The Effect of Cross-over Frequency on Binaural Hearing Performance of Adults using Electric-Acoustic Stimulation.

Paola V Incerti[abc] , Teresa YC Ching[ab] and Robert Cowan[bc]

[a]*National Acoustic Laboratories, Australian Hearing, Sydney, Australia;* [b]*The Hearing CRC, Melbourne, Australia;* [c]*Department of Audiology and Speech Pathology, The University of Melbourne, Melbourne, Australia.*

Abstract:

Objective: To investigate the effect of varying cross-over frequency (CF) settings for electric-acoustic (EA) stimulation in one ear combined with acoustic (A) hearing in the opposite ear on binaural speech perception, localization and functional performance in real life. Methods: Performance with three different CF settings set according to audiometric-based criterion were compared, following a four week familiarisation period with each, in ten adult cochlear implant recipients with residual hearing in both ears. On completion of all trials participants selected their preferred CF setting. Results: On average, CF settings did not have a significant effect on performance scores. However, higher ratings on device usage were associated with the preferred CF settings. Conclusion: Individuals who use EA +A stimulation may benefit from access to different CF settings to achieve maximal device usage.

Keywords: word; cochlear implants; hearing aids; electric and acoustic stimulation; fitting; cross-over frequency.

The Australian and New Zealand Clinical Trials Registry study number: ACTRN12610000773033.

Corresponding author:

Paola Incerti, MAud, MAudSA(ccp)
Research Audiologist
National Acoustic Laboratories
The Australian Hearing Hub
16 University Avenue
Macquarie University NSW 2109
Australia
Ph: +612 9412 6963
Fax: + F +61 2 9412 6769
Email: Paola.Incerti@nal.gov.au

Abbreviations:

A: Acoustic stimulation via a hearing aid

ACE: Advanced combination encoder

AuSTIN: Australian Sentence Test in Noise

CI: Cochlear implant

CF: Cross-over frequency

E: Electric stimulation via a cochlear implant

EA: Electric and acoustic stimulation in the same ear

E+A: Electric stimulation in one ear and acoustic stimulation in the opposite ear.

EA + A: Electric-acoustic stimulation in one ear and acoustic stimulation in the opposite ear

HA: Hearing aid

IE: Implanted ear

ILD: interaural level differences

ITD: interaural time differences

ITE: In-The-Ear

NAL-NL2: The National Acoustic laboratories-Non-linear 2 procedure

NIE: Non-implanted ear

REIG: Real-ear-insertion gain

RIC: Receiver-in-the-canal

SELF: SELF Evaluation of Listening Function Questionnaire

SD: Standard deviation

SSQ: The Speech, Spatial, and Qualities of Hearing questionnaire

SNR: signal-to-noise ratio

SRT: Speech reception thresholds

SRM: Spatial release from masking

Introduction

Advances in cochlear implant (CI) electrode design and improved surgical techniques have resulted in increasing numbers of CI recipients having preservation of usable acoustic hearing in their implanted ear (IE) (Nguyen et al., 2016). This has led to new approaches in which high frequency acoustic information delivered via electric stimulation "E" in a CI and low-frequency acoustic information delivered via amplification "A" through a hearing aid (HA) can be presented in combination to the same ear (EA). As terminology for describing combinations of devices varies across studies, this paper will use a simplified nomenclature first proposed by Dorman et al. (2010) for bimodal listeners and expanded by Ching et al. (2015) to include the range of amplification options available. For each ear, EA, E only or A only are possible options. Combining devices across the two ears is denoted by a plus '+' sign.

Previous studies with adult cochlear implant users with residual hearing in both ears have reported that significant benefit for speech perception can be obtained by combining EA in the same ear as compared to E alone both for listening in quiet (Adunka et al., 2010; Gstoettner et al., 2008) and listening in noise (Helbig et al., 2011; Lenartz et al., 2013; Lorens et al., 2008). Additional advantages such as functional performance in everyday life (Driver and Stark, 2010; Roland et al., 2016), music perception (Brockmeier et al., 2010; Gfeller et al., 2007) and user satisfaction (Erixon and Rask-Andersen, 2015; Gstoettner et al., 2011) have also been reported for the EA compared with E alone. The benefit obtained has been largely attributed to the enhanced delivery of temporal fine-structure, low-frequency cues via acoustic amplification, as these cues are not accurately preserved and delivered via the current CI envelope extraction-based processing strategies (Francart and McDermott, 2013; Zhang et al., 2010).

Postoperative preservation of low-frequency hearing in the IE also provides the potential for bilateral acoustic stimulation (EA+A). Binaural hearing enables use of the interaural time (ITD) and level (ILD) differences available in the acoustic information arriving at the two ears to localise sources of sounds and increase speech understanding in background noise and reverberation. A small number of studies have reported significant improvement in speech reception thresholds (SRTs) of approximately 2-3 dB for sentence perception in both complex noise and reverberation conditions when listeners used EA + A as compared to E + A (Plant and Babic, 2016; Skarsynski, et al., 2014). Furthermore, the degree of EAS benefit (EA+A minus E+A scores) was significantly correlated with postoperative low-frequency hearing thresholds in both ears and measured interaural time difference thresholds (Gifford et al., 2013).

Several studies investigating horizontal localization have also reported significant improvements in performance for binaural acoustic conditions (EA+A or A +A) as compared to the monaural acoustic amplification (EA) or (E+A) (Gifford et al., 2014; Plant and Babic, 2016). Additionally, the ability to localise wideband stimuli (Dunn et al., 2010; Incerti et al., 2014) on a horizontal plane has been reported to be equivalent for EA + A and A + A conditions. Also, there was no significant difference in localisation of wideband stimuli compared to low bandpass filtered stimuli, both of which were better than localisation of high pass stimuli (Loiselle et al., 2016). A significant correlation was also reported between, degree of hearing preservation in the IE, ITD thresholds and localisation (Gifford et al., 2014). These findings suggest that localization may be dependent on the participants' ability to extract ITD information presented through acoustic amplification to both ears, and was independent of whether E stimulation was used.

A review of current evidence supports the provision of acoustic amplification in both ears for recipients of a unilateral CI, in whom residual hearing that can be aided by acoustic amplification is preserved postoperatively (Ching, et al., 2015). However, it should be noted that there is considerable variability in the extent to which binaural hearing benefits may be obtained by individual users. Although systematic procedures for fine-tuning a E+A fitting, in which a HA is combined with a CI in opposite ears to optimise performance, are available (Ching et al., 2001), there is currently no consensus on validated procedures for fitting of EA devices in the same ear to maximise outcomes. Unlike conventional CIs that provide E stimulation spanning a full frequency range from 100 Hz to 8500 Hz, devices that provide EA in the IE can be programmed to restrict the lower frequency boundary of E stimulation by modifying the frequency-to electrode allocation tables (Wolfe and Schafer, 2015). This makes it possible to provide low-frequency information via acoustic amplification only and high frequency information via electrical stimulation. The input frequency at which A and E stimulation meet is referred to as the cross-over frequency (CF) in this paper. If acoustic amplification were provided at frequencies higher than the CF, overlapping inputs from a CI sound processor and acoustic amplification from a HA may occur for certain input frequencies. The same would occur if the lower frequency boundary of E stimulation were set to frequencies below the CF. This overlapping programming would result in information about the same input frequency being represented in two different locations along the cochlea via two modes of stimulation within the IE. Overlapping stimulation also increases the potential for within-fibre interactions to occur in populations of peripheral auditory neurons when the same region in the cochlea being stimulated electrically has functional hair cells (Nourski et al., 2007). Several researchers have employed animal models implanted with intracochlear or extracochlear electrodes to investigate this stimulus modality overlap at both the peripheral and central auditory level (Irving et al., 2014;Miller et al., 2009; Vollmer et al., 2007). Overlapping stimulation results in complex inhibitory and excitatory interactions that are dependent on the relative level and phase of the electric and acoustic stimuli. These animal models have provided a useful context around the potential beneficial and/or competing interactions at a physiological level.

Researchers have also investigated the effects of overlapping E and A stimulation in the IE of adults who retain hearing postoperatively. For these studies, overlapping stimulation refers to frequencies being transmitted for EA stimulation via E and A bandpass filtering. A number of studies have compared the speech perception performance of adult EA users when using a CI program that spanned the full frequency range with acoustic amplification ("overlapping" program) to their performance when using a CI program that set the lower frequency boundary of E stimulation to a predetermined frequency (referred to in different studies as "non-overlapping", "restricted" or "meet" program). The findings are mixed, with some studies showing that, on average, the users perceived speech better with a non-overlapping program than with an overlapping program when target speech and competing noise were presented from the same loudspeaker placed at 0° azimuth (coincident) (Karsten et al., 2013; Polak et al., 2010; Vermeire et al., 2008). Other studies, however, reported better speech perception results for overlapping programs in coincident noise (Kiefer et al., 2005) and in simulated background restaurant noise or "semi-diffuse" noise conditions (Gifford et al., 2017). Furthermore, studies have also reported no significant difference in performance for word recognition in quiet or sentence perception in coincident speech and noise between the two program settings (Büchner et al., 2009; Baumann and Mocka, 2017; Fraysse et al., 2006; Simpson et al., 2009). In all of these studies, there was considerable individual variability in performance. It is worth noting that in the majority of studies the participants used standard electrode arrays (Total length ≥18 mm) rather than electrode arrays specifically designed for EA fittings.

Several studies have also reported on participants' subjective preference or listening ratings for overlapping or non-overlapping settings. Again, there is considerable variability in the study findings, with some studies reporting that the majority of their participants preferred a non-overlapping program (Fraysse et al, 2006; Gantz et al., 2009; Karsten et al., 2013), whereas a few studies reported the majority of their participants preferred (Keifer et al., 2005) or reported lower subjective listening effort ratings (Gifford et al., 2017) with overlapping CI programs. In each of the previous studies, there were individuals whose performance or preferences varied from group results, suggesting the need to investigate further how best to optimise the programming of devices that provide E and A stimulation for the individual. It is worth noting that in many of the previous studies, limited listening experience with each condition was given prior to testing. The process of auditory acclimatization, whereby, individuals learn to make use of changes in acoustic information provided by unfamiliar signal processing in new hearing devices, has been widely reported in the research literature (Dillon, 2012). A recent study by Dawes and Munro (2017) reported that improved speech perception performance and self-reports of reduced distraction and annoyance in noise were significantly associated with severe hearing loss and consistent HA use during the acclimatization process. In addition, the majority of studies evaluated performance acutely in the IE only, excluding the contribution of the non-implanted ear (NIE), despite the likelihood that many of the participants would use residual hearing available in their contralateral NIE.

