J Am Acad Audiol 30:235–242 (2019)

Contralateral Routing of Signal Yields Significant Speech in Noise Benefit for Unilateral Cochlear Implant Recipients

DOI: 10.3766/jaaa.17117

Robert T. Dwyer*
David Kessler*
Iliza M. Butera†
René H. Gifford*‡

Abstract

Background: Bilateral cochlear implantation is the standard of care for individuals with moderate sloping-to-profound sensorineural hearing loss who do not receive benefit from appropriately fit hearing aids. Because of financial, insurance, or medical reasons, some unilateral cochlear implant (CI) recipients are unable to obtain a second CI. Here, we evaluated the first clinically available solution for individuals who have been unilaterally implanted and who do not or cannot use technology (e.g., hearing aid or CI) on the non-implanted ear.

Purpose: We aimed to investigate how the addition of a contralateral routing of signal (CROS) device could provide objective and/or subjective benefit to adult CI recipients with moderate-to-profound hearing loss in the non-implanted ear.

Research Design: Single-center prospective study using a within-subjects repeated-measures design.

Study Sample: Participants included ten experienced unilateral CI recipients with severe-to-profound (n = 9) or moderate-to-profound (n = 1) sensorineural hearing loss in the non-implanted ear. At the time of study enrollment, participants did not use any technology on the non-implanted ear. No other exclusion criteria were used.

Intervention: Individuals were tested with and without a CROS device worn on the non-implanted ear.

Data Collection and Analysis: We obtained measures of speech understanding in quiet (50 and 65 dBA) and in noise (+5-dB signal-to-noise ratio with a 65-dBA speech signal) both with and without the CROS device in an acute listening condition. Subjective benefit was assessed via the Speech, Spatial and Qualities 12-item questionnaire before CROS fitting and after two weeks of continuous use. A mixed-model, repeated-measures analysis of variance was completed with three talker locations and three presentation levels included as within-subjects factors and the presence or absence of a CROS device as a between-subjects factor.

Results: There was an 11% improvement in speech understanding in noise with the addition of the CROS device when speech was located at 0° azimuth. Subjective benefit in the speech domain of the SSQ was also observed.

Conclusions: Use of CROS provided both subjective and objective speech recognition benefit for unilateral CI recipients who do not have access to bilateral cochlear implantation.

Key Words: CROS, cochlear implant, contralateral routing of signal, face shadow effect, head shadow effect, R-SPACE™, unilateral hearing loss

Abbreviations: CI = cochlear implant; CROS = contralateral routing of signal; SD = standard deviation; SNR = signal-to-noise ratio

---

*Department of Hearing and Speech Sciences, Vanderbilt University Medical Center, Nashville, TN; †Vanderbilt Brain Institute, Vanderbilt University, Nashville, TN; ‡Department of Otolaryngology, Vanderbilt University Medical Center, Nashville, TN

Corresponding author: Robert T. Dwyer, Vanderbilt Bill Wilkerson Center, Nashville, TN 37232; Email: robert.dwyer@vanderbilt.edu

This research was supported by NIDCD DC009404 as well as a grant from Advanced Bionics, LLC (Valencia, CA) which provided CROS devices to the ten study participants.

INTRODUCTION

Oftentimes, unilateral cochlear implant (CI) recipients gain significant benefits to speech understanding after receiving a second CI. This improvement is due to several possible mechanisms, which are mostly inherent to binaural hearing and include summation effects of co-located signals and maskers (Litovsky et al, 2004; Buss et al, 2008; Kokkinakis and Pak, 2014) and spatial hearing benefits most likely arising from interaural-level difference cues (Grantham et al, 2008; Dorman et al, 2016; Loiselle et al, 2016). Binaural squelch, or binaural unmasking of speech, results from a central comparison of primarily interaural time differences, resulting in improved speech understanding in noise with the addition of a second ear with a poorer signal-to-noise ratio (SNR). Minimal binaural squelch has been reported for bilateral CI users (Schleich et al, 2004; Litovsky et al, 2006; Buss et al, 2008; Kokkinakis and Pak, 2014). This is likely due to the use of envelope-based signal processing and high channel stimulation rates in current CI sound processors, which allow for little-to-no transmission of fine timing information outside the carefully controlled laboratory setting.

Arguably, the largest benefit of bilateral cochlear implantation is in the head shadow effect, which is both significant and generally symmetrical across ears for bilateral CI recipients (Litovsky et al, 2004; Buss et al, 2008; Gifford et al, 2014). Unilateral CI recipients, however, are at a disadvantage for conditions in which the masking noise is presented to the CI ear (Litovsky et al, 2004; Gifford et al, 2014) or in conditions where the signal originates from the side of the non-implanted ear (Kolberg et al, 2015). In such cases, head shadow has a significant, negative impact on speech understanding.

