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ORIGINAL ARTICLE

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Integrated bimodal fitting and binaural streaming technology outcomes for unilateral cochlear implant users

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ABSTRACT

Objective: Adults typically receive only one cochlear implant (CI) due to cost constraints, with a contralateral hearing aid recommended when there is aidable hearing. Standard hearing aids differ from a CI in terms of processing strategy and function as a separate entity, requiring the user to integrate the disparate signals. Integrated bimodal technology has recently been introduced to address this challenge. The aim of the study was to investigate the performance of unilateral CI users with and without an integrated bimodal fitting and determine whether binaural streaming technology offers additional benefit.
Study sample: Twenty-six CI users using integrated bimodal technology.
Design: Repeated measures where outcomes and user experience were assessed using a functional test battery more representative of real life listening (speech perception in noise tests, localisation test, tracking test) and the speech, spatial and qualities-of-hearing scale (SSQ).
Results: Bimodal outcomes were significantly better than for CI alone. Speech perception in noise improvements ranged from 1.4 dB to 3.5 dB depending on the location of speech and noise. The localisation and tracking tests, and the SSQ also showed significant improvements. Binaural streaming offered additional improvement (1.2 dB to 6.1 dB on the different speech tests).
Conclusions: Integrated bimodal and binaural streaming technology improved the performance of unilateral CI users.

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Cochlear implant; hearing aid; integrated bimodal technology; real-life tests

Introduction

Hearing with both ears (binaural hearing) is important for spatial hearing in real-life listening environments, e.g. hearing in background noise and sound localisation. Providing the appropriate intervention for listeners with bilateral hearing loss can help restore some of the binaural functions of normal hearing. Research has shown that hearing-impaired listeners with bilateral hearing aid (HA) fittings have better binaural summation, binaural squelch, and head-shadow effects for speech understanding in noise (Bronkhorst and Plomp 1989) and superior localisation performance compared to those who have unilateral fittings (Byrne, Noble, and LePage 1992).

Adults with bilateral severe to profound hearing loss typically receive a single cochlear implant (CI) due to cost constraints. Bimodal hearing has become the standard care for adult unilateral CI users having residual hearing in their non-implanted ear, with the intention to restore some of the binaural hearing functions. Binaural summation, head-shadow effect and access to acoustic low-frequency information via the HA are primary underlying mechanisms for the bimodal hearing benefits (Ching et al. 2006; Berrettini et al. 2010; Veugen et al. 2016). However, research comparing bimodal and CI-alone performance has shown mixed outcomes and user benefit reports (Ching, Incerti, and Hill 2004; Dunn, Tyler, and Witt 2005; Berrettini et al. 2010; Bouccara et al. 2016; Devocht et al. 2020). Factors influencing bimodal benefit include loudness mismatch, differences in the signal-processing strategies used by CI and HA, and separate fitting of devices by different professionals at CI services and audiology departments.

Standard HAs are not specifically designed to work together with a CI. Consequently, bimodal technology users may experience temporal synchronisation difficulties and mismatch in stimulation place between the two cochleae (van Hoesel 2012; Francart and McDermott 2013). The HAs typically use multichannel fast-acting automatic gain control (AGC) whereas, the CI processors typically employ a single-channel dual-loop AGC system that incorporates both slow and fast-syllabic time-constant circuits (Vaerenberg et al. 2014; Spirrov et al. 2020). Veugen et al. (2016) assessed the effect of using a similar design of AGC in both the CI sound processor and HA to improve bimodal benefit. The parameters of CI AGC circuits were unmodified. However, the HA was programmed to have dual-action time constants approximating the dynamic properties of the CI processor and compression channels were coupled to mimic the signal-channel broadband compression in the CI

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processor. The results showed an improvement of speech perception in noise when the noise and speech were spatially separated, particularly when the noise was presented on the HA side.

Integrated bimodal technology

Sonova has developed an integrated bimodal system known as the Naida Link Bimodal system, which consists of the Advanced Bionics' Naida Q90 speech processor and Phonak Link UP HA. The two devices provide matched compression algorithms and time constants. This technology also uses a dedicated fitting formula, adaptive Phonak digital bimodal (APDB), which aligns the frequency response, loudness growth functions and AGC characteristics between the two devices. The alignment of frequency response is achieved by optimising low-frequency gain and bandwidth. Low-frequency gain is optimised by applying the model of effective audibility to ensure audibility of speech (55 dB SPL) in quiet environments (Advanced Bionics 2016). According to the audiometric profile, the gain is increased for frequencies below 1000 Hz compared to traditional HA fitting formulae, where the amplification is applied across the entire spectrum particularly in the frequency region required for speech understanding (1000–4000 Hz) (Cuda et al. 2019). Frequency bandwidth is optimised by making bandwidth as wide as possible for aidable frequencies (Neuman and Svirsky 2013), enhancing audibility of frequencies between 250 and 750 Hz, while ensuring that amplification does not extend into dead regions (Auletta et al. 2021). The loudness growth between the two devices is aligned by implementing the input-output function of the CI sound processors (compression knee point of 63 dB SPL and ratio of 12:1) in the HA. The AGC system is further aligned, in a dynamic sense, by porting the Naida CI dual loop AGC into the HA (Advanced Bionics 2016). The Naida CI processor has a single-channel dual-loop AGC system which includes both slow and fast attack-and-release time constants. To implement the latter compression system in the AGC of the HA, (1) the compression channels in the HA are coupled to mimic the single-channel compression, and (2) slow and fast time constants are applied in the HA (Vroegop et al. 2019).

Several studies (Vroegop et al. 2018; Cuda et al. 2019; Ernst et al. 2019; Vroegop et al. 2019; Holtmann et al. 2020; Warren et al. 2020; Auletta et al. 2021) assessed the benefits of integrated bimodal technology (Naida Link Bimodal system) for speech perception. Vroegop et al. (2018) measured the speech-reception threshold (SRT) in noise in both static and dynamic settings. The speech sentences were presented from the front loudspeaker placed at 0° azimuth for static conditions and randomly from either a loudspeaker at −45° or 45° for the dynamic condition. Four uncorrelated babble-noise maskers were presented from the loudspeakers placed at −45°, 45°, −135°, and 135°. There was no significant difference between using the CI only and using the CI with the Naida Link HA in static conditions. In contrast, there was a significant improvement in the SRT of 3.1 dB with integrated bimodal listening compared to the CI only in dynamic conditions. In a later study, Vroegop et al. (2019) found bimodal benefits of 1.6 dB and 2.5 dB when the noise was presented from the front, or the CI side respectively. There was no bimodal benefit when the noise was presented from the HA side. Similarly, Cuda et al. (2019) found a bimodal benefit of 3.9 dB for speech perception in noise when both the speech and noise were presented from the front speaker. Warren et al. (2020) also found a significant bimodal benefit of integrated fitting (approximately 19.2%) compared to using the CI only. However, the amount of bimodal benefit was highly variable (inter-subject variability), ranging from 1.5% to 61.4%. The results from these studies indicated that integrated bimodal technology could improve speech intelligibility in noise compared to using a CI only. However, the amount of benefit seems highly dependent on the location of the target speech and the noise masker.