Research investigating CF settings in the fitting of devices that provide EA stimulation have relied on the users' audiograms in various ways. These can be grouped into those that selected the frequency at which the individual's hearing thresholds were ≥ 60 dB HL (Gstoettner et al., 2011; Helbig et al., 2011; Polak, et al., 2010; Vermeire et al., 2008); and those that selected the frequency at which hearing thresholds were ≥80dB HL (Gantz et al., 2009; James et al., 2005; Lenarz et al., 2013; Simpson et al., 2009). Commercial devices that integrate EA stimulation in the IE also vary with regards to the default audiometric-based criterion CF setting recommended in clinical programming software (Gifford et al., 2017). A prescriptive approach for setting the CF based on audiometric criteria has the potential to provide a practical and efficient procedure for use with patients, given that the range of residual hearing preserved in the IE has been reported to vary postoperatively in the research literature. However, the diminishing benefit of amplification as the audiometric thresholds become more severe, particularly for high-frequency sounds, widely reported in the HA literature (Ching et al., 1998; Hogan et al., 1998), raises the question of whether there is an optimum approach for selecting the frequencies to be presented through E versus A stimulation. Systematic investigations into the effect of variations in CF settings based on audiometric-criterion are therefore warranted.

A recent study by Gifford et al. (2017) investigated the effect of different amounts of E and A bandpass filter overlap on perception of speech in semi-diffuse, restaurant noise and perceived listening difficulty in 11 adults implanted with standard length Nucleus® electrode arrays. All participants wore a Nucleus® 6 sound processor with an integrated acoustic component in the IE. The lower frequency boundary of electrical stimulation was systematically varied in six 125 Hz steps ranging from 188 to 938 Hz, which spanned the range of CF set according to an audiometric-based criterion of 70 dB HL and 90 dB HL. Acoustic amplification in the IE was provided up to hearing thresholds of 90dB HL. Therefore, the amount of E and A overlap in the IE systematically decreased as the lower frequency boundary of E stimulation increased in frequency. Participants were provided with four of the six CF settings in their sound processor and asked to use all four progams equally for 3 to 4 weeks prior to testing. The remaining two CF settings were tested acutely. No information about the hearing aid used in the participants' NIE was available. When speech perception was compared for the CF set to the 70 dB HL and 90 dB HL audiometric-based criterion, there was no significant difference in the EA+A configuration. The manufacturer's recommended audiometric-based criterion of 90 dB HL (Cochlear Limited, Sydney) did not yield the highest or the lowest speech perception scores or subjective listening difficulty ratings in the EA+A configuration in acute testing.

It is not clear whether generalisations from this study's findings are applicable to recipients with shorter electrode arrays (length < 18 mm) specifically designed for hearing preservation for the purpose of combined EA stimulation. It is important to investigate the effect of CF settings on performance in recipients with shorter electrode arrays as they typically have better post-operative median hearing thresholds across the low frequencies compared to the standard electrode arrays (Jurawitz, et al., 2014). Furthermore, the effect of variations in CF setting in the IE when used with amplification in the NIE on binaural hearing (EA+A) for sound localization performance, speech understanding in spatially separated noise and functional hearing in everyday life is uncertain.

The following aspects were considered important in the design of this present study: 1) to evaluate the effect of CF settings on performance in an EA+A condition given the majority of adults use residual hearing in both ears in their typical everyday listening situations; 2) to utilize outcomes measures that evaluate binaural hearing performance such as, spatially separated speech and noise, localization, and functional benefit in everyday life; 3) to select a range of CF settings set according to audiometric-based criterion reported in the literature and recommended in manufacturer's clinical programming software for non-overlapping programs at the time of this study. For the purpose of this study, non-overlapping programs for EA stimulation refer to the frequencies being transmitted via E and A filtering; and 4) to give the participants sufficient time to familiarize with alternative CF settings before measurements of performance.

Aim

The aim of this study was to investigate the effect of variations in CF settings set according to audiometric-based criterion on speech understanding, localization and everyday functional performance of adults who use EA stimulation in one ear combined with A hearing in the opposite ear (EA+A).

Methods

Study design

A repeated-measures, within-subject design, in which each participant acted as his/her own control was used. This design is widely used in studies of recipients of CIs as it accommodates the large variability in outcomes of the population. The study was conducted under the ethical oversight of the Human Research Ethics Committees of the Royal Victorian Eye and Ear Hospital in Melbourne and the Royal Prince Alfred Hospital in Sydney. Information about the study was provided, and written consent was obtained from all participants. The study was registered with the Australian and New Zealand Clinical Trials Registry prior to participant enrolment. All aspects of the study were conducted in accordance with the National Statement on Ethical Conduct in Human Research (NH&MRC, 2018).

Participants

Ten adults (mean age = 70.8 years; range = 53 to 81; Female = 4; Male = 6) were recruited from The Royal Victorian Eye and Ear Hospital Cochlear Implant Clinic in Melbourne and The Sydney Cochlear Implant Centre. Participants were adult native-speakers of Australian English; all of whom had normal middle-ear function bilaterally and residual hearing in both ears (see Figure 1). There was no criterion placed on the pure tone hearing thresholds in either ear.

Figure 1 about here

All participants used a Nucleus CI system in one ear. Five participants received a Hybrid™ – L24 electrode arrays (<18mm length) and five participants received standard length electrode arrays (>18mm length). All participants were required to have at least six months experience with a CI prior to enrolment. Demographic characteristics and CI information for each participant is shown in Table 1.

Table 1 about here

Device Fitting

Cochlear implants

All ten participants used the Advanced Combination Encoder (ACE) sound processing strategy with a monopolar 1+2 stimulation mode, 900-Hz per channel stimulation rate, eight maxima and pulse width of 25-microseconds. The 'C-SPL" parameter was changed from the clinical software default level of 65 dB to 75 dB SPL. C-SPL determines the level at which infinite output limiting compression of the signal begins, therefore C-SPL was increased to 75 dB to avoid the sound processor operating in saturation at elevated signal levels (Wolfe et al., 2009). The "Q-value" parameter, which determines the steepness of the amplitude growth function, was also adjusted from the clinical software default of 20 to 16 to maintain perception of lower level sounds (Busby et al., 2016). Three CI programs with different CF settings were set up for each participant. The CFs were set according to the frequency at which the residual acoustic hearing thresholds were 60, 75, and 90 dB HL respectively (referred to as CF60, CF75 and CF90 in this paper). Selection of the three CF settings used in this study was based on the range of settings typically used for different CI systems as reported in the literature (Incerti et al., 2013 for an overview). It should be noted that the clinical fitting recommendations provided in programming software for the Nucleus® Freedom™ Hybrid™ and Nucleus® 6 sound processor (Cochlear Ltd, Sydney), at the time of this study set a default CF to the frequency at which thresholds are 90 dB HL (Nucleus 6® Hybrid™ Mode Professionals Guide, 36969 1SS7 MAR13). The three programs were created in the Cochlear fitting software (Custom Sound version 4.3) by modifying the lower frequency boundary of the most apical active electrode to match the frequency determined by the individual's unaided audiogram in the "Acoustics" screen. The upper limit of stimulation for all programs was set at the default value of 7938 Hz. Information about the audiogram and CF settings for each participant are shown in Table 2.

Table 2 about here

Hearing aids

Participants were fitted bilaterally with either a Siemens Motion 701or Nitro In-The-Ear (ITE) HA for the IE and a Siemens 701 Pure Carat 701 XCEL receiver-in-the-canal (RIC) HA for the NIE (Sivantos Inc., New Jersey, USA). All devices featured 16-channel digital signal processing, automatic directional microphones, and noise reduction technology. For our study, the same Siemens' HA technology (701 series) was fit in both the IE and NIE through the Connex 6.4 software (Sivantos Inc., New Jersey, USA) to facilitate the adjustment process. In the IE, an ITE HA was used instead of the integrated Hybrid/N6 acoustic component (AC) to enable the adjustment of the same compression parameters for different input levels in both ears, during the HA fine-tuning procedure in this study. In the NIE, RITC HAs were selected because the range of receiver models and custom mould options provided amplification and fitting flexibility to accommodate a wide range of hearing loss.

The NAL-NL2 prescription method was used to prescribe the initial HA gain setting, compression threshold, compression ratio, and maximum output level in both ears. The appropriate vent size was selected, for each participant, according to the recommendation made in stand-alone NAL-NL2 v 2.0 (dll v 2.15) software to achieve gain targets and minimise occlusion effects (Dillon, 2012). Real-ear-insertion gain (REIG) measurements using the MedRx AVANT™ REM SPEECH+ system were used for verification of fitting to match prescriptive targets. All probe-microphone measurements were carried out in a sound-treated test booth. All adaptive features in the HA, including, automated directional microphones and noise reduction technology, were disabled during the measurements. A broadband speech-weighted stimulus was presented at 50, 65, and 80 dB SPL from a loudspeaker positioned 0.5 meter from the participant at 45° degree azimuth. For the IE, the HA gain was adjusted to match the prescribed insertion gain targets within 5 dB for each octave frequency at each input level from 250 Hz up to the designated CF (Refer to Table 2 for designated CF settings for each participant) for minimal overlap of E and A filter frequency assignment for EA stimulation. The HA gain beyond the designated CF was set to the minimum possible value as determined by the constraint of the Connex 6.4 software (Sivantos Inc., New Jersey, USA). Minimal overlap of E and A filter frequency assignment for CF settings were selected as this was the clinical programming software default recommendation for the Nucleus® Freedom™ Hybrid™ and Nucleus® 6 sound processors (Cochlear Ltd, Sydney) at the time of this study. For the NIE, the HA gain was adjusted to match the prescribed NAL-NL2 insertion gain targets within 5 dB from 250 Hz up to the frequencies where thresholds correspond to a hearing threshold better than 105 dB HL. If thresholds were vibrotactile or not measurable the HA gain was set to the minimum possible value.

Test Measures

Speech perception in noise

An adaptive Australian Sentence Test in Noise (AuSTIN) (Dawson et al., 2013) was used to evaluate speech perception in two conditions. In one condition, target speech and competing eight-talker babble were presented from the same loudspeaker placed at 0° azimuth (S_oN_0). In a second condition (S_oN_{90}), target speech was presented from the front at 0° azimuth, and uncorrelated four-talker babble noise was presented from each of two loudspeakers placed at ±90°azimuth (effectively eight-talker babble). The loudspeaker noise configurations were selected to evaluate binaural advantage (combined effects of summation and squelch) and minimise the effect of head shadow. The target speech was presented at a fixed level of 65 dB SPL and the continuous eight-talker babble was varied in level according to the participants' responses. The SRT for 50% correct was determined by presenting 32 sentences per test run. The SRT for each CF setting was the average of two runs. All testing was preceded by a practice run of 16 sentences. The difference between SRTs measured with coincident speech and babble and SRTs measured with spatially separated speech and babble gives a measure of spatial release from masking (SRM) (Akeroyd, 2006). A positive SRM value in dB indicated an advantage is obtained when speech and noise are separated compared to coincident speech and noise from the front.