One way to overcome the head shadow effect for unilateral CI recipients is to route the signal to the implanted ear. Contralateral routing of signal (CROS) devices have been available since the 1960s. CROS devices overcome the deleterious effects of the head shadow by placing a microphone on the poorer ear and transmitting acoustic information to the better ear. Although it is generally agreed that a CROS device will increase the effective SNR when the signal of interest originates from the side of the poorer hearing ear, the impact of the contralateral microphone on speech understanding when noise is presented to the CROS ear may not be favorable. As a result, the net benefit of CROS devices in unilateral CI recipients has been mixed. Whereas some groups have reported that adding the CROS is not detrimental to speech understanding in noise when noise is presented to the CROS ear (Weder et al, 2015) or not significantly different (Wimmer et al, 2017), other work has shown a negative impact on speech understanding (Arora et al, 2013; Van Loon et al, 2014; Grewal et al, 2015; Taal et al, 2016). For speech understanding in quiet, some studies have shown no benefit of CROS (Taal et al, 2016), whereas other studies have demonstrated significant benefit for CROS with unilateral CI recipients (Arora et al, 2013; Grewal et al, 2015; Guevara et al, 2015).

The conflicting results in the current CI CROS literature are largely a product of variability in test setup (e.g., device, location of noise, location of speech, directional microphones, etc.). In the present study, we investigated the benefit received from a commercially available CROS device for unilateral CI recipients at: (a) different speech presentation levels (in quiet and in noise) and, (b) for different sound source locations (0°, 90°, and 270°). Unlike previous work, we assessed speech recognition in a semi-diffuse noise condition delivered by the R-SPACE™ sound simulation system allowing greater generalization of results to typical auditory environments, such as social gatherings in which the talker moves among those in attendance. Our hypotheses were as follows: (a) benefit of the CROS device will depend on the location of the target talker (i.e., source location × CROS interaction) such that speech presented to the non-implanted side would benefit from the addition of the CROS; (b) benefit in quiet will vary depending on the presentation level of the speech (presentation level × CROS interaction); (c) speech presented to the CI side in the presence of noise will suffer from the addition of the CROS (presentation level × source location × CROS interaction); and, (d) significant subjective benefit following two weeks of continuous CROS use will be observed.

METHODS

Participants

Ten adults implanted with an Advanced Bionics (Valencia, CA) CI system participated in this study, which was conducted in accordance with institutional review board approval (see Table 1 for demographic information). Participants ranged in age from 19 to 68 years (mean = 45 years, standard deviation [SD] = 19 years). At the time of evaluation, no participant was using any technology on the non-implanted ear. Two participants (participants 4 and 9) were previously implanted with a CI in the non-implanted ear but had discontinued use because of non-auditory perception or because of complications requiring explantation of the internal device. The remaining eight participants did not wear any contralateral technology because of lack of perceived benefit. Four participants reported previous hearing aid use in the non-implanted ear, whereas six participants reported prior hearing aid use in the implanted ear. All participants had ≥10 months of experience with their CI (mean = 8.9 years; range = 0.8–16 years).

Table 1. Demographic Information

	Age (Years)	Gender	Pre/Postlingually Deafened	CI Experience (Years)	Device
1	19	Male	Pre	16.00	CII
2	62	Male	Pre	11.55	HR90K
3	59	Female	Post	13.58	HR90K
4	45	Female	Post	9.57	HR90K
5	52	Male	Post	2.85	HR90K
6	42	Male	Post	1.89	HR90K
7	22	Female	Pre	2.91	HR90K
8	68	Female	Post	0.86	HR90K
9	19	Male	Pre	14.96	CII
10	66	Male	Pre	14.19	CII
Mean	45.40	40% female	50% pre	8.84	–

Test Environment and Stimuli

Participants completed sentence recognition testing within a single-walled sound booth. Stimuli were presented in the Revitronix R-SPACE™ sound simulation system (Braintree, VT), which uses pre-recorded restaurant noise to simulate a real-world listening environment. The listener was surrounded by a circular array of eight loudspeakers placed at 45° intervals located 24″ from the center of the participant's head. R-SPACE™ system design and methods for recording restaurant environmental noise have been discussed previously in greater detail (Compton-Conley et al, 2004; Revit et al, 2007).

