The Benefit of Remote and On-Ear Directional Microphone Technology Persists in the Presence of Visual Information

Michael F. Dorman, PhD[1] Sarah Cook Natale, MS[1] Smita Agrawal, PhD[2]

[1] Department of Speech and Hearing Science, Arizona State University, Tempe, Arizona
[2] Advanced Bionics, Valencia, California

Address for correspondence Michael F. Dorman, PhD, mdorman@asu.edu

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Abstract

Background Both the Roger remote microphone and on-ear, adaptive beamforming technologies (e.g., Phonak UltraZoom) have been shown to improve speech understanding in noise for cochlear implant (CI) listeners when tested in audio-only (A-only) test environments.

Purpose Our aim was to determine if adult and pediatric CI recipients benefited from these technologies in a more common environment—one in which both audio and visual cues were available and when overall performance was high.

Study Sample Ten adult CI listeners (Experiment 1) and seven pediatric CI listeners (Experiment 2) were tested.

Design Adults were tested in quiet and in two levels of noise (level 1 and level 2) in A-only and audio-visual (AV) environments. There were four device conditions: (1) an ear canal-level, omnidirectional microphone (T-mic) in quiet, (2) the T-mic in noise, (3) an adaptive directional mic (UltraZoom) in noise, and (4) a wireless, remote mic (Roger Pen) in noise. Pediatric listeners were tested in quiet and in level 1 noise in A-only and AV environments. The test conditions were: (1) a behind-the-ear level omnidirectional mic (processor mic) in quiet, (2) the processor mic in noise, (3) the T-mic in noise, and (4) the Roger Pen in noise.

Data Collection and Analyses In each test condition, sentence understanding was assessed (percent correct) and ease of listening ratings were obtained. The sentence understanding data were entered into repeated-measures analyses of variance.

Results For both adult and pediatric listeners in the AV test conditions in level 1 noise, performance with the Roger Pen was significantly higher than with the T-mic. For both populations, performance in level 1 noise with the Roger Pen approached the level of baseline performance in quiet. Ease of listening in noise was rated higher in the Roger Pen conditions than in the T-mic or processor mic conditions in both A-only and AV test conditions.

Conclusion The Roger remote mic and on-ear directional mic technologies benefit both speech understanding and ease of listening in a realistic laboratory test environment and are likely do the same in real-world listening environments.

Keywords
- cochlear implant
- auditory prosthesis
- microphone technology

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In a review of their assessment of approaches to improving cochlear implant (CI) recipients' speech understanding in noise, Dorman and Gifford[1] reported that the largest gains in performance, over 40 percentage points, were obtained using a wireless remote microphone, that is, the Roger technology. The Roger (Phonak, Stäfa, Switzerland) is a digital, adaptive, wireless, remote microphone technology that transmits a speaker's voice to a hearing aid or CI sound processor. Audio signals are digitized and transmitted in short packets (160 μs) at different channels between 2.4 and 2.4835 GHz, thereby avoiding interference issues. Additionally, the gain at the receiver is increased adaptively from 0 dB (when ambient noise levels are below 56 dB sound pressure level [SPL]) to a maximum of +20 dB (for an ambient noise level exceeding 76 dB SPL). The benefits of Roger technology have been well-documented in adults and pediatric CI recipients.[2–6]

A second technological approach that produces large gains in speech understanding in noise is on-ear adaptive beamforming. Dual microphones mounted on a hearing aid or a CI sound processor allow phase, or time of arrival, at the two mics to be compared; maximum sensitivity is steered to the front of the listener and the null, or maximum attenuation, is steered adaptively toward the dominant noise source(s) located on the sides and back of the device user.[7] Studies with CI recipients have reported improvements of up to 37% or 6 dB in presence of noise source(s) located on the side(s) and/or back of the listener[8–10] and up to 23% or 5.3 dB in diffused noise.[7,11–14] The benefit of adaptive beamforming has also been demonstrated in children (5.8 dB improvement).[15]

The speech perception data reported above have mainly been collected in sound-alone test environments. While informative, their relevance to performance in the real-world environments of CI listeners can be questioned. CI listeners report that in most environments, they can see the person with whom they are talking.[16,17] This allows the listeners to use both visual and auditory information for lexical access.[18–20] When both visual and auditory information are available (audio-visual [AV]), performance is commonly high even at poor signal-to-noise ratios (SNRs) for normal hearing listeners[21] and for CI recipients.[16,22–24] For hearing aid (HA) users with sloping sensorineural hearing losses (on average, mild to severe), Wu and Bentler[25] concluded that the benefits of directional microphones can be overestimated in laboratory tests in audio-only (A-only) test conditions.