Localization

Horizontal localization ability was measured using an array of eight loudspeakers located in a 180-degree configuration in the horizontal plane and spaced equidistantly apart at 22.5° intervals in a sound-treated test booth. Pink noise bursts of 500 millisecond duration were randomly presented at 65 dB SPL (measured at the position of the listener's head in absentia) and with ± 4 dB random intensity variation in the overall level for each presentation to remove any residual overall loudness differences between loudspeaker output after calibration (van Hoesel et al., 2003). The 65dB SPL presentation level was selected to avoid asymmetrical activation of automatic gain controls (AGC) circuits of the participants' devices which can adversely affect localization performance due to the distortion of ILD cues (van Hoesel et al., 2002). The listener was seated directly facing the centre of the array, at a distance of about 1 metre and indicated the loudspeaker (designated by a number) from which the sound came. No feedback was given at any time and no repeats were allowed. Performance was derived by calculating the average root mean square (RMS) error in degrees. Two localization tests were conducted for each condition. Each test consisted of ten random presentations from each of the eight loudspeakers, with a total of 80 stimuli presented per test. All testing was preceded by a practice run. Chance performance for an eight loudspeaker array with a 180 degree configuration would be expected to be in the range of 59 to 86 degrees calculated using a method described by van Hoesel (2011).

Functional Assessment Measures

SELF Evaluation of Listening Function (SELF) Questionnaire

The SELF developed by Ching and Hill (2008) is a questionnaire used for self-report on functional performance in everyday life. The questionnaire consisted of 16 questions. Four questions focused on comfort and usage of device(s), five on functioning in quiet communicative situations, four on functioning in noisy communicative situations, and two on awareness and recognition of environmental sounds and one overall performance rating. Each question was rated on a 0 to 4 scale. The ratings for questions in each subgroup were expressed as percentage scores for each of four subscales labelled as: 1) Device usage, 2) Quiet, 3) Noise, and 4) Environmental sounds. Overall performance for each aided condition was calculated by summing the question ratings for Quiet, Noise and Environment subscales and converting them to a percentage score to give a “Total” score and a “Device usage” score.

The Speech, Spatial, and Qualities of Hearing questionnaire (SSQ)

The SSQ developed by Gatehouse and Noble (2004) was designed to measure self-reported auditory disability across a wide variety of realistic listening environments. The SSQ version 5.6 questionnaire used in this study consisted of three subscales which evaluate hearing functions requiring the binaural system including: understanding speech in a range of competing contexts (Speech Hearing subscale); ability to localise sounds as well as judging distance and movement (Spatial Hearing subscale); and judgements of sound quality, ease of listening, naturalness, clarity identification of different speakers, musical pieces or instruments and everyday sounds (Qualities of Hearing subscale). Participants completed the questionnaire by circling the response that best described hearing and understanding ability with each CF setting in the take-home environment. Two telephone questions #13 and #14 were removed from the analyses as the majority of participants used the telephone with their residual, acoustic hearing only or sent text on mobile phones. This test gives the three subscale scores: Speech, Spatial and Qualities and a Total score (47 questions).

Procedures

Figure 2 summarises the experimental protocol.

Figure 2 about here

HA Fine-tuning procedure:

Four weeks after initial HA fitting, the HAs were optimised for use with each of the three CF settings based on a HA fine-tuning procedure developed by Ching and colleagues (2001) as part of an optimization procedure for fitting the contralateral HA in combination with a CI. Firstly, the HA gain was adjusted from the original NAL-NL2 settings to give preferred loudness settings for speech intelligibility for 50, 65, and 80 dB SPL input levels for each CF setting in the IE and NIE. Secondly, a loudness balancing procedure was used to evaluate the overall gain of the HA in the NIE required to achieve equal loudness between acoustic and electrical stimulation between ears. . At the end of the procedure the participant's HA output setting was measured using a HA 2cc coupler. (AVANT Polar HIT, MedRx Polar HIT). Three HA fine-tuning sessions, one for each CF setting, were conducted over a period of six weeks. Each session lasted two hours and the time interval between sessions was two weeks.

Evaluation procedures

The speech, localization and functional performance of the three CF settings was evaluated over a total period of 12 weeks. Participants were given a four week take-home trial with each CF setting prior to testing for familiarisation. Participants wore their own CI sound processor and two hearing aids (EA +A) for these trials. The order of trial conditions was counterbalanced across participants as much as possible. Prior to the commencement of each take-home trial period, participants were given a copy of the SSQ and SELF questionnaires. At each evaluation test session, a subject's CI sound processor and HA were checked before evaluations. All adaptive features in the HA and CI, including, automated directional microphones and noise reduction technology, were disabled during the testing of speech perception and localization. The CI microphone sensitivity setting was fixed at the default level of 12 and user volume setting was held constant across all three CF settings for all testing for each participant. The participant's localization, speech perception and functional performance with the three CF settings were evaluated. Participants were blinded to the CF setting programmed in their CI programs during each of the trial periods. On completion of all evaluations, participants selected the CF setting to keep in their devices. This is designated as the "preferred take-home" setting (see Table 2).

Data Analysis

The data were analysed using Dell™ Statistica™ version 10 software (Tulsa, Okla). Descriptive statistics were used to report demographic information (e.g. age, duration of device use). Multi-variate analysis of variance (MANOVA) with repeated measures was used to investigate the effect of CFs setting on performance scores. Post-hoc analysis used Bonferroni corrections for critical p-values.

Results

Nine out of ten participants completed all tests with all CF settings. One participant (P1) completed trials with two CF settings only. This was due to the steep slope of P1's hearing loss, which allowed for only two CF settings between 60 dB HL and 90 dB HL on the audiogram. P1's scores were therefore excluded from the group analyses.

Speech perception in noise

Table 3 shows the adults' mean speech reception thresholds for 50% correct sentence perception (dB SNR) in two noise conditions, S_oN_o and S_oN_{90} for the three cross-over frequency (CF) settings.

Table 3 about here

Figures 3 shows the calculated SRM (SNR of S_oN_o minus SNR of S_oN_{90}) in dB for the three CF settings: CF60, CF75 and CF90 for the 10 participants and the group mean. Mean SRM (dB) and standard deviation (SD) for the three CF settings, CF60, CF75 and CF90 were -0.33 ± 1.60, -1.30 ± 0.96 and -0.99 ± 1.70 respectively. On average, no SRM was indicated for any of the CF settings. Individual SRM results showed that six of the ten participants (P2, P3, P4, P6, P9 and P10) exhibited SRM of approximately 1-2 dB in at least one CF setting. It should be noted that of the ten participants who reported a preference, seven (P2, P4, P5, P6, P8, P9 and P10) of these participants' preferred take-home CF setting was the same as their best performance (highest score) condition on SRM measures. For two participants (P1 and P7) similar performance was obtained with their preferred take-home setting and another CF setting. While one participant (P3) showed poorer performance with their preferred CF take-home setting compared to the other CF settings.

Figure 3 about here

Localization

Figure 4 shows the horizontal localisation RMS error scores in degrees for each participant and group mean. A lower RMS error indicates better localization performance. The mean RMS error (degrees) and SD for the three CF settings, CF60, CF75 and CF90 were 32.5 ± 14.2, 34.2 ± 14.6 and 31.3 ± 14.2 respectively. Individual results showed that eight out of ten participants (P1, P2, P3, P4, P5, P6, P8 and P10) scored above chance performance (shown as a dashed line on the chart) when using any of the three CF settings. Additionally, one participant (P7) performed at chance level with any of three CF settings on the localisation test and another participant (P9) performed at chance level with the CF60 setting but not CF75 or CF 90 settings.

Figure 4 about here

Functional Performance

SELF Evaluation of Listening Function (SELF) Questionnaire

Figure 5a show the SELF functional questionnaire “Total” scores in percentage for each participant together with the mean performance. The mean scores and SD for Total performance were 67.2 ± 11.6, 65.7 ± 16.9 and 65.8 ± 17.6, for the CF60, CF75 and CF90 respectively. Individual results show that eight participants (P2, P3, P4, P5, P6, P8 and P9) had similar performance rating scores for the SELF questionnaires with all three CF settings. While one participant’s (P10) preferred CF setting was the same as their highest performance rating score on the SELF measure. One participant (P1) completed the SELF questionnaire for the CF90 setting but not for the other settings.

Figure 5a about here

Figure 5b shows “Device Usage” scores in percentage for each participant together with the mean performance. The mean scores and SD for Device Usage were, 87.5 ± 8.8, 79.2 ± 17.7 and 75.0 ± 26.5, for the CF60, CF75 and CF90 respectively. Four participants (P2, P6, P7 and P9) reported the highest device usage with their preferred CF setting compared to the alternative CF settings. Two participants (P3 and P5) reported similar device usage scores with the three CF settings. While three participants (P4, P8, and P10) reported similar device usage scores with their preferred CF setting and another CF setting.

Figure 5b about here

Speech, Spatial and Qualities of Hearing Questionnaire (SSQ)

Table 4 shows the individual and mean scores for the three CF settings for the SSQ subscales.

Table 4 about here

Figure 6 shows the individual and mean total scores across all 47 questions of the SSQ for the three CF settings. Mean scores were, 6.3 ± 1.17, 6.1 ± 1.83 and 5.9 ± 1.99, for the CF60, CF75 and CF90 settings respectively Individual results for the SSQ questionnaire show very similar patterns to those obtained with the SELF questionnaire. For eight participants (P2, P3, P4, P5, P6, P8 and P9) total scores did not differ across the three CF settings. Participant P10's preferred CF setting was the same as their highest performance rating score on the SSQ measure. These individual SSQ fingings were in agreement with the SELF measure findings. One participant (P1) completed the SSQ questionnaire for the CF90 setting but not for the other CF settings.

Figure 6 about here

Effect of CF settings selected according to audiometric thresholds

MANOVA using averaged SRT across S_oN_o and S_oN_{90} conditions, SRM, localization errors, SSQ_Speech, Spatial and Quality subscale scores, SELF Use rating and SELF total scores as repeated measures and CF setting (CF60 vs CF75 vs CF90) as a categorical variable revealed that the main effect of CF setting was not significant ($F(12,16) = 1.74$, $p = 0.21$). On average, changing the CF settings according to audiometric thresholds did not have a significant effect on performance in any of the eight outcome measures.