Only one study has assessed the benefit of the integrated bimodal technology on localisation tasks as well as self-reported benefits using a subjective hearing-quality questionnaire (Holtmann et al. 2020). Four loudspeakers were placed at 0, 90, 180, and 270 degrees to assess the localisation performance using the Naida Link HA over the standard HA. There was no significant difference between the two HAs in localisation tests. The hearing implant sound quality index (HISQUI 19) showed a significant improvement of sound quality only at the end of the study (at 8-12 weeks after the Naida HA fitting). The Oldenburg inventory did not show any statistically significant change arising from use of the Naida Link HA.

Binaural streaming technology

Advanced Bionics' Binaural VoiceStream Technology allows the CI and HA to be linked wirelessly to stream full bandwidth audio signals for both ears in real time with short transmission delays. Different directional patterns and features are available with this technology that aim to improve speech understanding in different challenging listening situations, such as restaurants, classrooms, or when using a phone in noisy situations. This paper focuses on the most common features used for speech perception in noise, namely StereoZoom and ZoomControl.

StereoZoom

StereoZoom is a directional beamforming system (binaural beamformer) produced by wirelessly connecting the four omnidirectional microphones (two dual-microphone systems at each side, a Naida CI processor and a Naida Link HA). This feature can produce a much narrower fixed-target beam (± 45°) than is provided by a monoaural two-microphone first-order beamformer. StereoZoom allows listeners to focus on a single speaker standing directly in front of them while reducing interfering noise from the sides and back, as well as from near to the front (Advanced Bionics 2014).

Vroegop et al. (2018) assessed the benefit of using StereoZoom on the SRTs for 18 bimodal participants. A significant improvement of 4.7 dB on the SRT was found by using the StereoZoom compared to using the general set-up of the integrated bimodal technology (everyday map) in the static condition. However, the StereoZoom did not provide any significant benefit in the dynamic condition. This result indicated that the benefit of using StereoZoom is relevant only when the target speech is presented from the front. It also indicated that using the StereoZoom beamformer reduces the localisation performance as there was no improvement in the SRT in the dynamic listening condition. Therefore, activating StereoZoom for the more dynamic listening situations, such as in real-life listening environments, would be a disadvantage.

Ernst et al. (2019) measured the benefit of using StereoZoom over UltraZoom (monaural directional beamformer) and T-Mic setting (omnidirectional microphone) for bimodal CI users. They used two loudspeaker set-ups: (1) set-up A: speech fixed from front loudspeaker (0°) and the noise from loudspeakers placed at ± 60°, ± 120°, & 180°, (2) set-up B: speech fixed from front loudspeaker (0°) and the noise from loudspeakers placed at ±

30° and ± 60°. StereoZoom provided a significant benefit over the T-Mic of 4.6 dB and 2.6 dB in test set-ups A and B respectively. In addition, the StereoZoom provided an advantage of 1.3 dB (set-up A) dB and 1.2 dB (set up B) over UltraZoom. The amount of benefit seems largely dependent on the direction of the noise and the degree of separation between the target speech and the noise masker. A larger benefit can be obtained when the noise and speech are well separated.

ZoomControl

The ZoomControl feature allows the listeners to select a preferred direction that they want to listen to. They can select to focus to the right, left or back, in situations where they cannot see the speaker's face, for example when in a car. ZoomControl can switch the maximum sensitivity to the back when the listeners want to focus on speech from behind them. If the listeners want to focus on the right or left, the signal will be transmitted from one side to the other side where 75% of the direct microphone input in the non-attended side is suppressed to accommodate the transmitted signal (Advanced Bionics 2014). Holtmann et al. (2020) assessed the benefits of using the ZoomControl over the standard settings of the Naida Link HA when the speech was presented at the HA and the noise on the CI side. A significant improvement of 2.8 dB was found when enabling ZoomControl. Additionally, a considerable significant benefit (3.9 dB) was obtained when using ZoomControl compared to using a standard HA in the same test set-up. This finding indicates that ZoomControl can enhance speech understanding when the signal of interest is on the poorer hearing side and can help to overcome the effect of head shadow.

Rationale for present study

The benefits of integrated bimodal technology have been mainly assessed for speech perception with fixed speech presented from the front. There is a need to assess the benefits of this technology with test set-ups that are more representative for real-life listening situations, including roving speech in noise and speech and noise from opposite sides. Further research is also needed to determine the benefit of integrated bimodal technology for localisation and tracking. Finally, the potential benefit of using binaural streaming technology compared to the standard settings of the integrated bimodal technology has not been widely assessed and warrants further investigation.

Method

Ethics approval was granted by the University of Southampton Ethics Board (ERGO: 45969).

Participants

26 unilateral CI users with a Naida Q90 speech processor and Naida Link UP hearing aid in the non-implanted ear were recruited from University of Southampton Auditory Implant Service (see supplement for demographic information). The APDB fitting prescription was used to fit the Naida Link UP hearing aids and settings were checked ahead, within three weeks of the data collection. Participants ranged in age from 19 to 87 years (group mean age = 62 years, *SD* = 20 years). The inclusion criteria were: (1) ≥ 18 years, (2) > 6 months CI use, (3) > three months of integrated bimodal user experience with StereoZoom and ZoomControl, (4) BKB score in quiet of ≥ 50%, and (5) no cognitive or learning difficulties (as documented in the participant/CI user's records at the multi-disciplinary CI service). The participants' hearing thresholds in the non-implanted ears (tested ahead, within three weeks of the data collection) are presented in Figure 1.

Test protocol

1. Speech-in-noise tests:
   - SrN ± 60° (roving speech that was randomly presented from one of nine different loudspeakers arranged in a 180-degree arc to the front of the listener while uncorrelated multi-talker babble noise was played simultaneously from two of the loudspeakers placed at 60° to the left and right sides). This test simulates a group conversation in a noisy background.
   - S0°N ± 60° (fixed speech presented from the front in the presence of uncorrelated multi-talker babble presented simultaneously from two loudspeakers placed at 60° to the left and right sides). This test simulates a one-to-one conversation in a noisy background.
   - SHANCI (fixed speech at HA side at 90° and multi-talker babble noise at the CI side at 90°). This test simulates having a conversation with a person sat on the HA side of the CI user while there is competing noise on the CI side.
2. Spatial listening tests:
   - Localisation test using five loudspeakers with 30° separation. The stimulus is a phrase: *"Hello, what's this?"*, spoken by one of five different talkers presented at levels between 65 and 75 dB SPL with 11 roving intensity levels, and 0–10 dB of attenuation applied in 1 dB steps. Attenuation was chosen at random from trial to trial.
   - Tracking of moving sound test. Six movement trajectories of a horse galloping sound presented in a stepped manner at 65 dB SPL from an array of nine loudspeakers arranged in a 180-degree arc in front of the

