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Are There Real-world Benefits to Bimodal Listening?

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Abstract

Objective: To assess the benefits of bimodal listening (i.e., addition of contralateral hearing aid) for cochlear implant (CI) users on real-world tasks involving high-talker variability speech materials, environmental sounds, and self-reported quality of life (quality of hearing) in listeners' own best-aided conditions.

Study Design: Cross-sectional study between groups.

Setting: Outpatient hearing clinic.

Patients: Fifty experienced adult CI users divided into groups based on normal daily listening conditions (i.e., best-aided conditions): unilateral CI (CI), unilateral CI with contralateral HA (bimodal listening; CIHA), or bilateral CI (CICI).

Intervention: Task-specific measures of speech recognition with low (Harvard Standard Sentences) and high (Perceptually Robust English Sentence Test Open-set corpus) talker variability, environmental sound recognition (Familiar Environmental Sounds Test-Identification), and hearing-related quality of life (Nijmegen Cochlear Implant Questionnaire).

Main Outcome Measures: Test group differences among CI, CIHA, and CICI conditions.

Results: No group effect was observed for speech recognition with low or high-talker variability, or hearing-related quality of life. Bimodal listeners demonstrated a benefit in environmental sound recognition compared with unilateral CI listeners, with a trend of greater benefit than the bilateral CI group. There was also a visual trend for benefit on high-talker variability speech recognition.

Conclusions: Findings provide evidence that bimodal listeners demonstrate stronger environmental sound recognition compared with unilateral CI listeners, and support the idea that there are additional advantages to bimodal listening after implantation other than speech recognition measures, which are at risk of being lost if considering bilateral implantation.

Keywords

Bimodal hearing; Cochlear implant; Environmental sounds recognition; Low-frequency hearing

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The most recent National Health Interview Survey found that 15% of adults in the United States have hearing impairments, and approximately 750,000 people have severe-to-profound sensorineural hearing loss that may warrant cochlear implantation (1,2). Traditionally, cochlear implant (CI) candidates needed to be essentially deaf, with severe-to-profound hearing loss and no open-set speech recognition, even in quiet. In 2005, the Centers for Medicare and Medicaid Services expanded indications for cochlear implantation to include individuals with aided sentence recognition scores up to 40% correct and moderate-to-profound sensorineural hearing loss, and even more lax criteria are often accepted by private insurance companies (3). This broadening of CI candidacy has afforded more access to cochlear implantation for people with greater degrees of residual hearing in one or both ears.

Bimodal hearing describes when patients with aidable residual low-frequency hearing in the contralateral ear after cochlear implantation wear a hearing aid (HA) in the contralateral ear. In a large prospective study examining characteristics of CI candidates, up to 85% of CI candidates have contralateral residual hearing that might benefit from a HA (3,4). While residual low-frequency hearing alone is often inadequate to support high levels of speech perception, acoustical stimulation of residual hearing in the ear contralateral to a CI can have other significant benefits discussed in detail below (5–14). Further support for the benefits of additional low-frequency information comes from an entire body of research on electric-acoustic stimulation, which has shown a benefit in speech perception accuracy and sound quality with stimulation of residual acoustic hearing with a HA in the same ear as a shorter-electrode CI (15–17).

Compared with CI-only listening, the benefits of bimodal hearing can generally be divided into two categories. The first relates to the “binaural benefits” from receiving sound into two ears, such as localization, as well as benefits to recognizing speech in spatially separated noise from the head shadow effect, binaural summation, and binaural squelch (for summary see (18,19)). The second category of bimodal benefits relates to “low-frequency benefits,” supported by the additional information within low frequencies provided by acoustically stimulating the residual hearing through a HA, which will be the focus of this study.

Most of the research studies on bimodal benefits in CI users have examined speech perception, typically comparing performance in the bimodal (CI plus HA) versus CI-only condition within the same listener. In principle, bimodal listening might be expected to provide a benefit to speech perception even in quiet conditions, as a result of improved transmission of the low-frequency components of speech (8). However, findings have been inconclusive as to whether or not bimodal stimulation has benefits for speech perception in quiet, with some reports demonstrating significant bimodal benefit (7,9,10,12,13,20) and others finding no or minimal effect (5,7–9,14,21–24). One report even suggested that CI use with a contralateral HA may lead to interference in speech recognition in quiet (25).