Take-home CF setting based on preference

Individuals also indicated a preferred CF setting after they completed all home trials (Table 2). Of the ten participants, three (P1, P6, P9) selected the default CF setting recommended by the clinical software at the time of this study, which was set to the frequency at which thresholds are 90 dB HL. One participant (P3) had no preference. The remaining six participants selected a CF setting that was lower than default CF setting (CF60 or CF75). Of the ten participants, five selected a CF setting (P1, P3, P4, P6, P8) that was the same as their original CF setting prior to participation in this study. It is noteworthy that the four participants (P2, P5, P9, P10) who chose a setting different from that in their original processor appeared to gain advantages in speech perception (SRM) from that setting during field trials. The majority of participants made the selection of take-home CF setting based on listening comfort and subjective sound quality (refer to Table 2 for subjective reports). Two participants (P1, P2) with normal-to-mild hearing thresholds up to 750 Hz in the IE reported vibrotactile sensations with the lowest CF setting and based their selection on this. One participant (P3) had no preference for any CF setting, but selected a take-home CF setting that was the same as her spare CI processor. Two participants (P7, P10) also requested a second program that provided a full frequency CI program in addition to their take-home program. This program gave them the option to wear processors that provided electric only stimulation. This was the preferred mode when they were playing sport, fishing, camping or working with equipment in the shed. Overall, individual variability in preference was observed. Of the ten participants, five participants selected the CF60 as their preferred take-home program, three selected the CF90 program , one selected the CF75 program and one had no preference. There was no clear CF setting that was preferred by the majority of participants in this study. However, participants reported that they used the devices more often when their CI processors were programmed with a CF setting consistent with their final preference than with alternative CF settings. The ratings on device usage were 90.3 ± 8.3, 79.2 ± 17.6 and 72. ± 24.8 respectively for preferred take-home CF versus alternative CF1 and alternative CF2.

Effect of CF settings based on preference

It was reasoned that CFs preferred by participants might be related to their performance with the respective CF settings. Accordingly, we repeated the MANOVA using averaged SRT, SRM, localization errors, SSQ_Speech, Spatial and Qualities scores, SELF Use rating and SELF total scores as repeated measures, and CF setting (Preferred vs Other 1 vs Other 2) as a categorical variable. This revealed a significant main effect of setting ($F(2,16) = 4.01$, $p = 0.04$). The interaction between measures and CF setting was significant ($F(14,112)=3.34$, $p < 0.001$). Post-hoc comparisons revealed that usage of device was reported to be higher for the preferred setting than for either of the alternative CF settings ($p = 0.02$, $p<0.001$ respectively). There were no other significant interactions.

Figure 7 about here

Discussion

This study investigated the benefits of variations in relative electric to acoustic CF settings for adults who used EA+A. The three CFs settings were set according to the frequency at which the residual acoustic hearing thresholds were 60, 75, and 90 dB HL, respectively, with minimal E and A filter overlap. Evaluation of speech, localization and functional performance with each CF setting was compared, following a four week period of acclimatization with each setting. The participants selected the CF setting to keep in their devices on completion of all evaluations.

The results of this study showed no statistically significant different in speech scores on average across the three settings. While these findings are consistent with those reported by

Gifford et al (2017), they were unexpected, as the subjects in the current study had better post-op hearing as compared to those in the Gifford et al study, and would therefore have been expected to benefit more from the low frequency acoustic information. Previous studies have reported significant correlations between the degree of residual hearing and EA+A benefit for speech perception in noise (Gifford et al., 2014). Thus better hearing in the low frequencies could theoretically lead to variations in perception of speech cues with changes in CF settings. Furthermore, for individuals with severe to profound sensorineural hearing losses, the provision of high-frequency speech information via well-prescribed acoustic amplification, even if made audible, may provide limited benefit due to inner hair cell loss or damage in regions of the basilar membrane (Ching et al., 1998; Hogan et al., 1998). Thus providing participants, who have severe to profound hearing loss in the IE, with CF settings with wider frequency E stimulation ranges could potentially improve audibility of softer sounds and speech perception compared to A stimulation. However, no significant effect across CF settings for the group was found in this study. It may be possible that no effects were observed in our study because the absolute gain levels provided in the HA for the three CF settings were not sufficiently different. This warrants further investigations into the gain-frequency responses in acoustic amplification that was associated with the respective CF settings for the individual. We will be investigating the overall HA gain differences and E stimulation bandwidths for different CF settings in users with steeply sloping hearing loss further in a companion paper

Participants in the present study had a familiarisation period of four weeks with each CF setting prior to testing. Based on findings from previous HA acclimatization research studies, the participants were provided with the opportunity to adapt to the new signals in everyday listening situations to ensure that any significant effects observed were largely due to the CF settings examined. Despite different familiarisation time periods with each CF settings in the current study and the Gifford study (2017), the speech performance findings were similar. One potential explanation accounting for these findings is that EA +A users may not require long periods of acclimatization to accomodate to changes in CF settings in the IE. Alternatively, the sample sizes used in both studies may have been too small to detect any significant effect given the individual variability across subjects. It is not possible to draw any conclusions until further investigations into the effects of listening experience with different CF settings in larger populations are conducted.

Finally, the types of electrodes used by participants in this study differed from those in the Gifford study. The Gifford study investigated the effects of CF settings on speech understanding in participants with standard length Nucleus® electrode arrays with average angular insertion depths ranging from 360° to 440°. In the current study, half the participants used shorter length arrays (Hybrid™-L24) with average angular insertion depths of 206° and half used standard length electrode arrays with similar insertion depths to participants in the Gifford study. Complex inhibitory and excitatory interactions have been observed in regions of E and A stimulation overlap in the IE in animal model studies. It could be hypothesized that there is an increased potential for “with-in” fibre interactions to occur in participants with longer length electrode arrays compared shorter length electrode arrays, due to the reduced spatial separation in the cochlea between E and A stimulation (Miller et al., 2009). Despite the differences in array characteristics, the findings in the two studies are similar. No difference in speech perception perfomance in noise was observed on average across the CF setting selected based on an the audiometric thresholds (e.g. hearing level of 70 or 90 dB HL), irrespective of the electrode array used. Again, the participant sample sizes used in both studies may have been too small to detect any clinically significant effect. Future research to investigate CF settings in larger populations of EA+A users with various length electrode arrays is warranted.

The current study extends the Gifford et al., (2017) findings and previous studies by documenting the effect of variation in three audiometric-based criterion CF settings on horizontal localization performance and self-reported ratings of functional listening in everyday life. Research has shown that the ability to localise sounds on a horizontal plane was primarily dependent on participants' ability perceive the ITD cues in low frequency sounds through acoustic amplification to both ears in EA+A conditions (Loiselle et al., 2016). Different CF settings with different relative acoustic to electric outputs could potentially distort the lower frequency acoustic signal in one ear by introducing an electric "masking" signal (Karsten et al., 2013). Examination of possible detrimental or beneficial perceptual effects of different CF settings in users of EA+A on sound source localisation performance and in real world listening situations have not been investigated before this study. On average the three CF settings examined in this study did not have a significant effect on localization and functional listening in everyday life. These findings have clinical relevance as providing different CF settings to individuals who used EA+A would not likely impair binaural processes, such as sound source localisation and real world listening in daily life.

Effect of CF settings based on preference

The CF setting preferred by individual users on completion of all trials was associated with higher usage of devices in real life. The choice of preferred CF setting appears to be related to subjective quality, practical needs and previous experience (see Table 2). The majority of participants made their selection based on sound quality and the perceived benefits. Many of the participants’ subjective reports included remarks on the clarity, comfort and quality their own voice and others, as well as, listening in noisy environments and to music. However, for a few participants in the study, the preferred CF setting selection was based on their practical needs. For example, one participant selected a CF setting that was the same as their spare sound processor. Others selected CF settings that allowed them to wear processors that provided electric only stimulation (acoustic component or HA removed) in certain situations for convenience.

Three out of ten participants selected the default CF setting (CF90) recommended by the clinical software at the time of this study. One participant had no preference and the remaining six participants selected a lower CF setting (CF 60 or CF75) or E stimulation over a wider range than the default CF (CF90). Whilst for five of the ten study participants, the chosen setting was the same as that used in their original processors. It was not possible to tease out the extent to which preference might have been influenced by their experience with the settings prior to participation in the experiment. Irrespective of the different individual criteria that participants based their selection on, their device usage was significantly higher with their preferred CF settings. The present study revealed the potential benefits of providing more than one CF setting for individuals to select their preferred setting to maximise device usage. The question of 'Why do users prefer one CF setting over another, even when there are no differences found in their speech, localisation and functional scores?' is an important question which needs to be further examined. The study findings that listeners preferred specific CF settings, used their devices more regularly when programmed with these preferred settings and were potentially more satisfied with them has important clinical implications.

Major limitations of the present study included the potential confound of auditory experience on preferences, the restricted range of residual hearing, the variety of implant array types used by participants and the small sample size. The use of traditional self-report measures to evaluate functional hearing, such as those used in this study, also have some limitations. The questionnaires rely on input based on a participant's memory and experience of certain listening situations. Data logging in devices would have provided additional information about usage, but this feature was not available in devices worn by most of the participants at the time of the study. Future investigations into the optimal CF setting will need to engage a larger sample of users with different degrees of residual hearing configurations who are newly fitted with devices that combine EA stimulation.

Conclusion

This study evaluated the effect of varying CF settings for EA stimulation in one ear combined with acoustic (A) hearing in the opposite ear of ten adult listeners on their speech perception in noise, localization and functional performance in real life. Whereas performance for the group as a whole was not significantly different across CF settings based on audiometric-based criterion, higher ratings on device usage were associated with the CF setting preferred by individual users. Providing users of EA +A with a choice of CF settings in a clinical setting and allowing them to select their preferred CF may help achieve maximal device usage.

Acknowledgments

The authors acknowledge the financial support of the HEARing CRC, established under the Australian Government's Cooperative Research Centres (CRC) Program. The CRC Program supports industry-led collaborations between industry, researchers and the community. This project was also supported by the Commonwealth of Australia through the Office of Hearing Services. We are grateful to all the cochlear implant recipients who participated in this study. The authors would also like to thank the Royal Institute for Deaf and Blind Children, Royal Victorian Eye and Ear Hospital, The Melbourne Cochlear Implant Centre, and The Sydney Cochlear Implant Centre.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the authorship and/or publication of this article.

Table 1. Participants' demographic information.