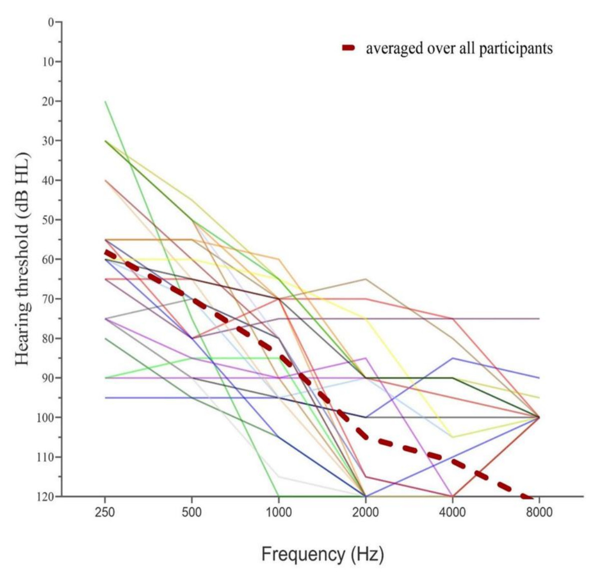

Figure 1. The unaided hearing thresholds of the individual participants for the non-implanted ear. The dashed red line displays the group mean threshold. For calculating the average, in case of "no response," the reading was given a value of 130 dB HL based on (BSA (British Society of Audiology) 2018).

listener: left-centre-right, right-centre-left, left-centre-left, right-centre-right, centre-right-centre and centre-left-centre. Each trajectory was repeated twice in a pseudo-random order.

3. The speech, spatial and qualities-of-hearing scale (SSQ) version 3.1.1 (Gatehouse and Noble 2004, Noble and Gatehouse 2004).

Apparatus

The AB-York Crescent of Sound which was developed by Kitterick et al. (2011) was used to administer the speech in noise, localisation and tracking tests. The AB-York Crescent of Sound consists of nine audio-visual stands (Plus XS.2, Canton loudspeakers) arranged in a semi-circular array with a radius of 1.45 m. Loudspeakers are placed at ± 90°, ± 60°, ± 30°, ± 15°, and 0° azimuth, where 0° is straight ahead of the listener. The axis of each loudspeaker is suspended at the height of 1.1 m. A 15" visual display unit (VDU) is placed below each loudspeaker from − 60° through to + 60°. The VDU was used to show the number of corresponding loudspeakers in the localisation test. Figure 2 shows the AB-York Crescent of Sound at the University of Southampton Auditory Implant Service.

Procedure

The testing was completed in a single session that lasted on average three hours, including short breaks of 10 min. The SSQ questionnaire was sent ahead of the time to allow participants time to think about the questions. The participants were seated on a chair in the centre of the Crescent of Sound loudspeaker array, one metre away from and facing the frontal loudspeaker which was placed at 0 degrees azimuth. A summary of listening conditions and main procedure for each test is given in Table 1. To minimise any possible order effects, the following steps were taken:

1. The order of the first two test categories (Table 1; speech-in-noise tests and spatial-listening tests) were firstly counterbalanced across participants with the SSQ always completed as the final category. In other words, the test session for half of the participants started with speech-in-noise tests, then spatial-listening tests. For other half of the participants, the test session started with spatial-listening tests followed by speech-in-noise tests
2. Within these two categories, the order of the listening conditions (device configuration) was counterbalanced using either a 3 × 3 or 2 × 2 Latin square design depending on the number of device configurations. For instance, the test session for some participants started testing them in the listening condition of using the CI only, while others started testing them when they use the CI with Naida HA or use the CI with Naida HA and binaural streaming technology (StereoZoom/ZoomControl)
3. Then the order of the sub-tests was also counterbalanced across participant for each device configuration using either a 3 × 3 or 2 × 2 Latin square design depending on the number of sub-tests (Table 1)

For the SSQ questionnaire, participants were asked to answer each question based on their experience when using: (1) the CI only, (2) the CI + their old (standard) HA, and (3) the CI + their Naida Link HA. For the latter listening condition, the

Figure 2. The AB-York Crescent of Sound at the University of Southampton Auditory Implant Service.

Table 1. Summary of the main procedures and the listening conditions for CI participants using the Naida Link HA.

Test category	Sub-test	Listening conditions	Head movement
Speech-in-noise tests	SrN ± 60°	1. CI only 2. CI + Naida Link HA	Allowed
	S0°N ± 60°	1. CI only 2. CI + Naida Link HA 3. CI + Naida Link HA + StereoZoom	Fixed facing the front loudspeaker
	ShaNci	1. CI only 2. CI + Naida Link HA 3. CI + Naida Link HA + ZoomControl	Fixed facing the front loudspeaker
Spatial-listening tests	Localisation	1. CI only 2. CI + Naida Link HA	Fixed facing the front loudspeaker
	Tracking	1. CI only 2. CI + Naida Link HA	Allowed
CI user experience	SSQ questionnaire	1. CI only 2. CI + standard HA 3. CI + Naida Link HA	–

CI: cochlear implant; HA: hearing aid; N: noise; r: roving; S: speech; SSQ: speech; spatial and qualities-of-hearing scale.

participants were asked to answer the questions based on their overall experience with the integrated bimodal technology, without any relation to specific settings or features (i.e. ZoomControl, StereoZoom, etc).

Results

Speech in noise tests

Figure 3 shows the SRTs of the integrated bimodal participants in the three speech in noise tests for different listening conditions (Cl alone, CI + Naida Link HA, and CI + Naida Link HA + binaural streaming feature).

A paired-samples *t*-test was used (no Bonferroni correction was applied) to determine whether there was a statistically significant mean difference between the two listening conditions (CI only vs. CI + Naida Link HA) in the SrN ± 60° test. The SRT was lower (better) in the listening condition of using CI + Naida HA (8.1 dB SNR ± 2.9) as opposed to when using the CI only (9.4 dB SNR ± 3.1). The results showed a statistically significantly difference: $t(25)=2.7$, $p < 0.05$, $d = 0.5$.

For the S0°N ± 60° and ShaNci tests, a one-way repeated measures ANOVA test was carried out for each test separately to determine whether there was an overall effect of listening conditions: (1) Cl only, (2) CI + Naida Link HA, and (3) CI + Naida Link HA + binaural Streaming technology (StereoZoom/ZoomControl). For all ANOVAs undertaken, Greenhouse-Geisser corrections were applied where assumptions of sphericity were violated.

In the S0°N ± 60° test, there was a significant overall effect of listening condition: $F(2, 50)=17.1$, $p < 0.01$. *Post hoc* analysis indicated that all three conditions were statistically significantly different from each other. For the ShaNci test, there was an overall effect of listening condition, $F(1.6,40.8)=62.6$, $p < 0.001$. Post hoc analysis indicated that all three conditions were statistically significantly different from each other. The mean difference and the 95% confidence intervals between the different listening conditions for each test are shown in Table 2, which shows an improvement with the integrated bimodal and binaural streaming technology.