Despite contradictory findings regarding basic speech perception abilities in quiet, it is likely that a bimodal benefit would be observed on certain “real-world” listening measures. For example, bimodal stimulation has consistently been shown to improve speech perception in multitalker babble compared with CI-only stimulation. This has been demonstrated both in

simulation studies using degraded speech (26–32) and in actual bimodal CI users tested using within-subjects study designs (5,6,8–10,12–14,18,20,27,33,34). One of the leading explanations for bimodal speech in noise benefits argues that increased access to the temporal fine structure of speech, such as variations in fundamental frequency (F0), allows the listener to “glimpse” the sound stream coming from the target talker and thus distinguish it from the noise (29,32,35). Likewise, low-frequency benefits of bimodal stimulation over CI-only listening include better perception of voice pitch, which allow bimodal listeners to distinguish different talkers (36) and recognize speech prosody (i.e., the pattern, rhythm, syllable stress, and word emphasis) intonation, and emotion (37,38).

Another potential area of bimodal “low-frequency” benefit could be environmental sound recognition. It has been demonstrated that CI listeners generally perform poorly on recognition of environmental sounds (39–42). This poor performance may be partially due to a lack of transmission of important low-frequency spectro-temporal cues through the CI, which might be more accessible to bimodal listeners (39,40).

Other bimodal advantages include improved reported sound quality and music perception (6,14,31,43–48). Similarly, bimodal hearing may improve patient-reported quality of life as a result of more natural sounding speech and reduced listening effort (49,50), as well as subjective functional improvements in real life situations (31,48,51). However, some authors have noted that these subjective benefits may be even greater with bilateral implantation (50,51).

A limitation of previous within-subjects study designs, in which bimodal listeners are tested in the bimodal (CI plus HA) condition and compared with performance in the CI-only condition (by removing the contralateral HA), is that they do not represent how participants listen normally in the real world. That is, testing bimodal listeners in the CI-only condition introduces an artificial and “nonecologically valid” listening situation that is different from their daily lives. In contrast, a between-subjects study design, which compares listener groups in their own daily listening “best-aided” conditions, permits direct comparison of performance across groups while using their normal listening devices (e.g., see (19)). We sought to determine whether bimodal listening provides an advantage to certain outcome measures that would be expected to demonstrate low-frequency bimodal benefits, when tested in listeners’ own best-aided conditions. We hypothesized that benefits to bimodal listening (i.e., better performance in a bimodal group of listeners) would be observed on tasks that relate to high-talker variability speech materials, environmental sound recognition, and self-reported quality of life (quality of hearing). In particular, we predicted that bimodal benefits would be found even when controlling for basic auditory perception abilities (isolated word recognition in quiet).

METHODS

Participants

Participants were 50 adults (24 female and 26 male) between the ages of 45 and 83 years. Fifteen participants used a single CI (CI), 14 used 2 CIs (CICI), and 21 were bimodal users (CIHA). All were postlingually deafened native-English speakers who were recruited from a

tertiary care adult Neurotology center. All participants met traditional candidacy requirements before implantation, had received implants at age 35 years or later, had a minimum of 12 months of CI use, and had observed their clinical audiologist within 6 months of testing to optimize their CI (and HA, when used) settings. Table 1 includes demographic information for each group. Demographic variables included age, duration of deafness (computed as current age minus reported age at onset of hearing loss), socioeconomic status (SES; as determined by a measure combining educational and occupational levels (52)), and better-ear unaided pure-tone average (PTA) across the frequencies .5, 1, 2, and 4 kHz. All participants passed a visually presented version of the Mini-Mental State Examination (53), ruling out cognitive impairment. Basic speech perception was also measured as percent correct word recognition of Central Institute of the Deaf W-22 (CID (54)) isolated words in quiet.