The central issue in this study, therefore, was whether the Roger technology (the Roger Pen) is of value to adult CI listeners (Experiment 1) and pediatric CI listeners (Experiment 2) when visual information is available. Additionally, we assessed the value of a T-mic relative to an omnidirectional behind-the-ear mic for children and the value of directional beamformer (UltraZoom) relative to a T-mic for adults. The T-mic is a concha-level, omnidirectional microphone which, because of its location, provides access to beamforming cues of the pinna.[26,27] Two outcome measures of value or benefit were obtained: (1) speech perception scores and (2) subject ratings of "ease of listening."

Experiment 1: Adult CI Listeners

Method

Institutional Review Board (IRB) approval: This research was reviewed and approved by the IRB at Arizona State University.

Listeners: The listeners were 10 adult CI patients (7 male, 3 female) fit with Advanced Bionics CIs and the Naida Q90 processor. The listeners' mean age was 63 years and they had an average of 6.1 years of experience with their CI. In everyday conditions, five used bilateral CIs and five were bimodal (CI with HA in the contralateral ear). For this experiment, all were tested CI only. For bilateral patients, testing was conducted with both CIs active. For the bimodal patients, the ear with partial hearing (non-CI ear) was plugged and muffed.

Test environment: Listeners were tested in the R-SPACE environment (Revitronix, Braintree, VT).[28] This environment consists of an eight-loudspeaker array placed in a circular pattern around the subject. Each speaker is 60 cm from the subject's head with speakers separated by 45 degrees. Directionally appropriate restaurant noise, that is, noise recorded in a large restaurant with 8 microphones set in a circular array pointing outward at every 45-degree angle around the circle, was output from 7 of the 8 loudspeakers. Noise was not presented from the loudspeaker from which the signal was presented, that is, at 0 degrees azimuth. A video monitor was mounted just below the loudspeaker at 0 degrees azimuth. The Roger Pen was suspended vertically in lanyard mode, 6 inches below the cone of the speaker.

Test stimuli: The stimuli were female voice AV sentences drawn from the AzAV test corpus.[16] The sentences are a re-recording of the AV sentences created by MacLeod and Summerfield.[29,30] There are 10 lists of 15 sentences each with equal auditory intelligibility and equal gain from the addition of visual information across lists. Two lists were used in each test condition.

Test conditions: Stimuli were presented in A-only and in AV test conditions in quiet and in noise. For the noise condition, two levels of SNRs were used. The first SNR was chosen individually so that performance in the baseline noise condition would be between 30 and 50% correct. The mean SNR in this condition was +4.3 dB (range of –2 dB to +10 dB). This is the range of SNRs found in common environments.[17,31] The second noise level was set by lowering the individualized SNR further by 5 dB to simulate a noisier restaurant or social gathering.

Within each condition, listening tests were conducted using a T-mic[26] as a baseline condition and with (1) an adaptive beamformer—Phonak UltraZoom,[8] and (2) the Phonak Roger Pen.[2] The Roger Pen was programed with 70% direct input and 30% environmental input, simulating the use case where listeners desire to primarily focus on the target speaker while maintaining awareness of the acoustic environment.

Ease of listening: Ease of listening was assessed following each test condition using a 5-point numerical scale printed on a visual schematic with 1 = extremely difficult, 2 = difficult, 3 = moderate, 4 = easy, and 5 = extremely easy. Responses were given orally.