Spatial-listening tests

The mean performance on the sound-localisation test (30° separation) for the integrated bimodal participants in the two listening conditions, (1) CI only and (2) CI + Naida Link HA, is shown in Figure 4 (left panel). The chance range for randomly guessing

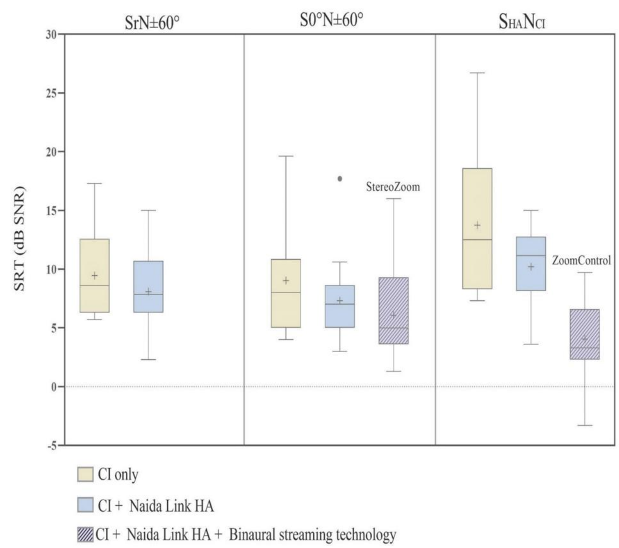

Figure 3. Box plots representing the SRTs in dB SNR for the three listening conditions: (1) Cl only, (2) CI + Naida Link HA + binaural streaming technology OFF, and (3) CI + Naida Link HA + binaural streaming technology ON in SrN ± 60° (left), S0°N ± 60° (middle), and ShaNci (right) tests. The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean. The outliers are plotted as solid circles. Lower SRTs indicate better performance could add. $N = 26$.

was calculated using the "Monte-Carlo" simulation method in the MATLAB (version R2019a) software indicating the mean percentage correct of the chance range of random guessing is 20%. Performance when using the CI only was close to chance (mean = 21.4%, $SD = 7.8$). However, the performance was higher than chance in the integrated bimodal condition (mean = 33.7%, $SD = 10.1$). Paired-sample *t*-tests showed that localisation accuracy was significantly higher in the bimodal condition by 12.3% (95% confidence interval, 7.6–17) compared to using the CI-only condition (t (25)=5.4, $p < 0.001$).

The right panel in Figure 4 shows mean performance on tracking moving sounds in the two listening conditions, (1) CI only and (2) CI + Naida Link HA. The chance range was calculated using binomial distribution with $n = 12$ trials, each with a chance success rate of 0.167 indicating the mean percentage correct of the chance range of random guessing is 16%. Mean performance when using the CI only was within the chance range (mean = 17.9%, $SD = 15.4$). Although there was considerable variability in the performance among the participants when using the Naida

Table 2. Mean difference (95% confidence intervals) between the listening conditions for the SrN ± 60°, S0°N ± 60° and SHANCI tests.

Test	Mean difference (95 % confidence interval)
SrN ± 60°	(CI + Naida Link HA) - CI only = −1.4 db (−2.4 to 0.3)
S0°N ± 60°	(CI + Naida Link HA) - CI only= − 1.7 dB (−2.8 to −0.6)
	(CI + Naida Link HA + StereoZoom) − (CI + Naida Link HA) = −1.2 dB (−2.3 to −0.2)
SHANCI	(CI + Naida Link HA) - CI only = −3.5 dB (−5.5 to −1.5)
	(CI + Naida Link HA + ZoomControl) − (CI + Naida Link HA) = − 6.1 dB (−7.5 to −4.8)

CI: cochlear implant; HA: hearing aid; N: noise; r: roving; S: speech.

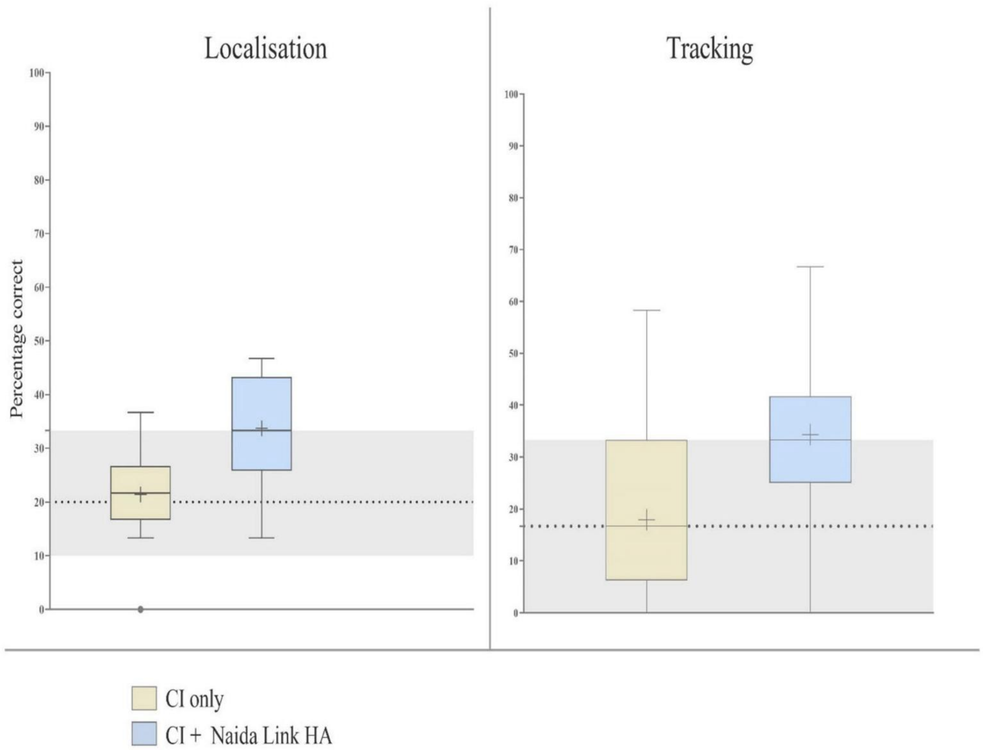

Figure 4. Results of the localisation (left-hand panel) and tracking test (right-hand panel) for the adult CI participants in the listening condition of using the CI only (yellow box plots) and in the listening condition of CI + Naida Link HA (blue box plots). The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean. The dashed horizontal line shows the level of performance expected by chance, with the grey shaded area showing the 5th and 95th percentiles of the chance range. The outliers are plotted as solid circles. $N = 26$.

Link HA with CI, the mean performance was higher than chance (mean = 34.3%, $SD = 15.6$). Paired-sample t-tests showed that the difference between the two listening conditions was statistically significantly different ($t(25) = 4.5$, $p < 0.001$). The tracking of moving sounds was better in the bimodal condition than when using one CI by 16.4% (95% confidence interval, 8.9–23.9).

SSQ

Only complete questionnaires for the three listening conditions were included in the analysis ($n = 20$; 77%). Figure 5 shows the self-rated scores on the overall SSQ and each of the three subscales for the integrated bimodal participants in the three listening conditions.