General Approach

This study was approved by the local Institutional Review Board, and written informed consent was obtained from all participants. Participants underwent testing in acoustically insulated spaces and sound-proof booths. Visual stimuli were presented on a computer monitor placed 2 feet in front of the participant. Auditory stimuli were presented at 68 dB SPL through a loudspeaker (Roland MA-12C, Roland Corp., Los Angeles, CA) at 0° azimuth at a distance of 1 m from the individual. Participant performance was audio-visually recorded for subsequent offline scoring through a Sony HDR-PH260 High Definition Handycam (Sony Corp, Tokyo, Japan). All participants were tested using their usual auditory devices: single CI (CI group), two CIs in those with bilateral implants (CICI group), or CI plus contralateral hearing aid (CIHA). None of the participants used combined electric-acoustic stimulation in the same ear.

Sentence Recognition

Two sentence recognition tests in quiet were used, which were prerecorded and presented at 68 dB SPL. First were Harvard standard (IEEE (55)) sentences, which are contextually meaningful sentences spoken by a single male talker. Second were sentences from the Perceptually Robust English Sentence Test Open-set (PRESTO (56)) corpus. The PRESTO sentences are high-talker variability sentences, with each sentence spoken by a different talker, and include both sexes and six different regional dialects within the United States. For each sentence recognition task, participants were asked to repeat 32 sentences. Responses were calculated as the percent total words correct (for Harvard) and percent key words correct (for PRESTO) on the final 30 sentences, with the first two used for practice.

Familiar Environmental Sound Test-Identification (FEST-I)

The Familiar Environmental Sounds Test-Identification (FEST-I (57)) is a closed-set, forced-choice test requiring the participant to select 1 of 25 answer choices. The test includes a selection of environmental sounds that occur in daily life (57–59). In young normal-hearing listeners, these sounds have been demonstrated to be very familiar and easily identified. Scores were determined as percent of responses correct.

Quality of Life

Quality of life was measured by the CI-specific measure the Nijmegen Cochlear Implant Questionnaire (NCIQ) (60). It includes 60 questions using Likert scale responses between 1 (never) and 5 (always) that assess different subdomains: basic and advanced sound perception and speech production (Physical), Psychological, and social activity and interactions (Social). Subdomain scores are manipulated to be out of 100, with a maximum total score of 600. Higher scores represent better self-report quality of life. Responses of “not applicable” and missing values were excluded.

Analyses

SPSS Statistics (Version 22; IBM Corp., Armonk, NY) was used to perform statistical analyses. Group demographics, including age, SES, duration of deafness, and best PTA, as well as percent of CID words correct (assessed as a general measure of basic auditory perception) were compared using measures of central tendency, tested via one-way analysis of variance, and were used as appropriate as covariates in additional analyses. Controlling for CID word recognition, group means were then compared for Harvard standard sentence recognition, PRESTO sentences, FEST-I, and NCIQ using a multivariate one-way analysis of variance. Post hoc Least Significant Difference analyses were performed where appropriate. As mentioned above, we predicted that when controlling for basic auditory perception on CID words, we would see bimodal benefits (better performance in the CIHA group than the CI or CICI groups) on high-variability sentence recognition (PRESTO), environmental sound recognition (FEST-I), and hearing-related Quality of Life (QOL) (NCIQ). In contrast, we would not see bimodal benefits for Harvard standard sentences spoken by a single talker.

RESULTS

Patient Characteristics

Means and SD for participant demographics for each group are reported in Table 1. Groups did not differ on age, duration of deafness, or percent of CID words correct in quiet. The groups differed on mean SES; post hoc analyses demonstrated that SES was higher for the CIHA group than both the CI ($p = 0.005$) and CICI ($p = 0.039$) groups, but SES for CI and CICI groups were not significantly different ($p = 0.483$). The better-ear PTA differed between groups; the CIHA group had better/lower PTA than the CI ($p < 0.001$) and CICI ($p < 0.001$) groups, and the CICI group had better/lower PTA than the CI group ($p = 0.046$), although all qualified as severe to profound hearing loss.