Participants	Age (y)	Gender	Aetiology	Duration of Hearing loss prior to CI (y)	Duration of HA use prior to CI in both ears (y)	Duration of CI use (y)	Duration of EA use in IE (y)	Implant type, electrode type, length (L) and angular insertion depth (AID)*	Active channels
P1	74	F	Unknown	23	15	6.1	0.6	Hybrid L24, Straight,. L:16 mm, AID: 206°	18
P2	77	M	Measles	69	13	4.3	4.3	Hybrid L24, Straight,. L:16 mm, AID: 206°	21
P3	70	F	Unknown	55	12	1.9	1.9	CI422, Straight, L:25 mm, AID: 360-450°	21
P4	73	F	Unknown	33	13	4.6	4.5	Hybrid L24, Straight,. L:16 mm, AID: 206°	18
P5	70	M	Hereditary/ Industrial	22	21	5.5	5.5	Hybrid L24, Straight. L:16 mm, AID: 206°	18
P6	53	F	Possible oxygen deprivation	50	49	5.5	5.5	Hybrid L24, Straight. L:16 mm, AID: 206°	17
P7	81	M	Hereditary/ Industrial	60	20	4.3	4.3	MRA, Modiolar, L:17 mm, AID: 360-420°	22
P8	61	M	Unknown	30	20	8.1	8.1	Freedom CA, Modiolar, L:18mm, AID: 360-420°	22
P9	76	M	Familial	20	13	1.1	1.1	CI422, Straight, L:25 mm, AID: 360-450°	22
P10	74	M	Unknown	32	25	0.8	0.4	CI422, Straight. L:25 mm, AID: 360-450°	22
Mean	70.8			39.4	20.1	4.2	3.6		
Standard deviation	8.3			17.6	11.1	2.3	2.4		

*Dhanasingh and Jolly (2017).

CI = cochlear implant, CF = cross-over frequency, F = female, Hz = Hertz, IE = implanted ear, M= male, P= participant, y = years.

Table 2. Implanted ear information: Devices worn; frequency (Hz) at which the hearing loss was 60; 75, and 90 dB HL on unaided audiogram and where HA gain beyond the designated CF was set to the minimum; lower frequency boundary for electric (E) stimulation for each CF setting; participant's original CF setting; participant's preferred take-home CF settings and comments on CF settings.

		Frequency (Hz) at which hearing loss was			Lower frequency boundary of E stimulation (Hz)			Original CF setting	Preferred CF setting	Comments
Participant	Devices worn	60 dB HL	75 dB HL	90 dB HL	CF@ 60 dB HL	CF@ 75 dB HL	CF@ 90 dB HL			
P1	Hybrid Freedom + Motion 701 ITE (118/50)	*	630	800	*	563	688	CF90	CF90	CF75: 'vibrating that creates a feeling which makes it intolerable' and 'distorted'.
P2	Hybrid Freedom + Motion 701 ITE (118/50)	800	1000	1250	688	938	1188	CF90	CF60	CF60: 'has a slight vibration' and 'has a good first impact when someone speaks or when it starts'.
P3	CP810 + Nitro 701 ITE (128/70)	500	630	800	438	563	688	CF90	CF90	No preference. Used original CF program so compatible with spare processors.
P4	Hybrid Freedom\ + Motion 701 ITE (118/50)	800	1000	1250	688	938	1188	CF60	CF60	CF60:'comfortable'. CF75 and CF90 reported as 'very high pitch' and that 's too pronounced'.

P5	Hybrid Freedom + Motion701 ITE (118/50)	500	800	1000	438	688	938	CF90	CF75	CF75: 'hear well' CF90: 'troubled by children screaming and whistling'
P6	Hybrid Freedom + Motion 701 ITE (118/50)	500	630	800	438	563	688	CF90	CF90	CF90: 'better in noise'. CF60: 'worst in noise'.
P7	Hybrid Freedom + Nitro 701 ITE (128/70)	400	500	630	313	438	563	Nucleus CI full frequency range (188 -7938 Hz)	CF60	CF60: 'clear' and 'own voice normal'. CF75= 'own voice too deep' CF90= 'not clear', 'women sound like men', 'too deep'.
P8	CP810 + Nitro 701 ITE (128/70)	250	400	630	188	313	563	CF60	CF60	CF60 and CF75 programs both 'better' than CF90. CF90: 'sounded distorted' and 'deeper'.
P9	CP810 + Nitro 701 ITE (128/70)	400	630	800	313	563	688	Nucleus CI full frequency range (188-7938 Hz)	CF90	CF90: 'more than satisfied with my hearing' and 'better for music'. CF60 and CF 75: 'echoey', 'throaty' and 'low pitch'.
P10	CP810 + Nitro 701 ITE (128/70)	400	630	1000	313	563	938	Nucleus CI full frequency range (188-7938 Hz)	CF60	CF75: 'mostly unintelligible'. CF90: 'unacceptable' and 'unable to understand anything without immense concentration'.

dB = decibels, CI = cochlear implant, CF = cross-over frequency, HL: Hearing loss, Hz = Hertz, IE = implanted ear, ITE = in-the-ear, P= participant.
* P1 had only two CF settings between 60 dB HL and 90 dB HL on the audiogram as the hearing loss was so steeply sloping

Table 3. Comparisons of speech outcomes for three different CF settings. Speech reception threshold scores (dB SNR) for sentence material presented in S0N0 (SNR_ S_oN_o) conditions and S0N±90 (SNR_ S_oN_{90}) conditions for the three cross-over frequency (CF) settings. More negative (lower) dB SNR values indicates better performance.

Participants	SNR_S_oN_o			SNR_S_oN_{90}		
	CF60	CF75	CF90	CF60	CF75	CF90
P1	*	-1.4	2.5	*	3.0	4.0
P2	0.6	-0.2	0	-1.3	-0.5	1.3
P3	0.7	-0.2	-0.9	-0.3	1.0	1.0
P4	-1.4	-0.5	-0.2	-3.3	0.7	2.5
P5	2.1	0.9	2.1	4.4	2.1	4.0
P6	1.7	2.9	3.6	3.6	3.2	2.3
P7	2.6	3.2	3.4	3.8	5.4	4.7
P8	0.6	0.5	1.2	1.6	2.8	3.9
P9	0.4	0	-0.5	1.9	2.7	-2.8
P10	1.1	1.7	5.6	0.8	2.7	6.5
Mean	0.9	0.9	1.6	1.2	2.2	2.6
Standard deviation	1.2	1.4	2.3	2.5	1.7	2.7

*

* P1 had only two CF settings between 60 dB HL and 90 dB HL on the audiogram as the hearing loss was so steeply sloping.

Table 4. Comparison of Speech, Spatial and Qualities subscale scores for the three cross-over frequency (CF) settings.

Participants	Speech Hearing subscale			Spatial Hearing subscale			Qualities of Hearing subscale		
	CF60	CF75	CF90	CF60	CF75	CF90	CF60	CF75	CF90
P1	*	§	6.4	*		4.29	*	§	4.29
P2	7.1	8.1	7.1	7.4	7.4	8.1	7.0	7.2	7.3
P3	7.0	6.8	6.8	7.7	7.7	8.0	8.9	8.4	8.6
P4	4.7	4.4	3.9	5.1	5.8	4.6	6.0	6.3	5.8
P5	3.4	6.8	5.8	7.9	7.4	7.1	5.7	7.3	7.7
P6	7.6	6.8	8.1	6.1	7.2	7.4	5.9	6.4	8.3
P7	4.7	4.2	4.0	8.9	8.5	7.8	8.1	8.7	6.9
P8	6.0	5.0	4.7	3.6	4.3	3.5	6.8	7.2	6.6
P9	6.5	5.9	5.9	6.8	5.8	5.8	7.7	6.9	6.9
P10	3.9	1.7	2.4	3.8	1.8	2.0	4.9	1.8	0.6
Mean	5.6	5.5	5.5	6.4	6.2	5.9	6.8	6.7	6.7
Standard deviation	1.5	1.9	1.8	1.9	2.1	2.2	1.3	2.0	2.4

* P1 had only two CF settings between 60 dB HL and 90 dB HL on the audiogram as the hearing loss was so steeply sloping.

§ P1 did not complete questionnaire for CF75.setting (see Table 2 for comments)

Figures

Figure 1. Pure-tone thresholds in the implanted (left panel) and non-implanted (right panel) ears for the 10 participants.

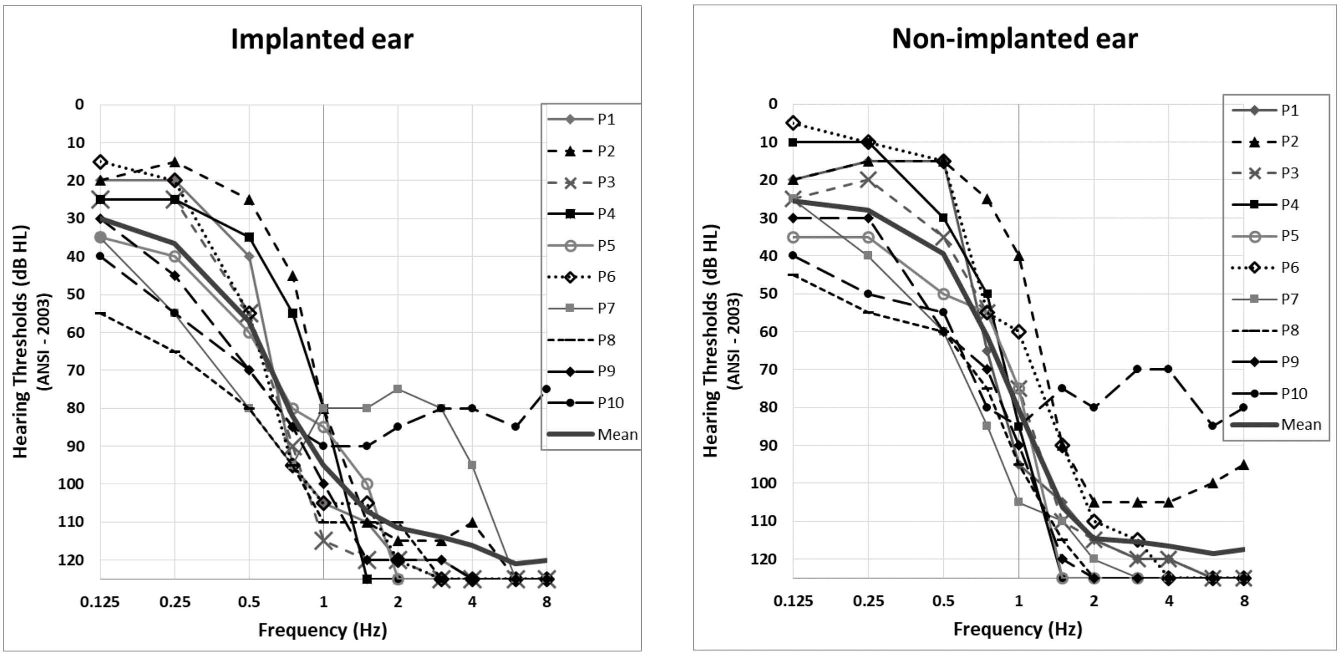


Figure 2. Evaluation procedure overview. The order of three cross-over frequency (CF) settings (CF60, CF75 and CF90) was counterbalanced across participants as much as possible. The numbers between the parentheses are the number of participants in each trial condition. One participant completed trials with two CF settings only. In the final session, participants selected their preferred CF setting to take home.