A two-way repeated measures ANOVA test was performed, with the listening condition and type of subscale as the independent variables. The main effect of listening condition was statistically significant ($F(2,38)=19.6$, $p < 0.001$). *Post hoc* tests revealed that scores were statistically significantly higher when using CI with a Naida Link HA compared to using CI alone ($p < 0.001$) and to CI with the standard HA ($p < 0.001$). The tests also showed that there was no statistically significant difference in the scores of the listening conditions of using CI with the standard HA and using CI alone ($p = 0.3$). The main effect of the type of subscale was statistically significant ($F(2,38)=22.4$, $p<.001$). *Post hoc* tests revealed that the scores for spatial subscales were significantly lower than that for the speech ($p = 0.001$) and qualities subscale ($p < 0.001$). The tests also showed that the scores for qualities of hearing were significantly higher than that for the speech ($p = 0.021$) and spatial subscale ($p < 0.001$) scores. The interaction between listening condition and subscale was not statistically significant, $F(2.9, 54.9)=1.2$, $p = 0.3$.

Correlation between unaided hearing thresholds of the non-implanted ear and integrated bimodal technology

The relationship between the unaided hearing thresholds of the non-implanted ear and the performance scores of the participants when using the Naida Link HA was examined, based on the hypothesis that residual hearing acuity might account for inter-subject variance in bimodal benefit. The data of all 26 participants were included in the correlation analysis, except for the

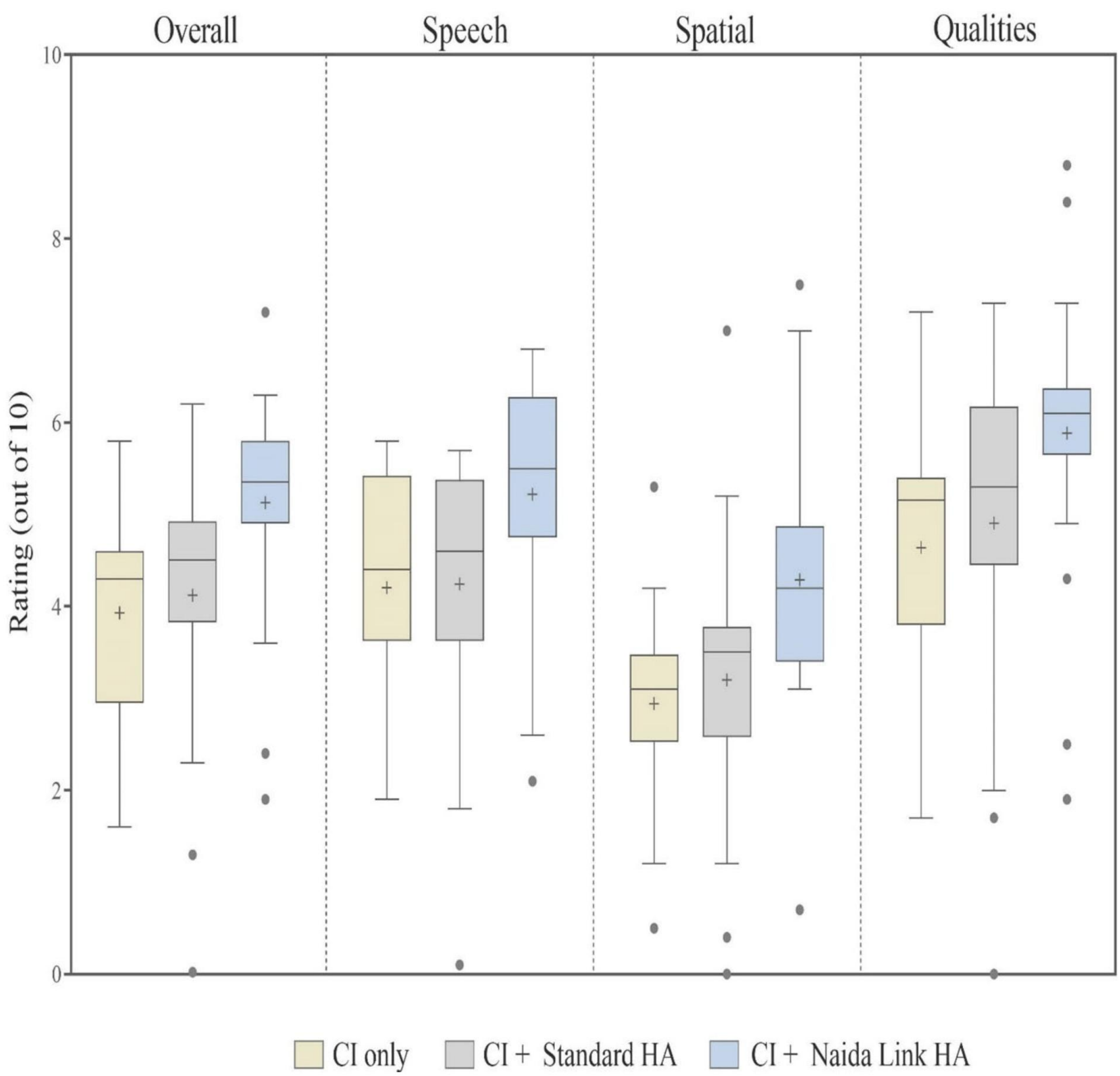

Figure 5. Scores on the overall SSQ and each of the three subscales: speech, spatial and qualities of the listening conditions: (1) the CI alone (yellow box plots), (2) CI + previous standard HA (grey box plots), and (3) CI + Naida Link HA (blue box plots). The boxes represent the two middle quartiles. The solid horizontal lines within each box indicate the median; the cross inside the box shows the mean. The outliers are plotted as solid circles. $N = 20$.

SSQ, where data on 24 participants who completed the questionnaire for the listening condition of CI + Naida Link HA were included. Pearson correlation analysis was used, with different combinations of hearing thresholds applied as predictor variables (250 Hz, 500 Hz, 1000 Hz, 250–500 Hz average, or 500–1000–2000 Hz average of the non-implanted ear); however, this failed to show any significant associations between hearing thresholds and results of any of the performance tests using the CI + Naida Link condition, or SSQ questionnaire (as shown in Table 3). It should be noted that the scores of the performance tests included in the analysis were presented as:

1. Average scores of the three speech-in-noise tests on the best-aided condition. The average scores of the speech-in-noise tests were calculated by taking the average scores of the three tests: (1) SrN ± 60° in CI + Naida Link HA condition, (2) S0°N ± 60° in CI + Naida Link HA + StereoZoom condition and (3) ShaNci in CI + Naida Link HA + ZoomControl condition.
2. Average performance scores of the spatial-hearing tests (localisation and tracking).
3. Rating scores of the overall SSQ.

Discussion

The first aim of this study was to compare the outcomes of the integrated bimodal technology (Naida Q90 CI processor and Phonak Link UP HA) to using the CI alone using a test battery with tests that are more representative for real-life listening situations as opposed to only using standard speech tests. The results showed a significant bimodal benefit on improving speech perception with the integrated bimodal technology. Mixed outcomes of the standard bimodal technology have been reported in the literature. Some studies reported a significant benefit with bimodal hearing (as in Flynn and Schmidtke 2004; Ching et al. 2006; Gifford et al. 2007; Dorman et al. 2008; Berrettini et al. 2010, Devocht et al. 2017), while other studies showed non-

Table 3. Results of correlation analyses, *r* values (95% confidence interval), between the unaided thresholds of non-implanted and the performances scores when using the CI with the Naida Link HA (*$n = 24$).