Outcome Measures

Means and standard deviations for outcome measures can be found in Table 2. Broad variability in all outcomes was demonstrated within groups. Multivariate analysis of variance of all outcomes, controlling for PTA, SES, and CID scores, demonstrated that the entire model was significant ($F[12,72] = 1.921$, $p = 0.046$, partial eta squared = 0.242). The group effect results for each outcome measure are also shown in Table 2. There was no group effect found for Harvard standard sentences, PRESTO sentences, NCIQ Physical

domain, NCIQ Psychological domain, NCIQ Social domain, or total NCIQ score. However, a group effect was found on environmental sound recognition using the FEST-I. Post hoc analyses demonstrated that this effect could be attributed to better performance by the CIHA group than the CI group ($p = 0.006$) with a nonsignificant trend toward better performance by the CIHA group than the CICI group ($p = 0.218$), and a nonsignificant trend toward better performance by the CICI group than the CI group ($p = 0.131$).

DISCUSSION

In this study, we sought to examine the real-world benefits of bimodal listening by comparing groups in their usual listening condition of unilateral CI, bilateral CI, or bimodal. Participants were tested on speech recognition, environmental sound recognition, and hearing-related QOL, and comparisons were made while controlling for basic auditory perception abilities. We predicted that certain outcome measures would be sensitive to a “low-frequency” bimodal effect provided by a contralateral HA. Specifically, bimodal CI users were expected to show better performance on high-talker variability sentence recognition, environmental sound recognition, and hearing-related QOL than unilateral and bilateral CI users.

Regarding sentence recognition, we predicted a bimodal benefit on PRESTO high-talker variability sentence recognition, in contrast with Harvard standard sentences spoken by a single male talker. Counter to our hypothesis, however, we did not find significant bimodal benefits on either PRESTO or Harvard standard sentence recognition. In normal-hearing listeners, fundamental frequency (F0) and other temporal fine structure cues provide important talker information, relevant to talker identity, accent, sex, or emotion, which can support recognition of speech signals (61). Current CI systems usually provide the listener with temporal envelope of speech (62) without the temporal fine structure necessary for conveying fundamental frequency (F0) (63). Most CI users are poor at recognizing challenging speech forms, reflective of real-world conditions, such as high-variability speech (56,64), conversational speech (65), and rapid speech (66), and are worse at talker sex discrimination than normal-hearing listeners (67). While CIs alone do not effectively provide F0 and temporal fine structure cues (68), a contralateral HA seems to improve delivery of these cues through bimodal stimulation (6,12,31). In a simulation study of normal-hearing listeners, Ba kent et al. (36,69) demonstrated that addition of low pass filtered speech below 150 Hz and below 300 Hz to CI-simulated speech improved perception of F0 cues and recognition of degraded sentences, suggesting that limited low-frequency cues allow for perceptual integration of degraded speech. This is consistent with findings that low-pass filtered speech containing F0 alone (even if only 125 Hz) is adequate to improve speech recognition compared with electric only conditions (12,35,70), which may be attributed to a listener relying on voice cues to mark syllable structure and word boundaries.

Our observed lack of a bimodal effect on sentence recognition could be the result of broad within-groups variability demonstrated on the task, limiting our ability to identify an effect. In contrast, very low-frequency input through the hearing aid may simply have not provided sufficient support to assist perception of high-talker variability speech recognition, since other components of low-pass filtered speech beyond F0 can allow for speech perception of

high-variability talkers, such as spectral cues that represent vocal tract length (29,35,71). Our patient population may not have had adequate bimodal acoustic bandwidth and sensitivity to access these additional voice cues. To this point, Dorman et al. (20) found that bimodal benefits for speech perception in quiet were greater for individuals with mild (0–40 dB HL) or moderate (41–60 dB HL) hearing loss at low frequencies compared with those with more severe (>60 dB HL) hearing loss. The mean PTAs for all three groups included in our study fell into this severe category; therefore, they may have had inadequate residual hearing to derive a significant bimodal benefit during sentence recognition.