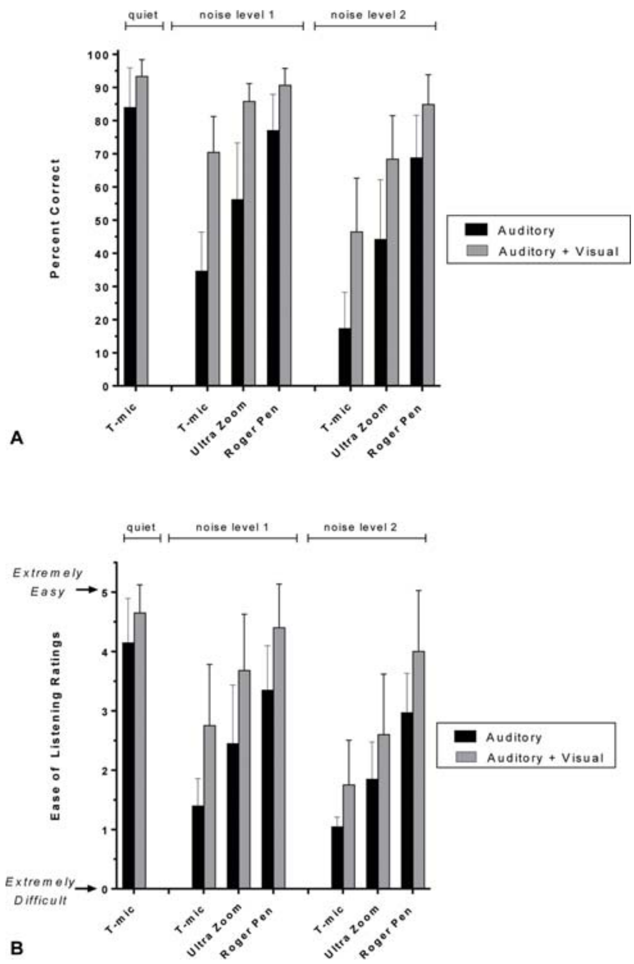

Fig. 1 Performance by adult cochlear implant (CI) listeners on the AzAV sentences when using auditory information (black bars) and when using both auditory and visual information (gray bars). (**A**) Speech understanding scores. Ease of listening ratings are shown in (**B**). Error bars = ±1 standard deviation.

Table 1 Mean percent correct score in each test condition for adults

	Quiet		Noise level 1		Noise level 2	
	A	A + V	A	A + V	A	A + V
T-mic	84	93	35	70	17	45
UltraZoom			56	86	44	68
Roger Pen			77	91	69	85

Results

The sentence understanding results from Experiment 1 are shown in ►**Fig. 1A** and in ►**Table 1**. Input modality (A-only and AV), noise level (level 1 and level 2), and microphone technology (T-mic, UltraZoom, Roger Pen) were entered into a three-way, repeated-measures (RM) analysis of variance (ANOVA). The RM ANOVA showed a main effect for modality ($F(1, 9) = 175.4$, $p < 0.0001$), a main effect for noise level ($F(1, 9) = 58.97$, $p < 0.0001$), a main effect for microphone technology ($F(2, 18) = 174.5$, $p < 0.0001$), and significant interactions.

Post hoc tests were conducted using the Holm–Sidak method for multiple comparisons. Four of the tests were of particular importance. Consider first, in noise level 1, the mean score in the T-mic AV condition (70.4% correct) versus the mean score in the UltraZoom AV condition (85.5% correct). The difference was significant indicating that, even when visual information was available, the UltraZoom allowed higher scores than the T-mic. The second comparison was the T-mic AV condition (70.4% correct) versus the Roger Pen AV condition (90.6% correct). The difference was significant and, as was the case for the UltraZoom, even when visual information was available, the Roger Pen allowed higher scores than the T-mic.

A third test compared the mean score in the Roger Pen in noise AV condition (90.6% correct) and the mean score (93.3% correct) in the T-mic in quiet AV condition. At issue here was whether the Roger Pen in noise brought performance up the level of the T-mic in quiet. The difference in scores was not significant but both scores were near the performance ceiling.

In the fourth test, the mean score in the UltraZoom in noise AV condition (85.8% correct) was compared with the T-mic in quiet AV condition (93.3% correct). The means were significantly different indicating that the UltraZoom in noise did not bring performance up the level of the T-mic in quiet.

Consider now scores in level 2 noise. The four post hoc tests described above for level 1 noise were also conducted for performance in level 2 noise. The mean scores in the AV UltraZoom condition (68.3% correct) and in the AV Roger Pen condition (84.8% correct) were higher than the mean score in the AV T-mic condition (46.4% correct). Thus, in level 2 noise, even when visual information was available, both the UltraZoom and Roger Pen allowed higher scores than the T-mic.