Performance test	PTA (500–1000–2000 Hz)	PTA (250–500 Hz)	1000 Hz	500 Hz	250 Hz
Average speech tests with best aided condition	−0.1 (−0.4 to 0.3)	−0.1 (−0.5 to 0.3)	−0.1 (−0.5 to 0.3)	−0.1 (−0.5 to 0.3)	−0.1 (−0.5 to 0.3)
Average spatial tests	−0.1 (−0.5 to 0.3)	0.2 (−0.2 to 0.5)	−0.2 (−0.5 to 0.2)	0.1 (−0.3 to 0.4)	0.3 (−0.1 to 0.6)
SSQ overall*	0.1 (−0.3 to 0.5)	0.4 (−0.1 to 0.7)	0.1 (−0.3 to 0.5)	0.4 (−0.01 to 0.7)	0.3 (−0.1 to 0.6)

CI: cochlear implant; HA: hearing aid; PTA: pure tone average; SSQ: speech, spatial and qualities-of-hearing scale.

significant benefits or a decrement in the performance compared to CI alone (as in Tyler et al. 2002; Dunn, Tyler, and Witt 2005; Morera et al. 2005; Mok et al. 2006; Pyschny et al. 2011; Bouccara et al. 2016).

The largest benefit of the integrated bimodal technology in the current study was 3.5 dB, found when the noise was presented on the CI side and the speech on the HA side. This is similar to the findings of Vroegop et al. (2019) who reported their largest bimodal benefit (2.5 dB) when using the Naida Link HA with the noise presented at the CI and the speech from the front compared to other test set-ups in their study. Likewise, Spirrov et al. (2020) found their largest bimodal benefit of 4.4 dB with the matched AGC between the CI and HA when the noise was on the CI side compared to when the noise was presented from the front, or on the HA side. It should be noted that Spirrov et al. (2020) used a Nucleus 6 processor from Cochlear (Sydney, Australia) and an Enzo 3D HA from GN hearing (Copenhagen, Denmark) in their study.

In the test condition using fixed speech from the front and diffuse noise from the two loudspeakers placed at ± 60°, the bimodal benefit was 1.7 dB which is comparable to the 1.6 dB benefit found by Vroegop et al. (2019), when the speech and noise were presented from the front. Cuda et al. (2019) also reported a significant bimodal benefit when the speech and noise were presented from the front; however the amount of the benefit (3.9 dB) was larger than those found in the current study and in the one by Vroegop et al. (2019). The finding in the current study is in line with Warren et al. (2020) who found a significant improvement in the speech perception with using the CI and Naida Link HA compared to using the CI only when the speech and noise were presented from the front.

The smallest significant bimodal benefit in the present study was 1.4 dB, found in the test of roving speech in uncorrelated multi-talker noise presented from the two loudspeakers at 60°. This study used roving speech that can be presented randomly from an array of nine loudspeakers placed at ± 90°, ± 60°, ± 30°, ± 15°, and 0° azimuth. This test set-up simulates one of the common listening situations in real life where the listener is sitting around a table with a group of people with background noise present. However, this set-up might have been challenging to the CI users as they needed first to locate where the speech was coming from and then spontaneously turn their heads and focus on the target sentence. Although the participants were not asked to identify the direction of the speech during the test trial, it was challenging for them to adapt to speech that was not presented from a fixed location. This could explain the smallest bimodal benefit found for this test set-up. Few studies have previously used roving target speech set-ups with adult CI users who were using the integrated bimodal technology. Vroegop et al. (2018) used speech randomly presented from two loudspeakers placed at + 45° and − 45°, with a babble noise presented from four loudspeakers placed at ± 45° and ± 135°. They found a bimodal benefit of 3.1 dB using the Naida Link HA, better than the benefit found with roving speech in the current study. The discrepancy might be related to the number of loudspeakers used to present the speech in the Vroegop et al. (2018) study with only two loudspeakers, as against nine loudspeakers been used in the current study.

The findings from the present study show that using integrated bimodal technology significantly improved the speech perception in noise. However, the amount of bimodal benefit seems largely dependent on the direction of the noise and speech as the improvement in the SRT in dB SNR ranged from 1.4 dB to 3.5 dB depending on the test set-up. This is likely to be as a result of the better-ear effect particularly when the speech target is at the CI side.

The localisation and tracking tests showed significant improvement when using integrated bimodal technology compared to using the CI only. Although the improvement was statistically significant, more than half of the participants still performed close to or within the chance range. The single published study assessed the performance of CI users when using a Naida Link HA compared to the standard HA (Holtmann et al. 2020). The test set-up consisted of four loudspeakers placed at 0°, ± 90°, and 180°. Their results did not show a significant difference between the Naida Link HA and the standard HA in the localisation test. These findings suggest that benefits of integrated bimodal technology in the domain of localisation have not been established as clearly as for speech perception in noise.

The self-rated scores on the SSQ were significantly higher when using the integrated bimodal technology compared to using the CI only and also to using the CI with the participants' previous standard HA. The mean rating of the overall SSQ score using the Naida Link HA was about 5.1 points which is at the mid-range scoring scale suggesting an improvement in the hearing skills needed for everyday functions; however, difficulties can remain. This finding was in line with Vroegop et al. (2018) who found an overall rating score of the SSQ of about 5.2 and 5.4 points for using the Naida Link HA when programmed with the APDB and NAL-NL2 formulae respectively. A similar finding was reported by Holtmann et al. (2020) where there was a significant improvement in the hearing implant sound quality index (HISQUI) − 19 at the 8–12 week assessment post-fitting when using the Naida Link HA over the standard HA. However, apparent benefit of integrated bimodal technology over the standard HA should be treated with caution as the validity of rated scores for the listening condition of using the standard HA might be affected by the participants' memory, e.g. some participants always use the Naida link HA which makes it hard for them to remember what the standard HA was like in the past.

The second aim of this study was to assess whether using binaural streaming technology would add a further improvement compared to the standard settings of integrated bimodal technology. Additional benefit of 1.2 and 6.1 dB were found by enabling the StereoZoom and ZoomControl features respectively. The significant benefit of the StereoZoom in this study was smaller than the benefit found in previous studies. Vroegop et al. (2018) found a benefit of 4.7 dB when the speech was presented from the front and the noise from the loudspeakers was at ± 45° and ± 135°. Similarly, StereoZoom benefits of 4.6 and 2.6 dB over the standard settings (using T mic) were found by Ernst et al. (2019) in test set-ups A (S0° N ± 60°, ± 120°, & 180°) and B (S0°N ± 30° & ± 60°) respectively. These studies used similar and narrower degrees of separation between the noise and the target speech compared to the current study. The reason for this discrepancy is unclear. However, it could be attributed to a random error given the 95% confidence interval estimate reported in Table 2.