In contrast to our lack of finding a bimodal benefit for sentence recognition, a bimodal benefit was observed for environmental sounds. Environmental sound recognition is an important clinical outcome for many CI users (72,73). Some environmental sounds relevant for safety, such as alarms or collisions, and others, such as the sound of a bird song or a flowing river, are pleasant sounds that enhance individual experience (57). Our findings corroborate previous evidence that CI stimulation alone may not support effective environmental sound recognition. For example, Harris et al. (40) demonstrated that CI users only recognized 65% of environmental sounds, compared with 90% in the normal-hearing controls, while Reed and Delhorne (74) found large variability in CI users' environmental sound recognition, ranging from 45.3 to 98.3%. Moreover, Hamel et al. (41) found no difference in safety-related sound recognition between experienced CI users and deaf CI candidates, and both groups overall performed significantly worse than age-matched controls. In the current study, the bimodal group outperformed the single CI only group by approximately 10% on environmental sound recognition.

Since many environmental sounds tested in the current experiment are distinguished by spectro-temporal cues in lower frequencies than are effectively transmitted by CI electrodes, stimulation of these low-frequency regions through a HA may have contributed to improved environmental sound identification (40), and could explain some of the variability on environmental sound recognition tasks in previous research. Shafiro et al. (39) found that both spectral and temporal factors, including spectral skew (i.e., change in spectra over short periods of time), dynamic variation of the envelope (burst duration/total duration), and amplitude of the strongest burst had the greatest predictive value for environmental sound identification in CI participants. Moreover, environmental sound recognition has been correlated with the ability to process temporal orders of tone in normal-hearing listeners, a measure requiring identification of different frequency tones within a sequence (75,76). This is consistent with results of CI simulation studies demonstrating that temporal cues, especially burst duration and total duration, account for a large amount of variance in environmental sound identification (58,77,78). It is possible that the spectro-temporal cues provided in low frequencies may contribute to the improved environmental sound recognition we observed for our bimodal participants. However, it should be kept in mind that environmental sound awareness (i.e., the ability of the listener to be alerted by a sound) may be more important than environmental sound recognition (i.e., the ability to identify and label a sound) for safety reasons, and it is likely that bimodal listeners would not demonstrate a bimodal benefit to sound awareness.

Regarding self-report QOL, we did not find group differences for NCIQ scores. This contrasts with several studies demonstrating that bimodal hearing seems to improve QOL in CI users (44–46,48,51,79). A recent survey of unilateral CI users demonstrated a subjective preference for bimodal hearing among many listeners in that population, with higher self-reported speech understanding, music appreciation, and sound quality (45). One potential source of this bimodal preference is improvement in hearing in the presence of background noise, allowing for greater speech recognition in social settings (14,46). However, several studies have shown only weak correlations between speech recognition ability and various QOL metrics in CI users (80,81), suggesting that benefits to speech recognition may not translate to self-report QOL benefits. Thus, the preference for bimodal stimulation of CI-only listening reported in the Neuman et al. (45) study may be driven by improved sound quality (14,31,44,46–48), more natural sounding speech and reduced listening effort (49,50), or the ability to better appreciate melody and music (6,43).

Similar to the sentence recognition results, the lack of bimodal benefit for QOL could also be due to broad within-group outcome variability. Moreover, neither the bilateral CI nor the bimodal group showed better self-report QOL than the single CI patient group. Although some studies have demonstrated improvements in sound processing with bilateral implantation compared with bimodal listening, including better speech perception in noise (82), especially in dynamic listening environments (19), and improved QOL (46,50,51), our data do not corroborate these findings. It may simply be that some individual listeners gain more subjective benefits with bilateral CI stimulation, while others demonstrate a preference for bimodal hearing. In fact, Gifford and Dorman (19), recently suggested that because our traditional clinical assessment tools are not sensitive to differences between bilateral CI and bimodal listening, simply asking the patient, “Do you think you need a second CI?” may be a sufficiently sensitive clinical approach to identifying which patients might benefit most from a second CI.