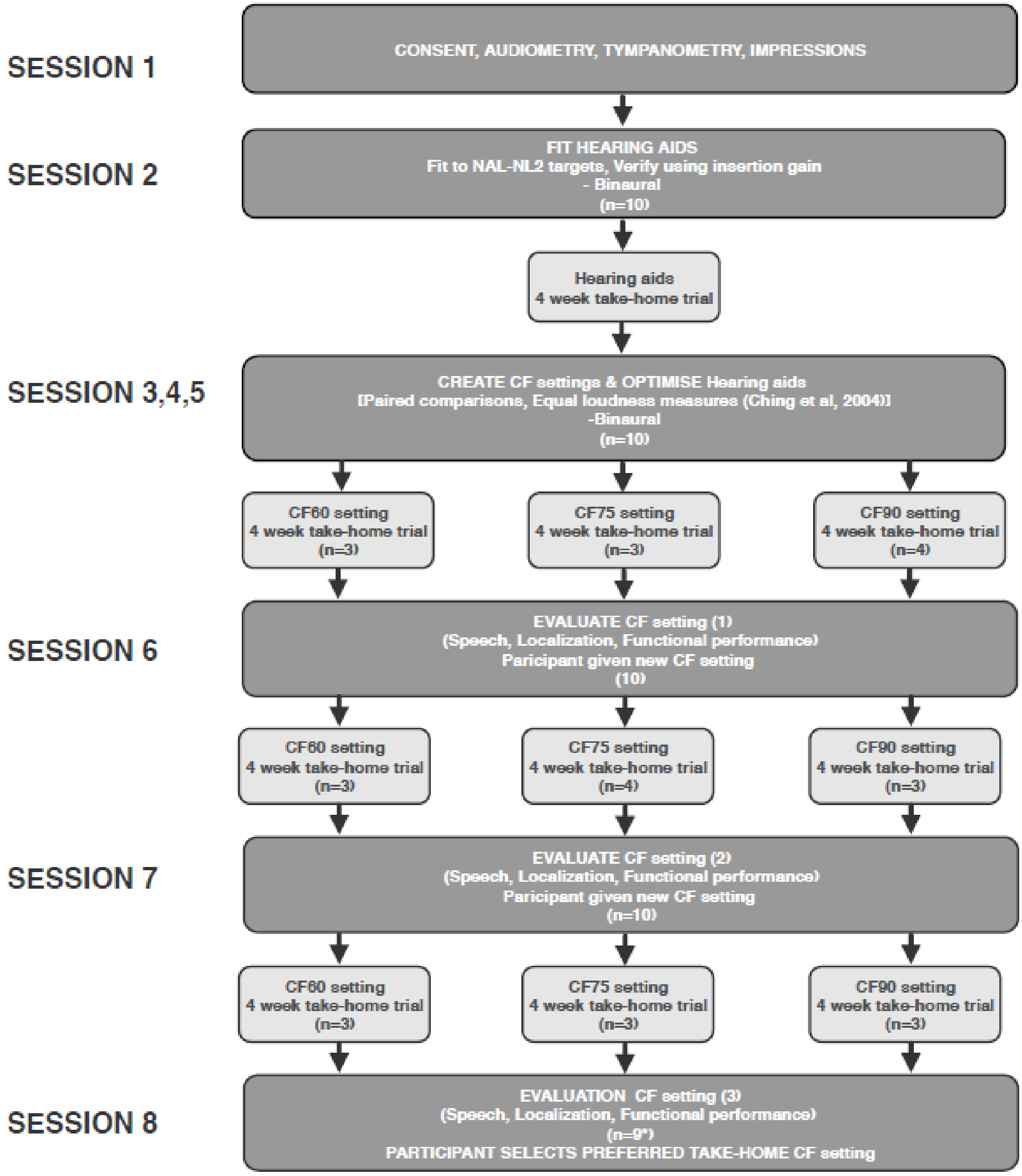


Figure 3. Comparison of Spatial Release from Masking scores in dB for the three cross-over frequency (CF) settings: CF60 (grey bars), CF75 (white bars) and CF90 (striped bars) for the 10 participants and the group mean score. Positive scores indicate SRM. Error bars for grouped data indicate the standard error of the difference scores. Star symbol denoted participant's preferred CF setting.

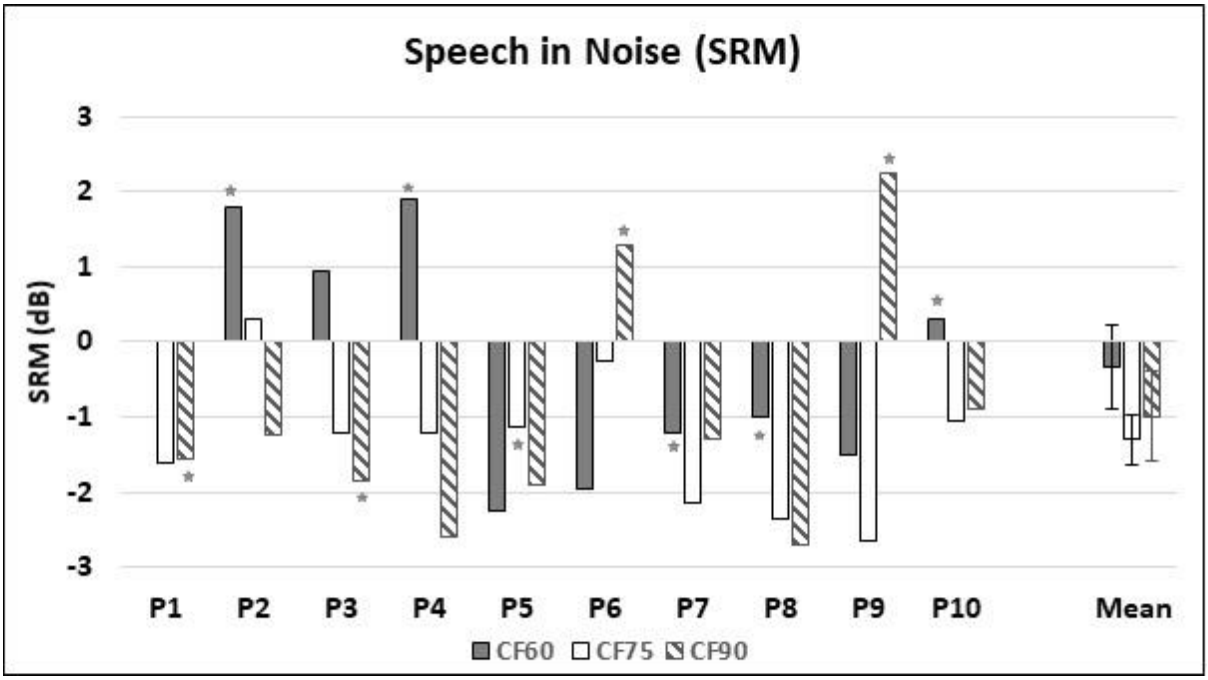


Figure 4. Comparison of individual and group horizontal localization scores and standard deviation in RMS errors (degrees) for the three cross-over frequency (CF) settings: CF60 (grey bars), CF75 (white bars) and CF90 (striped bars). The dashed black line represents chance score. Error bars for grouped data indicate the standard error of the difference scores. Star symbol denoted participant's preferred CF setting.

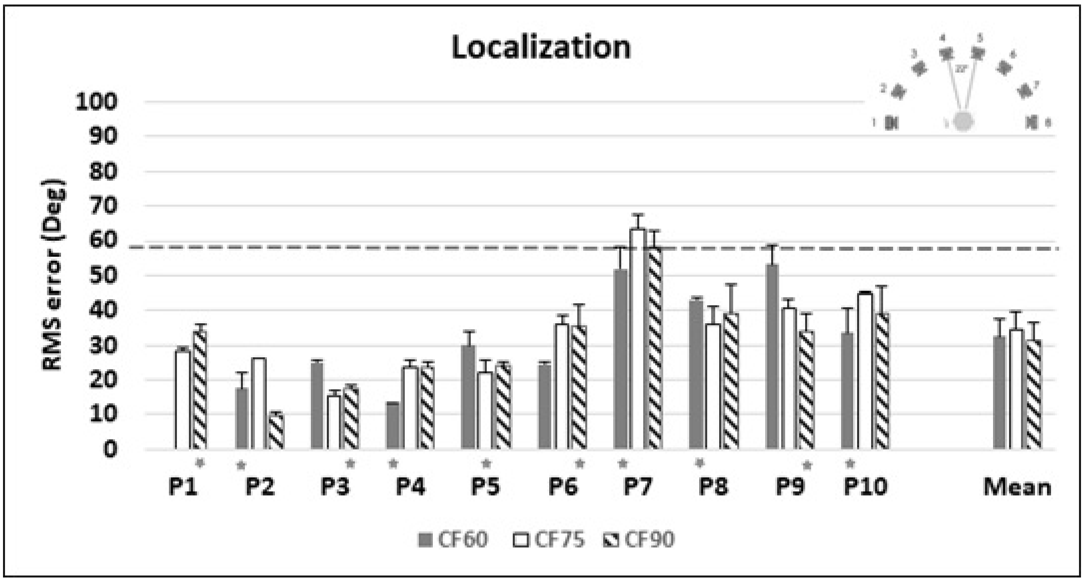


Figure 5a. Comparison of SELF Evaluation of Listening Function (SELF) Questionnaire total performance rating scores (%) for the three cross-over frequency (CF) settings: CF60 (grey bars), CF75 (white bars) and CF90 (striped bars) for the 10 participants and the group mean score. Error bars for grouped data indicate the standard error of the difference scores. Star symbol denoted participant's preferred CF setting.