Speech stimuli consisted of a subset of sentences from the Texas Instruments/Massachusetts Institute of Technology (TIMIT) Acoustic-Phonetic Continuous Speech Corpus (Lamel et al, 1989). The TIMIT corpus, which was created and recorded by researchers at Texas Instrument, Inc., Massachusetts Institute of Technology, and Stanford Research Institute International, consists of sentences recorded with male and female speakers in eight American English dialects. Previous work by Dorman et al (2003; 2005) and Loizou et al (2000) split 680 TIMIT sentences into 34 lists (20 sentences per list) equated for intelligibility. In the present study, these lists were compiled in groups of three to create ten lists of 60 sentences per group.

Procedure

All participants had been programmed by licensed audiologists resulting in mean CI-aided detection thresholds of 25.6-dB HL from 250 through 6000 Hz. Each participant was fit with a new AB Naída™ Link CROS device. After the participant's Naída™ Q70 or Q90 CI speech processor was initialized to communicate with the CROS device, no additional programming changes were made. Speech testing was completed in each participant's preferred program, employing an omnidirectional microphone.

Immediately after the fitting, participants completed sentence recognition testing both with and without the CROS device. Sentences were presented in quiet at 50 and 65 dBA as well as in a semi-diffuse restaurant noise at +5-dB SNR, with speech at 65 dBA, for a total of six listening conditions. Stimulus presentation order was counterbalanced such that half of the participants completed the first three test conditions with the CROS device, whereas the remaining half of participants began testing without the CROS device. Condition and list order were randomized for each participant and no lists were repeated. Sentences were presented from one of three loudspeakers located at an azimuth of 0°, 90°, and 270°. For speech-in-noise testing, the speech signal was presented from one source, whereas noise was presented from the remaining seven loudspeakers. Stimulus presentation location was alternated randomly between three loudspeakers (see Figure 1) for a total of 20 sentence presentations at each azimuth per test condition or 60 sentences per listening condition. Responses were scored for the number of words correct for each signal location.

Participants were instructed to face the speaker placed at 0°, irrespective of source azimuth, and asked to repeat what they had heard following each sentence. Each participant was equipped with a transmitting lapel microphone. Experimenters wore earphones connected to the transmitting microphone to ensure that the participants' responses were audible and that noise did not interfere with scoring. Furthermore, a video camera in the sound booth transmitted an image of the participants' faces to a monitor in the laboratory, providing the experimenter with visual cues, which aided sentence scoring.

Subjective Benefit Assessment

Each participant completed the Speech, Spatial and Qualities 12-item questionnaire (SSQ12, Noble et al, 2013) before CROS evaluation in the sound booth. The participants were asked to continuously wear the CROS device for two weeks. After two weeks of consistent CROS use, participants completed the SSQ12

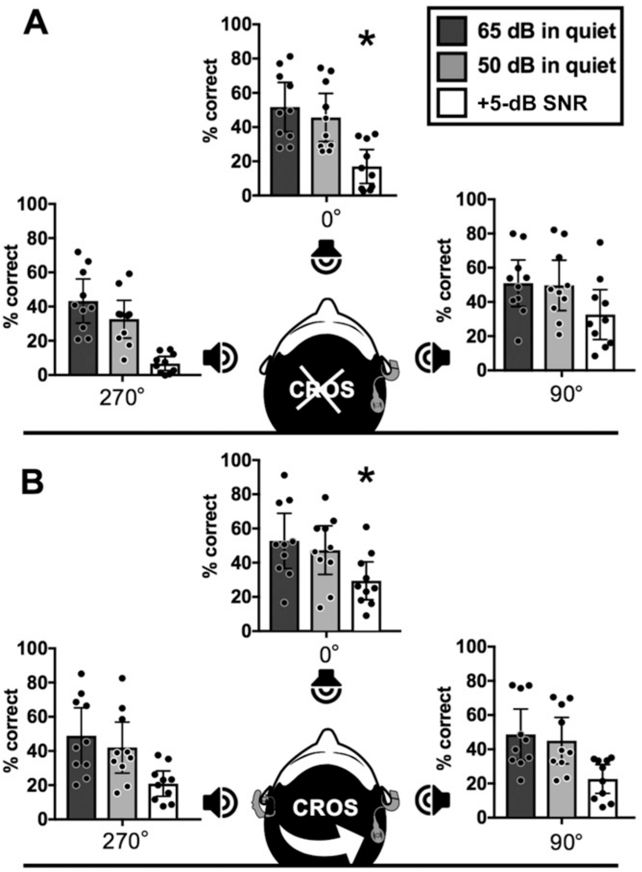

Figure 1. Mean speech understanding as a function of three source locations and three speech levels without the CROS device (A) and with CROS (B). Error bars represent the 95% confidence interval. Circles represent individual data. $*p = 0.002$.

again to evaluate each participant's perception of CROS use in everyday listening environments.