Finally, neither the Roger Pen (84.8% correct) nor the UltraZoom (68.3 correct) in noise brought performance to the level of the T-mic in quiet (93.3% correct).

Analyses of the ease of listening data indicated that listening with the T-mic in level 1 noise in the AV condition was rated as "difficult" (mean rating 2.79), whereas for the UltraZoom the rating was "relatively easy" (mean rating 3.68) and for the Roger Pen the rating was "easy" (mean rating 4.4). In level 2 noise, similar but lower ratings were observed. The ratings for the Roger Pen in level 1 and level 2 noise were similar (mean rating 4.4 and 4.0).

Interim Discussion

In the introduction, we noted that (1) most CI listeners report that in most listening environments they can see the person with whom they are conversing and (2) providing visual information in a speech understanding experiment commonly brings speech understanding scores to a relatively high level. This was the case in level 1 noise where the mean score in the T-mic AV condition was 70.3% correct. At issue was whether two microphone technologies, a beamformer (UltraZoom) and a remote microphone (Roger Pen), would provide benefit to speech understanding in an AV test condition when performance in a baseline condition (AV T-mic) was already high. This was, in fact, the case. In both the UltraZoom condition (85.5% correct) and the Roger Pen condition (90.6% correct) performance was higher than in the T-mic condition (70.3% correct). Moreover, performance in the Roger Pen condition in noise condition (90.6% correct) was as high as performance in the T-mic in quiet condition (93.3% correct). However, because both sets of scores were near the ceiling, the absence of a difference in performance is difficult to interpret.

Analyses of the ease of listening data were consistent with the analyses of the percent correct scores. In level 1 noise, listening with the T-mic in noise in the AV condition was, on average, rated as "difficult" whereas for the UltraZoom the rating was "relatively easy" and for the Roger Pen the rating was "easy." In level 2 noise, scores for the T-mic and the UltraZoom were poor as would be expected when the SNR decreased. However, the score for the Roger Pen (mean rating 4.0) was close to the score in level 1 noise (mean score 4.4). Thus, there is reason to believe that both technologies will be of value to adult CI patients in real-world situations and not just in the laboratory.

Experiment 2

The aim of Experiment 2 was to determine whether changes in speech understanding in AV test conditions with the use of the Roger Pen, found for adult CI listeners in Experiment 1, could be found for pediatric CI listeners.

Method

IRB approval: This research was reviewed and approved by the IRB at Arizona State University.

Listeners: The listeners were seven pediatric CI patients (three male, four female) fit with Advanced Bionics CIs and Naida Q90 processors. Their mean age at implantation was 3.9 years (range 1.4–8.1 years) and, on average, were 13.4 years old (range 9.2–16.2 years) at the time of testing. They had an average of 9.5 years (range 2.6–13.4 years) of experience with their CI. In everyday conditions, four used bilateral CIs, two were bimodal and one used a single CI only. For this experiment, all were tested with a single CI. For bilateral patients, the better CI, in terms of score on the AzBio sentence material in quiet, was used. For the bimodal patients, the ear with partial hearing was plugged and muffed.[32]

Test environment and test stimuli: These were the same as for Experiment 1.

Test conditions: As in Experiment 1, signals were presented in both A-only and AV test conditions in quiet and in noise. For the noise conditions, the SNR was determined as in Experiment 1 (noise level corresponding to 30–50% of speech understanding in quiet). Only one level of noise was used. Within each condition, listening tests were conducted using the processor mic as a baseline condition in quiet and in noise. Tests in noise were also administered using a T-mic and a Roger Pen. In contrast to Experiment 1, only one noise level was used and the UltraZoom condition was omitted. Both changes were driven by the relatively short attention span of children.

Ease of listening: As in Experiment 1, ease of listening was assessed via subjective ratings.