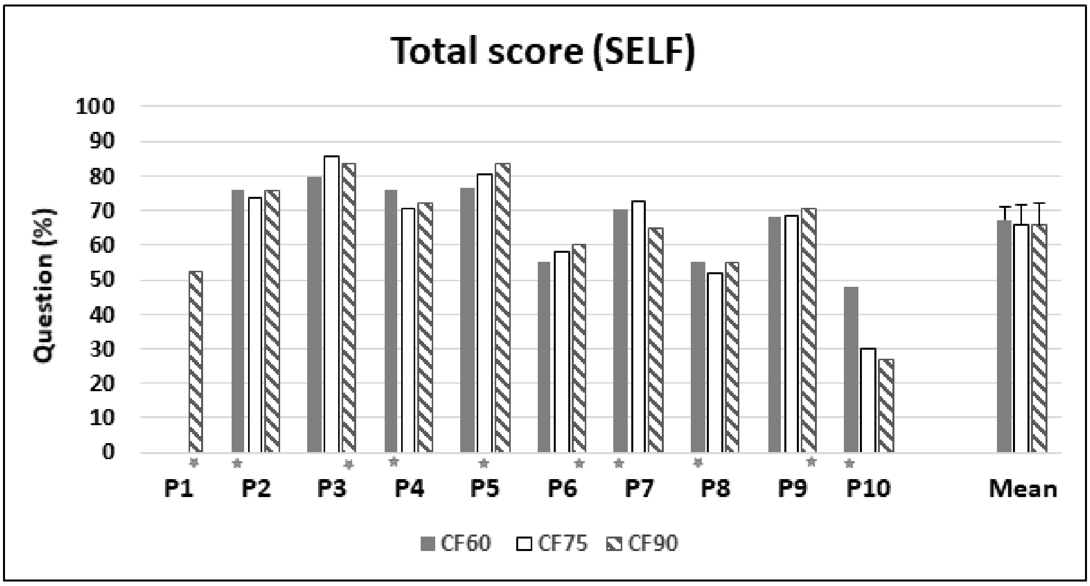


Figure 5b. Comparison of SELF Evaluation of Listening Function (SELF) Questionnaire device usage scores (%) for the three cross-over frequency (CF) settings: CF60 (grey bars), CF75 (white bars) and CF90 (striped bars) for the 10 participants and the group mean score. Error bars for grouped data indicate the standard error of the difference scores. Star symbol denoted participant's preferred CF setting.

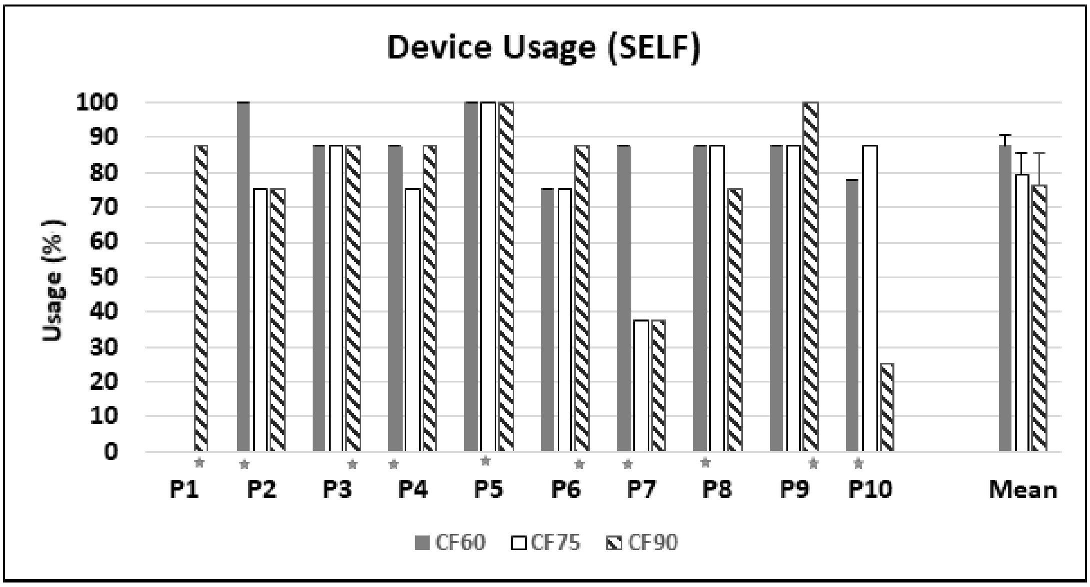


Figure 6. Comparison Speech, Spatial and Qualities questionnaire Total rating scores for the three cross-over frequency (CF) settings: CF60 (grey bars), CF75 (white bars) and CF90 (striped bars) for the 10 participants and the group mean score. Error bars for grouped data indicate the standard error of the difference scores. Star symbol denoted participant's preferred CF setting.

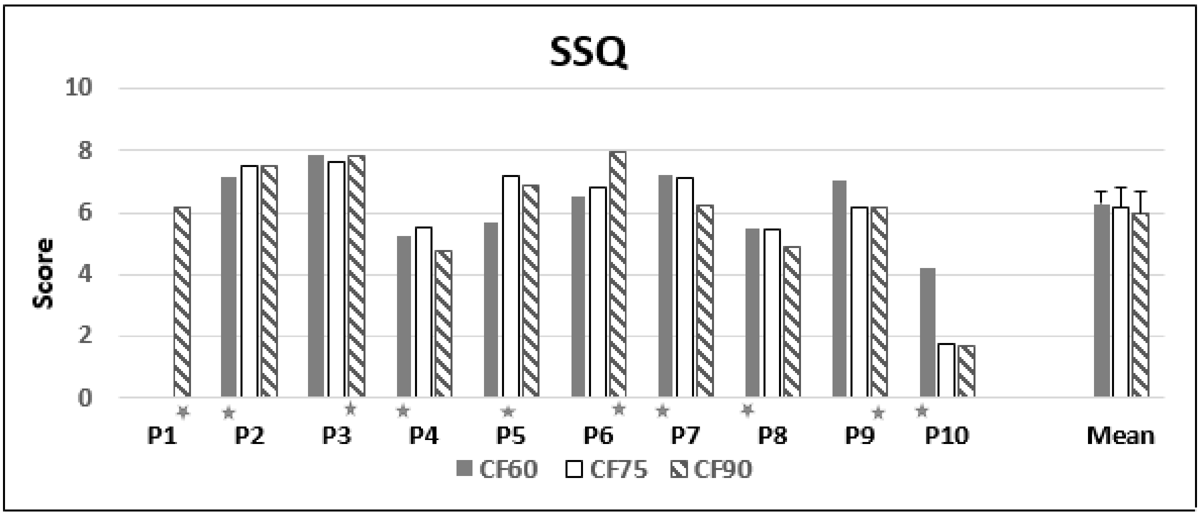
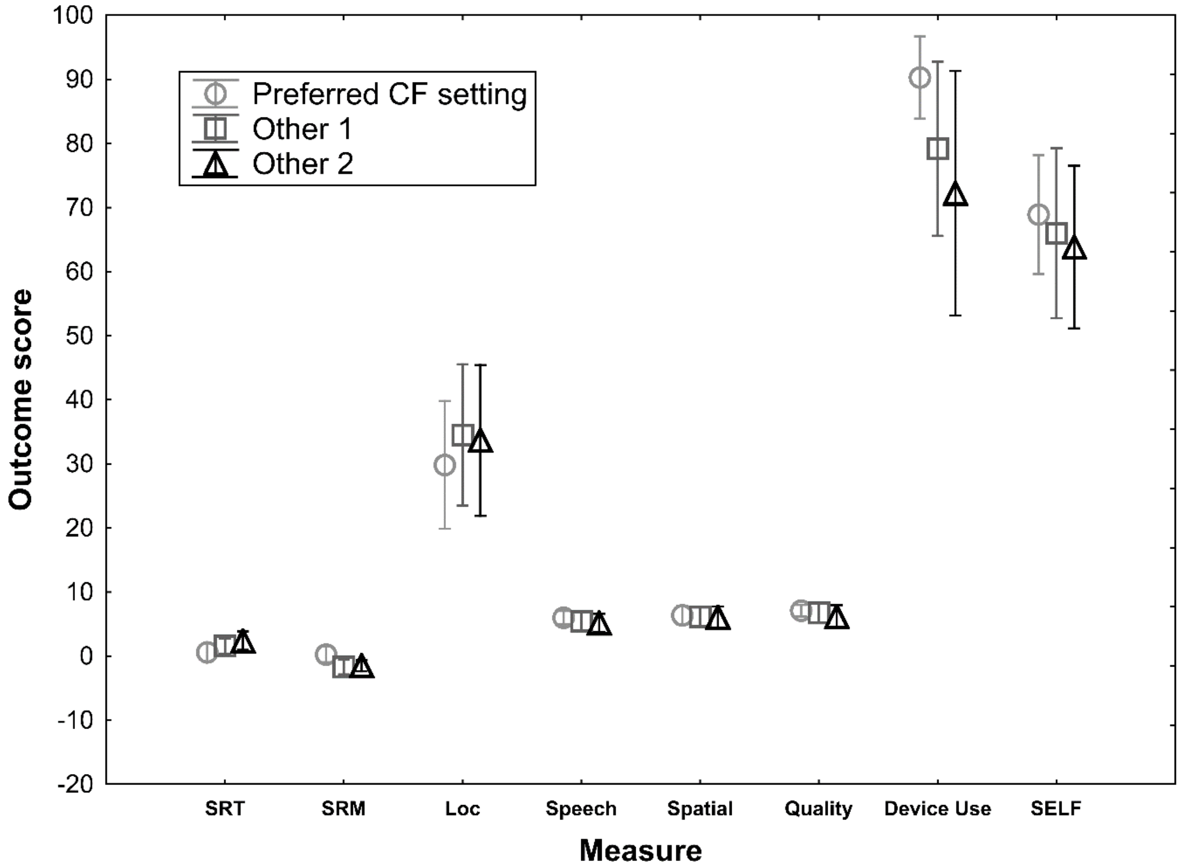


Figure 7. Mean performance of the three cross-over frequency (CF) settings, the preferred CF setting (labelled "Preferred CF setting") and the two alternative CF settings (labelled "Other 1" and "Other 2") for eight measures. The vertical axis shows the average performance outcome scores and the horizontal axis shows the eight measures evaluated (1.Averaged SRT across S_oN_o and S_oN_{90} conditions, 2. Averaged SRM score, 3. localization rms errors score, 4. SSQ_Speech subscale score, 5. _SSQ_Spatial subscale score 6. SSQ_Quality subscale score, 7. SELF Device Usage rating 8. SELF total score). The preferred take-home CF setting is denoted by the open circle symbols. The alternative CF1 and CF2 settings are denoted by the open square and open triangle symbol, respectively.



References

Adunka, O. F., Pillsbury, H.C., Adunka, M. C., Buchman,C.A. 2010. Is electric acoustic stimulation better than conventional cochlear implantation for speech perception in quiet? *Otology and Neurotology,* 31(7): 1049-1054.

Akeroyd, M. A. 2006. The psychoacoustics of binaural hearing. *International Journal of Audiology,* 45, 25-33.

Baumann, U. and Mocka, M. 2017. Impact of the overlap region between acoustic and electric stimulation. *Laryngorhinootologie*. Feb 8. doi: 10.1055/s-0042-117639.

Brockmeier, S. J., Peterreins, M, Lorens, A., Vermeire, K., Helbig, S., Anderson, I., et al. 2010. Music perception in electric acoustic stimulation users as assessed by the Mu.S.I.C. test. *Advances In Oto-Rhino-Laryngology,* 67: 70-80.

Büchner, A., Schüssler, M., Battmer, R. D., Stöver, T., Lesinski-Schiedat, A., Lenarz, T. 2009. Impact of low-frequency hearing. *Audiology and Neurotology,* 14(Suppl 1): 8-13.