To the best of the researchers' knowledge, there is only one recent published study that assessed the benefit of ZoomControl for CI users with integrated bimodal technology (Holtmann et al. 2020). They found a significant improvement when first enabling ZoomControl. They also found a further improvement following 12 weeks of acclimatisation: median SRTs at + 0.97 dB with the standard settings of a Naida Link HA compared −1.8 dB with ZoomControl activated. Although they used a similar test set-up (ShaNci), the ZoomControl benefit found in the present study is relatively larger than the benefit found by Holtmann et al. (2020). The SRTs for all the participants in the current study improved by at least 1.3 dB, with the largest improvement being 12.3 dB. The benefit of ZoomControl for the participants in this study probably resulted from the head-shadow effect that results in a level difference between the two ears (Veugen et al. 2017) and the better ear effect, particularly when the speech is at the CI side as a result of the dominance of the CI in speech understanding. Another reason is the 12 dB reduction at the microphone of the CI sound processor when ZoomControl is activated.

For future work, it would be useful to compare the integrated bimodal technology to bilateral CI. Conducting such a comparison would provide a better understanding of whether the integrated bimodal technology can offer comparable benefits to bilateral CI, particularly in spatial listening as a result of matching signal processing between devices. Future research using a test battery that includes more representative real-life tests is advised. Lastly, it is recommended that this research be extended to look at CI user outcomes with the newer and recently launched Naida Link Marvel integrated bimodal and bilateral technology. The Marvel CI sound processor's technology, comprises an automated operating system that adapts to the listener's surroundings, blending multiple features to create distinct settings for the user's unique listening environment.

Conclusion

Integrated bimodal technology outcomes were significantly better than for the CI alone, as shown in improved performance on a test battery that integrated tasks that are more representative of real-life listening, particularly for speech understanding in noise where the target speech and noise masker were spatially separated. Improved performance was also found for localisation and tracking, despite considerable variation noted among the users. Finally, binaural streaming technology can provide an additional improvement for speech understanding in noise above that offered by integrated bimodal technology. Further research comparing integrated bimodal and bilateral CI fitting outcomes on a real-life test battery is recommended.

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Authors contributions

First author**:** Data collection, analysis of data and writing of first draft. Second author: Conceptualisation of study, oversaw data collection, contributed to analysis and writing. Third author: Oversaw analysis and contributed to writing. Fourth author: Contributed to writing.

Ethical approval

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References

Advanced Bionics. 2014. "*Binaural VoiceStream Technology: Improving speech understanding in challenging listening environments*." (Advanced Bionics AG and affiliates).

Advanced Bionics. 2016. "*Optimizing Hearing for Listeners with a Cochlear Implant and Contralateral Hearing Aid: Adaptive Phonak Digital Bimodal Fitting Formula*." (Advanced Bionics AG and affiliates).

Auletta, G., A. Franzè, C. Laria, C. Piccolo, C. Papa, P. Riccardi, D. Pisani, A. Sarnelli, V. Del Vecchio, R. Malesci, et al. 2021. "Integrated Bimodal Fitting for Unilateral CI Users with Residual Contralateral Hearing." *Audiology Research* 11 (2):200–206. https://doi.org/10.3390/audiolres11020018.

Berrettini, S., S. Passetti, M. Giannarelli, and F. Forli. 2010. "Benefit from Bimodal Hearing in a Group of Prelingually Deafened Adult Cochlear Implant Users." *American Journal of Otolaryngology* 31 (5):332–338. https://www.ncbi.nlm.nih.gov/pubmed/20015774. https://doi.org/10.1016/j.amjoto.2009.04.002.

Bouccara, D., E. Blanchet, P. E. Waterlot, M. Smadja, B. Frachet, B. Meyer, and O. Sterkers. 2016. "Benefit of Contralateral Hearing Aid in Adult Cochlear Implant Bearers." *European Annals of Otorhinolaryngology, Head and Neck Diseases* 133 (3):161–165. https://www.ncbi.nlm.nih.gov/pubmed/26679231. https://doi.org/10.1016/j.anorl.2015.11.002.

Bronkhorst, A. W., and R. Plomp. 1989. "Binaural Speech Intelligibility in Noise for Hearing-Impaired Listeners." *The Journal of the Acoustical Society of America* 86 (4):1374–1383. https://doi.org/10.1121/1.398697.

BSA (British Society of Audiology) Professional Practice Committee. 2018. "*Recommended Procedure: Pure-Tone Air-Conduction and Bone conduction Threshold Audiometry with and without Masking*". British Society of Audiology. https://www.thebsa.org.uk/wp-content/uploads/2023/10/OD10