Our study has several limitations worth considering. Although there is an “ecological validity” to testing participants in their own best-aided listening conditions, the between-groups design does not effectively take into account sources of broad individual variability in demographics, hearing, and perception. For example, we ruled out cognitive dysfunction using the Mini-Mental State Examination, and we tried to control for individual differences in SES, PTA, and basic auditory perception in our analyses, but we did not consider other sources of variability that might contribute to performance, such as differences in cognitive functions (83). In addition, all of our participants had severe hearing loss in the ear contralateral to the CI, which likely does not provide as great of a bimodal benefit as for individuals with better residual hearing, as mentioned above. Finally, in this particular study, we did not assess speech recognition in noise, which may be more sensitive to beneficial “low-frequency” effects of bimodal stimulation than speech recognition in quiet.

CONCLUSIONS

This study aimed to determine whether there would be bimodal benefits to real-world outcome measures, including high-talker variability sentence recognition, environmental sound recognition, and QOL. Bimodal listeners were able to better identify environmental

sounds compared with the CI only group. More and more bimodal CI users are now seeking a second CI (46), but one of the greatest risks of implantation is loss of residual acoustic hearing. Our results suggest that the cost of losing residual acoustic hearing with bilateral implantation may be a risk to safety-related and aesthetic environmental sound recognition. Therefore, recommendation of a second implant should take into account the potential loss of any advantage provided with residual acoustic aidable hearing.

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TABLE 1.
Participant demographics for unilateral cochlear implant (CI) users, bilateral cochlear implant users (CICI), and bimodal users (CIHA)

	CI (n = 15)			CICI (n = 14)			CIHA (n = 21)		
	Mean	(SD)		Mean	(SD)		Mean	(SD)	
Demographics									
Age (years)	68.1	(8.4)		62.3	(9.0)		68.9	(10.2)	
Duration of deafness (years)	47.3	(19.0)		36.4	(19.1)		35.5	(17.4)	
Better ear PTA (dB HL)	101.3	(14.3)		115.0	(8.2)		78.3	(22.9)	
SES	19.5	(11.0)		23.0	(12.9)		32.9	(15.3)	
CID W-22 words (% words correct)	63.9	(19.6)		72.2	(21.3)		67.1	(21.2)	

Bold values indicate $p < 0.05$

Fvalues and p values for analyses of variance (ANOVAs) are shown, bolded where $p < 0.05$.

Due to missing data, n was 13 for CICI group for analyses comparing group means for PTA and CID W-22 scores.

SES indicates socioeconomic status.

TABLE 2.

Group mean scores for unilateral cochlear implant (CI) users, bilateral cochlear implant users (CICI), and bimodal users (CIHA)

	CI (n = 13)		CICI (n = 13)		CIHA (n = 20)		F Value	p Value	Effect Size
	Mean	(SD)	Mean	(SD)	Mean	(SD)			
Speech recognition									
Harvard standard sentences (% all words correct)	75.5	(13.8)	73.3	(21.1)	75.5	(15.4)	0.731	0.488	0.035
PRESTO sentences (% keywords correct)	52.2	(14.5)	60.4	(26.3)	59.7	(22.9)	0.871	0.426	0.042
Environmental sound recognition									
Familiar environmental sounds test-identification (% correct)	55.4	(9.06)	63.7	(14.5)	65.8	(14.4)	4.402	0.019	0.180
Quality of life									
Physical	66.6	(13.4)	72.3	(16.4)	63.1	(12.3)	1.218	0.307	0.057
Psychological	69.4	(18.8)	69.0	(16.4)	61.3	(15.4)	0.384	0.684	0.019
Social	71.9	(11.0)	71.6	(8.9)	67.5	(16.8)	0.221	0.802	0.011
Total NCIQ	207.8	(37.8)	212.9	(37.9)	191.9	(38.3)	0.082	0.922	0.004

Bold values indicate $p < 0.05$.

F values and p values for multivariate analyses of variance are shown, controlling for PTA, SES, and CID W-22 word recognition.

Due to missing data, n was 13 for CI and CICI groups and 20 for CIHA for analyses.