Statistical Analysis

All statistical analyses were completed with IBM SPSS Statistics for Macintosh, Version 24.0. A mixed-model analysis of variance (ANOVA) was used to test whether there were differences in speech understanding with versus without CROS (between-subjects factor) as a function of different listening conditions (within-subjects factor; three source locations and three presentation levels). Greenhouse–Geisser corrections were applied for any significant violations of sphericity (Mauchly's test) and original degrees of freedom with adjusted p values are reported. Follow-up, pairwise t-tests with Bonferroni corrections for multiple comparisons were then used to investigate interactions. When comparing nonparametric data between two repeated measures (i.e., SSQ12), a Wilcoxon signed-rank test was used. Statistical significance was determined using an α of 0.05, and adjusted p values (p_{adj}) are reported where corrections were applied. Finally, to investigate apparent outliers in the noise conditions shown in Figure 2, we ran two multivariate tests by calculating Mahalanobis distances, which indicated that participant 4 (Figure 2, filled-circles) was a significant outlier for both face shadow as a function of CROS benefit (Figure 2G; $p = 0.0269$) and head shadow as a function of CROS benefit (Figure 2H; $p = 0.0285$). These two data points were excluded from respective linear regressions.

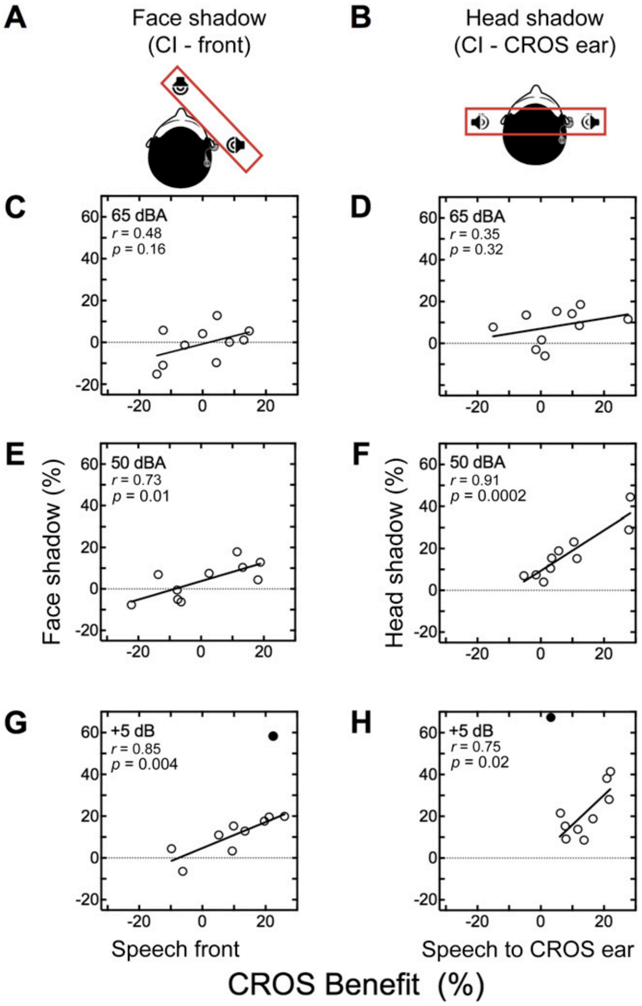

Figure 2. The difference in speech understanding when speech is presented to the front of the listener vs. when it is presented to the CI side (i.e., "face shadow" [A]) as a function of benefit from the addition of the CROS for 65-dB speech (C), 50-dB speech (E), and +5-dB SNR (G). The difference in speech understanding when speech is presented to the listener's CI side vs. when it is presented to the non-CI side (i.e., head shadow [B]) as a function of benefit from the addition of the CROS for 65-dB speech (D), 50-dB speech (F), and +5-dB SNR (H). (This figure appears in color in the online version of this article.)

