudspeakers, 108° horizontal arc, +/- 54°	Everyday sounds					Individual data not provided-Overall improved localization performance noted in binaural condition. Data at 3-12 month post-op available for 6 participants suggests improvements in performance over time		
Hassepass et al. (2013) ****	7 loudspeakers, 180° arc, 30° intervals	OLSA sentences, 59-71 dBSPL	**37(1)**- 27.1% **38(2)**- 25.7%	**37(1)**- <20% **38(2)**- <20%	**37(1)**- <40% **38(2)**- 20%			**37(1)**- 57.1% **38(2)**- 51.4% *	
Tavora-Vieira et al. (2014)	13 loudspeakers, 10° intervals	A§E localization software					Mean RMS error- 44.9	Mean RMS error- 22.8* sig. Improvement	

* Individual scores were not reported, median localization error scores are what were reported
** Localization degree was approximated from study figure for each of the three participants as localization error was not provided.
**** Individual % correct data for the two participants. CI- aided localization reported was at a 12 month follow up.
*-Localization testing was also conducted 6 months post op with sig. improvement noted.