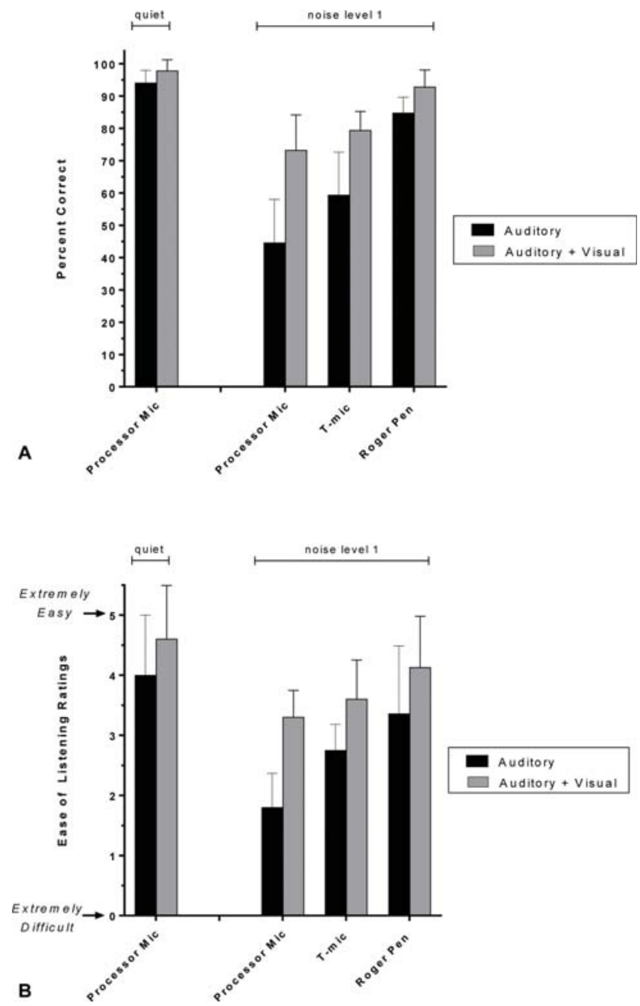

Fig. 2 Performance by pediatric cochlear implant (CI) listeners on the AzAV sentences when using auditory information (black bars) and when using both auditory and visual information (gray bars). (**A**) Speech understanding scores. Ease of listening ratings are shown in (**B**). Error bars = ±1 standard deviation.

Results

The sentence understanding results from Experiment 2 are shown in ►**Fig. 2A** and ►**Table 2**. A two-way RM ANOVA revealed a significant main effect for modality ($F(1, 6) = 56.04$, $p < 0.0003$), for microphone type ($F(2, 12) = 35.61$, $p < 0.0001$), and a significant interaction ($F(2, 12) = 8.58$, $p < 0.0049$).

In the A-alone condition, post hoc tests showed that the mean score in the T-mic in noise condition (59% correct) was significantly higher than the mean score in the processor mic condition (45% correct) and that performance in the Roger Pen condition (85% correct) was higher than in either the T-mic or processor mic conditions. Performance in the Roger Pen in noise condition (85% correct) was significantly different from performance in the processor mic in quiet condition (94% correct).

In the AV condition, post hoc tests indicated that performance levels in the processor mic (73% correct) and T-mic conditions (79% correct) did not differ significantly. However,

Table 2 Mean percent correct score in each test condition for children

	Quiet		Noise level 1	
	A	A + V	A	A + V
Processor mic	94	98	45	73
T-mic			59	79
Roger Pen			85	93

performance in the Roger Pen condition (93% correct) was higher than in the processor mic and T-mic conditions. The mean performance levels in the processor mic in quiet condition (98% correct) and in the Roger Pen in noise condition (93% correct) were not significantly different.

The ease-of-listening ratings indicated that listening in the processor mic and T-mic AV conditions in noise was moderate in difficulty (3.3 and 3.6, respectively) but listening in the Roger Pen in noise condition was easy (4.1).

General Discussion

As suggested in the introduction, testing with AV materials is not common in the CI field because visual information adds so much to speech intelligibility that there is little room to show benefit from, for example, a change in signal processing or from a new microphone technology.[25] For that reason, testing using auditory input alone is preferred. However, this condition does not pass one test of ecological validity, that is, that the test environment reflects common, real-world listening situations.

As described in the introduction, the Roger Pen is one example of a remote microphone technology that produces very large increments in speech understanding scores in noise in A-alone test conditions. The UltraZoom, an example of an on-ear adaptive dual microphone beamformer, also improves speech understanding scores significantly. At issue in this article was whether the UltraZoom and the Roger Pen would continue to show benefit in an ecologically plausible test environment—with restaurant noise surrounding the listener and when the listener could see the talker.