Ching, T.Y.C., Dillon, H., Byrne, D. 1998. Speech recognition of hearing-impaired listeners: Predictions from audibility and the limited role of high-frequency amplification. *The Journal of the Acoustical Society of America*, 103(2): 1128-1140

Ching, T.Y.C., Psarros, C., Hill, M., Dillon, H., Incerti, P. 2001. Should children who use cochlear implants wear hearing aids in the opposite ear?. *Ear and Hearing,* 22(5): 365-380..

Ching, T.Y.C., Hill, M., & Dillon, H. 2008. Effect of variations in hearing-aid frequency response on real-life functional performance of children with severe or profound hearing loss. *International Journal Of Audiology*, 47(8): 461-475.

Ching, T.Y.C., Incerti, P., Plant, K. 2015. Electric-acoustic stimulation: for whom, in which ear, and how. *Cochlear Implant International*, 16 (Suppl 1): 12-15.

Dhanasingh, A. and Jolly,C. 2017. An overview of cochlear implant electrode array designs. *Hearing Research*, 356: 93-103.

Dawes, P., and Munro, K. J. 2017. Auditory Distraction and Acclimatization to Hearing Aids *Ear and Hearing* , 38: 174-183.

Dawson, P. W., Hersbach, A. A., Swanson, B. A. 2013. An Adaptive Australian Sentence Test in Noise (AuSTIN). *Ear and Hearing* , 34(5): 592-600.

Driver, S. and Stark, E. 2010. Real Life Outcomes for Adult EAS Patients and Adult Traditional CI Patients. *Cochlear Implants International,* 11(3): 113-118.

Dorman, M. F. and Gifford, R. H., Spahr, A. J., McKarns, S. A. 2008. The benefits of combining acoustic and electric stimulation for the recognition of speech, voice and melodies. *Audiology and Neurootology,* 13(2): 105-112.

Dunn, C. C., Perreau, A., Gantz, B., Tyler, R.S. 2010. Benefits of localization and speech perception with multiple noise sources in listeners with a short-electrode cochlear implant. *Journal of the American Academy of Audiology,* 21: 44-51.

Erixon, E., Rask-Andersen, H. 2015. Hearing and Patient Satisfaction Among 19 Patients Who Received Implants Intended for Hybrid Hearing: A Two-Year Follow-Up. *Ear and Hearing,* 36(5): 271-278.

Francart, T. and McDermott, H. J. 2013. Psychophysics, fitting, and signal processing for combined hearing aid and cochlear implant stimulation. *Ear And Hearing,* 34(6): 685-700.

Fraysse, B., MacÃas, Ã. R., Sterkers, O., Burdo, S., Ramsden R, Deguine, O., et al. 2006. Residual hearing conservation and electroacoustic stimulation with the Nucleus 24 Contour Advance cochlear implant. *Otology and Neurotology,* 27(5): 624-633.

Gatehouse, S. Noble, W. 2004. The Speech, Spatial and Qualities of Hearing Scale (SSQ). *International Journal Of Audiology*, 43(2): 85-99.
Gfeller, K., C. Turner, Oleson, J., Zhang, Z., Gantz, B., Froman, R., et al.. 2007. Accuracy of cochlear implant recipients on pitch perception, melody recognition, and speech reception in noise. *Ear and Hearing*, 28(3): 412-423.
Gifford, R. H., Dorman, M. F., Skarzynski, H., Lorens, A., Polak, M., Driscoll, C. L. W., et al. 2013. Cochlear implantation with hearing preservation yields significant benefit for speech recognition in complex listening environments. *Ear and Hearing*, 34(4): 413-425.
Gifford, R. H., Grantham, D. W., Sheffield, S.W., Davis, T.J., Dwyer, R., Dorman, M.F. 2014. Research paper: Localization and interaural time difference (ITD) thresholds for cochlear implant recipients with preserved acoustic hearing in the implanted ear. *Hearing Research*, 312: 28-37.
Gifford, R. H., Davis, T.; Sunderhaus, L., Menapace, C.; Buck, B., Crosson, J.; O'Neill, L. 2017. Combined Electric and Acoustic Stimulation With Hearing Preservation: Effect of Cochlear Implant Low-Frequency Cutoff on Speech Understanding and Perceived Listening Difficulty. *Ear and Hearing*, 38(5): 539-553.
Gstoettner, W. K., Van de Heyning, P., Fitzgerald O'Connor, A., Morera, C., Sainz, M., Vermeire, K., et al. 2008. Electric acoustic stimulation of the auditory system: results of a multi-centre investigation. *Acta Oto-laryngologica*, 128(9): 968-975.
Gstoettner, W. K., Van de Heyning, P., Fitzgerald O'Connor.A, Kiefer, J., Morera, C., Sainz, M., et al. 2011. Assessment of the Subjective Benefit of Electric Acoustic Stimulation with the Abbreviated Profile of Hearing Aid Benefit. *ORL J Otorhinolaryngol Relat Spec*, 73(6): 321-329.
Helbig, S., Van de Heyning, P., Kiefer, J., Baumann, U., Kleine-Punte, A., Brockmeier, H., et al. 2011. Combined electric acoustic stimulation with the PULSARCI(100) implant system using the FLEX(EAS) electrode array. *Acta Oto-laryngologica*, 131(6):1-11.
Hogan, C. and Turner, C. 1998. High-frequency audibility: Benefits for hearing-impaired listeners. *The Journal of the Acoustical Society of America*, 104(1): 432-441.
Incerti, P. V., Ching, T. Y. C., Cowan, R. 2014. Electric-acoustic stimulation in adults: localization and speech perception. *Cochlear Implants International*, 15 (Suppl 1): 17-20.
Incerti, P. V., Ching, T. Y. C., Cowan, R. 2013. A systematic review of electric-acoustic stimulation: device fitting ranges, outcomes, and clinical fitting practices, *Trends in Amplification*, 17(1): 3-24.
Irving, S., Wise, A. K., Millard, R. E. ; Shepherd, R. K. Fallon, J. B. 2014. A partial hearing animal model for chronic electro-acoustic stimulation. *Journal of Neural Engineering*, 11(4): 046008-046008.
James, C. J., Fraysse, B., Deguine, O., Lenarz, T., Mawman, D., Ramos, A.,et al. 2006. Combined electroacoustic stimulation in conventional candidates for Cochlear Implantation. *Audiology and Neurotology*, 11(Suppl 1): 57-62.
Jurawitz, M.C., Büchner, A., Harpel, T., Schüssler, M., Majdani, O., Lesinski-Schiedat, A.,et al.. 2014. Hearing Preservation Outcomes with Different Cochlear Implant Electrodes: Nucleus® Hybrid™-L24 and Nucleus Freedom™ CI422. *Audiology and Neuro-Otology*, 19(5): 293-309.
Karsten, S.A., Turner, C.W., Brown, C.J., Joen, E. K., Abbas, J. Gantz, B.J. 2013. Optimising the combination of acoustic and electric hearing in the implanted ear. *Ear and Hearing*, 34(2): 142-150.

Kiefer, J., Pok, M., Adunka, O., Stürzebecher, E., Baumgartner, W., Schmidt, M.et al.. 2005. Combined electric and acoustic stimulation of the auditory system: results of a clinical study. Audiology and Neuro-Otology, 10(3): 134-

Lenarz, T., James, C., Cuda, D., O'Connor, F., Frachet, B., Frijns, J., et al. 2013. European multi-centre study of the Nucleus Hybrid L24 cochlear implant. *International Journal of Audiology*, 52(12): 838-848.

Loiselle, L. H., Dorman, M. F., Yost, W.A., Cook, S.J., Gifford, R.H. 2016. Using ILD or ITD cues for sound source localization and speech understanding in a complex listening environment by listeners with bilateral and with hearing-preservation cochlear implants. *Journal of Speech, Language, and Hearing Research*, 59: 810-818.

Lorens, A., Polak, M., Piotrowska,P., Skarzynski H. 2008. Outcomes of Treatment of Partial Deafness With Cochlear Implantation: A DUET Study. *The Laryngoscope*, 118(2): 288-294.

Miller, C., Abbas, P., Robinson, B., Nourski, K., Zhang, F., Jeng, F. 2009. Auditory nerve fiber responses to combined acoustic and electric stimulation. *Journal of the Association for Research in Otolaryngolog*y,.10(3): 425-445.

Nguyen, S., Cloutier, F., Philippon, D., Côté, M., Bussières, R., Backous, D., 2016. Outcomes review of modern hearing preservation technique in cochlear implant. *Auris, Nasus, Larynx*, 43(5):485-488.

Nourski, K. V., Abbas, P. J., Miller, C. A., Robinson, B.K., Jeng, F. 2007. Acoustic–electric interactions in the guinea pig auditory nerve: Simultaneous and forward masking of the electrically evoked compound action potential. *Hearing Research*, 232(1), 87-103.

Plant, K., L. Babic 2016. Utility of bilateral acoustic hearing in combination with electrical stimulation provided by the cochlear implant. *International Journal of Audiology*.55:S1-S8.

Polak, M., Lorens, A., Helbig, S., McDonald, S., McDonald, S., Vermeire, K. 2010. Fitting of the hearing system affects partial deafness cochlear implant performance. *Cochlear Implants International*, 11(2): 1117-1121.

Roland, J, Gantz, B., Waltzman, S., Parkinson, A., Roland, J. T. 2016. United States multicenter clinical trial of the cochlear nucleus hybrid implant system. *Laryngoscope*, 126(1): 175-181.

Simpson, A., McDermott, H. J., Dowell, R. C., Sucher, C., Briggs, R. J. S. 2009. Comparison of two frequency-to-electrode maps for acoustic-electric stimulation. *International Journal of Audiology*, 48(2): 63-73.

van Hoesel, R. M., Litovsky, R. Y. 2011. Statistical bias in the assessment of binaural benefit relative to the better ear. *Journal Of The Acoustical Society Of America*, 130(6): 4082-4088.

Vermeire, K., Anderson, I., Flynn, M., Van de Heyning, P. 2008. The influence of different speech processor and hearing aid settings on speech perception outcomes in electric acoustic stimulation patients. *Ear and Hearing*, 29(1): 76-86.

Vollmer, M., Beitel, R.E., Snyder, R.L., Leake, P. A. 2007. Spatial selectivity to intracochlear electrical stimulation in the inferior colliculus is degraded after long-term deafness in cats. *Journal of Neurophysiology*. 98(5): 2588-2603.

Wolfe, J., Schafer, E. C. 2015. Programming cochlear implants. San Diego, CA : Plural Publishing.

Zhang. T., Dorman, M.F., Spahr, A.J. 2010. Information from the voice fundamental frequency (F0) region accounts for the majority of the benefit when acoustic stimulation is added to electric stimulation. *Ear and Hearing*, 31(1): 63–69.