4-32-Recommended-Procedure-Pure-Tone-Audiometry-August-2018-FINAL-1.pdf.
Byrne, D., W. Noble, and B. LePage. 1992. "Effects of Long-Term Bilateral and Unilateral Fitting of Different Hearing Aid Types on the Ability to Locate Sounds." *Journal of the American Academy of Audiology* 3 (6):369–382.
Ching, T. Y. C., P. Incerti, and M. Hill. 2004. "Binaural Benefits for Adults Who Use Hearing Aids and Cochlear Implants in Opposite Ears." *Ear and Hearing* 25 (1):9–21. https://doi.org/10.1097/01.aud.0000111261.84611.c8.
Ching, T. Y., P. Incerti, M. Hill, and E. van Wanrooy. 2006. "An Overview of Binaural Advantages for Children and Adults Who Use Binaural/Bimodal Hearing Devices." *Audiology & Neuro-Otology* 11 Suppl 1 (Suppl 1):6–11. https://www.ncbi.nlm.nih.gov/pubmed/17063004. https://www.karger.com/Article/Pdf/95607. https://doi.org/10.1159/000095607.
Cuda, D., A. Murri, A. Mainardi, and J. Chalupper. 2019. "Effectiveness and Efficiency of a Dedicated Bimodal Fitting Formula." *Audiology Research* 9 (1):219. https://doi.org/10.4081/audiores.2019.219.
Devocht, E. M. J., A. M. L. Janssen, J. Chalupper, R. J. Stokroos, and E. L. J. George. 2017. "The Benefits of Bimodal Aiding on Extended Dimensions of Speech Perception: Intelligibility, Listening Effort, and Sound Quality." *Trends in Hearing* 21:2331216517727900. https://doi.org/10.1177/2331216517727900.
Devocht, E. M. J., A. M. L. Janssen, J. Chalupper, R. J. Stokroos, H. Kingma, and E. L. J. George. 2020. "Self-assessment of Unilateral and Bimodal Cochlear Implant Experiences in Daily Life." *PloS One* 15 (12):e0242871. https://doi.org/10.1371/journal.pone.0242871.
Dorman, M. F., R. H. Gifford, A. J. Spahr, and S. A. McKarns. 2008. "The Benefits of Combining Acoustic and Electric Stimulation for the Recognition of Speech, Voice and Melodies." *Audiology & Neuro-Otology* 13 (2):105–112. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3559130/pdf/nihms338427.pdf. https://doi.org/10.1159/000111782.
Dunn, C. C., R. S. Tyler, and S. A. Witt. 2005. "Benefit of Wearing a Hearing Aid on the Unimplanted Ear in Adult Users of a Cochlear Implant." *Journal of Speech, Language, and Hearing Research: JSLHR* 48 (3):668–680. https://doi.org/10.1044/0192-4388(2005/046.
Ernst, A., K. Anton, M. Brendel, and R.-D. Battmer. 2019. "Benefit of Directional Microphones for Unilateral, Bilateral and Bimodal Cochlear Implant Users." *Cochlear Implants International* 20 (3):147–157. https://doi.org/10.1080/14670100.2019.1578911.
Flynn, M. C., and T. Schmidtke. 2004. "Benefits of Bimodal Stimulation for Adults with a Cochlear Implant". *International Congress Series* 1273:227–230. https://doi.org/10.1016/j.ics.2004.08.040.
Francart, T., and H. J. McDermott. 2013. "Psychophysics, Fitting, and Signal Processing for Combined Hearing Aid and Cochlear Implant Stimulation." *Ear and Hearing* 34 (6):685–700. https://doi.org/10.1097/AUD.0b013e31829d14cb.
Gatehouse, S., and W. Noble. 2004. "The Speech, Spatial and Qualities of Hearing Scale (SSQ)." *International Journal of Audiology* 43 (2):85–99. https://doi.org/10.1080/14992020400050014.
Gifford, R. H., M. F. Dorman, S. McKarns, and A. J. Spahr. 2007. "Combined Electric and Contralateral Acoustic Hearing: Word and Sentence Recognition with Bimodal Hearing." *Journal of Speech, Language, and Hearing Research: JSLHR* 50 (4):835–843. https://doi.org/10.1044/1092-4388(2007/058.
Holtmann, L. C., A. Janosi, H. Bagus, T. Scholz, S. Lang, D. Arweiler-Harbeck, and S. Hans. 2020. "Aligning Hearing Aid and Cochlear Implant Improves Hearing Outcome in Bimodal Cochlear Implant Users." *Otology & Neurotology: Official Publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology* 41 (10):1350–1356. https://doi.org/10.1097/MAO.0000000000002796.
Kitterick, P. T., R. E. S. Lovett, A. M. Goman, and A. Q. Summerfield. 2011. "The AB-York Crescent of Sound: An Apparatus for Assessing Spatial-Listening Skills in Children and Adults." *Cochlear Implants International* 12 (3):164–169. https://doi.org/10.1179/146701011x13049348987832.
Mok, M., D. Grayden, R. C. Dowell, and D. Lawrence. 2006. "Speech Perception for Adults Who Use Hearing Aids in Conjunction With Cochlear Implants in Opposite Ears." *Journal of Speech, Language, and Hearing Research: JSLHR* 49 (2):338–351. https://doi.org/10.1044/1092-4388(2006/027).
Morera, C., M. Manrique, A. Ramos, L. Garcia-Ibanez, L. Cavalle, A. Huarte, C. Castillo, and E. Estrada. 2005. "Advantages of Binaural Hearing Provided Through Bimodal Stimulation Via a Cochlear Implant and a Conventional Hearing Aid: A 6-Month Comparative Study." *Acta Oto-Laryngologica* 125 (6):596–606. https://www.ncbi.nlm.nih.gov/pubmed/16076708. https://doi.org/10.1080/00016480510027493.
Neuman, A. C., and M. A. Svirsky. 2013. "Effect of Hearing Aid Bandwidth on Speech Recognition Performance of Listeners Using a Cochlear Implant and Contralateral Hearing Aid (Bimodal Hearing)." *Ear and Hearing* 34 (5):553–561. https://doi.org/10.1097/AUD.0b013e31828e86e8.
Noble, W., and S. Gatehouse. 2004. "Interaural Asymmetry of Hearing Loss, Speech, Spatial and Qualities of Hearing Scale (SSQ) Disabilities, and Handicap." *International Journal of Audiology* 43 (2):100–114. https://doi.org/10.1080/14992020400050015.
Pyschny, V., M. Landwehr, M. Hahn, M. Walger, H. von Wedel, and H. Meister. 2011. "Bimodal Hearing and Speech Perception with a Competing Talker." *Journal of Speech, Language, and Hearing Research: JSLHR* 54 (5):1400–1415. https://doi.org/10.1044/1092-4388(2011/10-0210).
Spirrov, D., E. Kludt, E. Verschueren, A. Büchner, and T. Francart. 2020. "Effect of (Mis)Matched Compression Speed on Speech Recognition in Bimodal Listeners." *Trends in Hearing* 24:2331216520948974. https://doi.org/10.1177/2331216520948974.
Tyler, R. S., A. J. Parkinson, B. S. Wilson, S. Witt, J. P. Preece, and W. Noble. 2002. "Patients Utilizing a Hearing Aid and a Cochlear Implant: Speech Perception and Localization." *Ear and Hearing* 23 (2):98–105. https://doi.org/10.1097/00003446-200204000-00003.
Vaerenberg, B., C. Smits, G. De Ceulaer, E. Zir, S. Harman, N. Jaspers, Y. Tam, M. Dillon, T. Wesarg, D. Martin-Bonniot, et al. 2014. "Cochlear Implant Programming: A Global Survey on the State of the Art." *The Scientific World Journal* 2014:1–12. https://doi.org/10.1155/2014/501738.
van Hoesel, R. J. M. 2012. "Contrasting Benefits from Contralateral Implants and Hearing Aids in Cochlear Implant Users." *Hearing Research* 288 (1–2):100–113. https://doi.org/10.1016/j.heares.2011.11.014.
Veugen, L. C., J. Chalupper, A. F. Snik, A. J. Opstal, and L. H. Mens. 2016. "Matching Automatic Gain Control Across Devices in Bimodal Cochlear Implant Users." *Ear and Hearing* 37 (3):260–270. https://www.ncbi.nlm.nih.gov/pubmed/26656192. https://doi.org/10.1097/AUD.0000000000000260.
Veugen, L. C. E., J. Chalupper, L. H. M. Mens, A. F. M. Snik, and A. J. van Opstal. 2017. "Effect of Extreme Adaptive Frequency Compression in Bimodal Listeners on Sound Localization and Speech Perception." *Cochlear Implants International* 18 (5):266–277. https://doi.org/10.1080/14670100.2017.1353762.
Vroegop, J. L., N. C. Homans, A. Goedegebure, J. G. Dingemanse, T. van Immerzeel, and M. P. van der Schroeff. 2018. "The Effect of Binaural Beamforming Technology on Speech Intelligibility in Bimodal Cochlear Implant Recipients." *Audiology & Neuro-Otology* 23 (1):32–38. https://doi.org/10.1159/000487749.
Vroegop, J. L., N. C. Homans, M. P. van der Schroeff, and A. Goedegebure. 2019. "Comparing Two Hearing Aid Fitting Algorithms for Bimodal Cochlear Implant Users." *Ear and Hearing* 40 (1):98–106. https://doi.org/10.1097/AUD.0000000000000597.
Warren, S. E., M. Noelle Dunbar, C. Bosworth, and S. Agrawal. 2020. "Evaluation of a Novel Bimodal Fitting Formula in Advanced Bionics Cochlear Implant Recipients." *Cochlear Implants International* 21 (6):323–337. https://doi.org/10.1080/14670100.2020.1787622.