The results from Experiment 1, using adult listeners, and from Experiment 2, using older pediatric listeners, were similar. In the critical AV test conditions, when baseline performance in noise was relatively high, the Roger Pen improved speech understanding significantly. For adults the gains were 21 percentage points in level 1 noise and 22 percentage points in level 2 noise. For children the gain was 19 percentage points in level 1 noise. Moreover, ease of listening mirrored the improvement for speech understanding for both adults and pediatric patients. Thus, the microphone technologies evaluated in the present study pass two ecological validity requirements for demonstrating improvements in speech understanding for CI listeners, that is, the technologies lead to improved performance (1) in the presence of noise from a crowded restaurant and (2) when the listener can see the face of the talker. Clinicians can be comfortable recommending these technologies for use in the real world.

Limitations: Many other test conditions could have been implemented in our experiments. For example, the bimodal patients could have been tested in bimodal mode rather than CI-alone mode. We chose the CI-alone mode because our interest was the value of microphone technologies for patients who use electrical stimulation. A bimodal test condition would have added to the generality of our findings.

We could have used different microphone settings for our experiments. We used a 70 to 30% direct input to environmental input setting but could have used 50 to 50%—especially with pediatric patients. For young children, hearing other children's language input is very valuable and the 50 to 50% setting could facilitate that. A test in a 50 to 50% condition would have added significantly to the generality of our findings.

Conflict of Interest

Dr. Dorman reports grants and personal fees from Advanced Bionics, during the conduct of the study; grants and personal fees from MED-EL Corporation, outside the submitted work. Dr. Agrawal reports personal fees from Advanced Bionics, during the conduct of the study. Dr. Natale has nothing to disclose.

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References

1 Dorman MF, Gifford RH. Speech understanding in complex listening environments by listeners fit with cochlear implants. J Speech Lang Hear Res 2017;60(10):3019–3026
2 De Ceulaer G, Bestel J, Mülder HE, Goldbeck F, de Varebeke SP, Govaerts PJ. Speech understanding in noise with the Roger Pen, Naida CI Q70 processor, and integrated Roger 17 receiver in a multi-talker network. Eur Arch Otorhinolaryngol 2016;273(05): 1107–1114
3 Wesarg T, Arndt S, Wiebe K, et al. Speech recognition in noise in single-sided deaf cochlear implant recipients using digital remote wireless microphone technology. J Am Acad Audiol 2019;30(07): 607–618
4 Wolfe J, Morais M, Schafer E, et al. Evaluation of speech recognition of cochlear implant recipients using a personal digital adaptive radio frequency system. J Am Acad Audiol 2013;24(08):714–724
5 Wolfe J, Morais M, Schafer E, Agrawal S, Koch D. Evaluation of speech recognition of cochlear implant recipients using adaptive, digital remote microphone technology and a speech enhancement sound processing algorithm. J Am Acad Audiol 2015;26(05): 502–508
6 Zanin J, Rance G. Functional hearing in the classroom: assistive listening devices for students with hearing impairment in a mainstream school setting. Int J Audiol 2016;55(12):723–729
7 Geißler G, Arweiler I, Hehrmann P, Lenarz T, Hamacher V, Büchner A. Speech reception threshold benefits in cochlear implant users with an adaptive beamformer in real life situations. Cochlear Implants Int 2015;16(02):69–76
8 Dorman MF, Natale S, Spahr A, Castioni E. Speech understanding in noise by cochlear implant patients using a monaural adaptive beamformer. J Speech Lang Hear Res 2017;60(08):2360–2363
9 Mauger SJ, Warren CD, Knight MR, Goorevich M, Nel E. Clinical evaluation of the Nucleus 6 cochlear implant system:

performance improvements with SmartSound iQ. Int J Audiol 2014;53(08):564–576
10 Mosnier I, Mathias N, Flament J, et al. Benefit of the UltraZoom beamforming technology in noise in cochlear implant users. Eur Arch Otorhinolaryngol 2017;274(09):3335–3342
11 Buechner A, Dyballa KH, Hehrmann P, Fredelake S, Lenarz T. Advanced beamformers for cochlear implant users: acute measurement of speech perception in challenging listening conditions. PLoS One 2014;9(04):e95542
12 Dorman MF, Cook Natale S, Agrawal S. The value of unilateral CIs, CI–CROS and bilateral CIs, with and without beamformer microphones, for speech understanding in a simulation of a restaurant environment. Audiol Neurotol 2018;23(05):270–276
13 Ernst A, Anton K, Brendel M, Battmer RD. Benefit of directional microphones for unilateral, bilateral and bimodal cochlear implant users. Cochlear Implants Int 2019;20(03):147–157
14 Mauger SJ, Jones M, Nel E, Del Dot J. Clinical outcomes with the Kanso™ off-the-ear cochlear implant sound processor. Int J Audiol 2017;56(04):267–276
15 Johnstone PM, Mills KET, Humphrey E, et al. Using microphone technology to improve speech perception in noise in children with cochlear implants. J Am Acad Audiol 2018;29(09):814–825
16 Dorman MF, Liss J, Wang S, Berisha V, Ludwig C, Natale SC. Experiments on auditory-visual perception of sentences by unilateral, bimodal and bilateral cochlear implant patients. J Speech Lang Hear Res 2016;59(06):1505–1519
17 Wu Y-H, Stangl E, Chipara O, Hasan SS, Welhaven A, Oleson J. Characteristics of real-world signal-to-noise ratios and speech listening situations of older adults with mild-to-moderate hearing loss. Ear Hear 2018;39(02):293–304
18 Altieri NA, Pisoni DB, Townsend JT. Some normative data on lip-reading skills (L). J Acoust Soc Am 2011;130(01):1–4
19 Rosenblum LD. Speech perception as a multimodal phenomenon. Curr Dir Psychol Sci 2008;17(06):405–409
20 Summerfield Q. Some preliminaries to a comprehensive account of audio-visual speech perception. In: Dodd B, Campbell R, eds. Hearing by Eye: The Psychology of Lip-Reading. London, UK: Lawrence Erlbaum Associates, Inc; 1987:53–83
21 Sumby WH, Pollack I. Visual contribution to speech intelligibility in noise. J Acoust Soc Am 1954;26(02):212–215
22 Desai S, Stickney G, Zeng F-G. Auditory-visual speech perception in normal-hearing and cochlear-implant listeners. J Acoust Soc Am 2008;123(01):428–440
23 Gray RF, Quinn SJ, Court I, Vanat Z, Baguley DM. Patient performance over eighteen months with the Ineraid intracochlear implant. Ann Otol Rhinol Laryngol Suppl 1995;166(166):275–277
24 Kaiser AR, Kirk KI, Lachs L, Pisoni DB. Talker and lexical effects on audiovisual word recognition by adults with cochlear implants. J Speech Lang Hear Res 2003;46(02):390–404
25 Wu Y-H, Bentler RA. Impact of visual cues on directional benefit and preference: part I–laboratory tests. Ear Hear 2010;31(01): 22–34
26 Kolberg ER, Sheffield SW, Davis TJ, Sunderhaus LW, Gifford RH. Cochlear implant microphone location affects speech recognition in diffuse noise. J Am Acad Audiol 2015;26(01):51–58, quiz 109–110
27 Gifford RH, Revit LJ. Speech perception for adult cochlear implant recipients in a realistic background noise: effectiveness of preprocessing strategies and external options for improving speech recognition in noise. J Am Acad Audiol 2010;21(07):441–451, quiz 487–488
28 Compton-Conley CL, Neuman AC, Killion MC, Levitt H. Performance of directional microphones for hearing aids: real-world versus simulation. J Am Acad Audiol 2004;15(06):440–455
29 MacLeod A, Summerfield Q. Quantifying the contribution of vision to speech perception in noise. Br J Audiol 1987;21(02): 131–141
30 MacLeod A, Summerfield Q. A procedure for measuring auditory and audio-visual speech-reception thresholds for sentences in noise: rationale, evaluation, and recommendations for use. Br J Audiol 1990;24(01):29–43
31 Smeds K, Wolters F, Rung M. Estimation of signal-to-noise ratios in realistic sound scenarios. J Am Acad Audiol 2015;26(02): 183–196
32 Spahr AJ, Dorman MF, Litvak LM, et al. Development and validation of the AzBio sentence lists. Ear Hear 2012;33(01):112–117