RESULTS

Mean speech understanding as a function of three source locations and three speech levels without the CROS device (A) and with CROS (B) are shown in

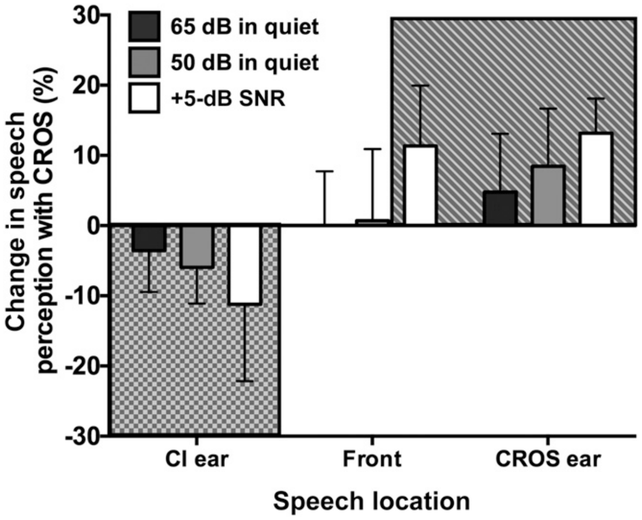

Figure 3. Mean percent change in speech perception for all testing conditions with the CROS on, such that positive values indicate improved performance (diagonal striped), negative values indicate reduced performance (checkered), and 0% indicates no change. Error bars indicate 95% confidence interval of the mean.

Figure 1. To illustrate the difference in speech perception with the CROS device, or CROS-derived benefit (Figure 3), we subtracted performance in the CI-alone condition (Figure 1A) from the CROS condition (Figure 1B) for each participant and plotted the mean per condition. Figure 3 illustrates a general trend that for all conditions where speech was presented to the CI ear, average performance decreased with the addition of the CROS device (i.e., negative percent change in speech perception with CROS). However, when speech was presented to the CROS ear, average performance improved in all conditions. To investigate the effect sizes and statistical significance, we used a mixed-model ANOVA with speech understanding for each listening condition as the dependent variable.

Effect of Talker Location

A mixed-model ANOVA with location (0°, 90°, and 270°) and level (65 dB, 50 dB, and +5-dB SNR) as within-subjects factors and CROS use (with and without) as a between-subjects factor indicated a significant main effect of location [$F_{(2,9)} = 24.9$, $p < 0.001$, $\eta_p^2 = 0.58$]. In addition, a strong location × CROS interaction [$F_{(2,9)} = 14.7$, $p < 0.001$, $\eta_p^2 = 0.45$] necessitated follow-up, pairwise *t*-tests. To test which location preferentially affected performance with the CROS device, we collapsed across presentation levels and performed independent samples *t*-tests of CROS use at the three source locations. Although the large location × CROS interaction effect (i.e., $\eta_p^2 > 0.25$) appeared to be driven by performance at the 0° speaker location across all presentation levels (mean accuracy 42.6% with CROS and 30.6% without CROS), this effect was not statistically significant after correcting for multiple comparisons [$t_{(58)} = -2.18$, $p_{\text{adj}} = 0.099$]. Thus, we cannot conclusively state which location (irrespective of level) may be preferentially impacted by CROS use.

Effect of Sound Level

We also found a main effect of presentation level on speech understanding [$F_{(2,9)} = 96.1$, $p_{\text{adj}} < 0.001$, $\eta_p^2 = 0.84$]. Contrary to our expectation, we did not find a level × CROS interaction [$F_{(2,9)} = 0.52$, $p = 0.6$, $\eta_p^2 = 0.028$]. Because our a priori hypotheses also involved CROS benefit at specific presentation level and source location combinations, we anticipated an additional CROS × location × level interaction; however, this also did not reach statistical significance [$F_{(4,9)} = 2.28$, $p = 0.069$, $\eta_p^2 = 0.113$]. In an exploratory analysis of pairwise comparisons, we found that one level and location in particular was significantly different with CROS—speech perception in noise where speech is presented at 0° [$t_{(18)} = -3.5$, $p_{\text{adj}} = 0.02$].

Partial Head Shadow or "Face Shadow"

Because we had not anticipated CROS-derived benefit for conditions in which speech originated from 0°, we explored the presence of a partial head shadow effect that we have termed a *face shadow* effect. In Figure 2, we have illustrated the effects of both head and face shadow. Specifically, the difference in speech understanding for speech presented to the front of the listener as compared with the CI side (face shadow, Figure 2A), is plotted as a function of CROS benefit at the 0° location for 65-dB speech (Figure 2C), 50-dB speech (Figure 2E), and +5-dB SNR (Figure 2G). For comparison, the effect of head shadow (Figure 2B), or the difference in speech understanding when speech is presented to the CI side as compared with the non-CI side, is plotted as a function of CROS benefit at the contralateral ear (Figures 2D, F, and H).

For conversational-level (65 dB) speech, CROS benefit does not correlate with either face shadow (Figure 2C) or head shadow (Figure 2F). In the quiet speech condition (50 dB), however, there is a significant, positive correlation between the magnitude of the face shadow (Figure 2E) and CROS benefit from the front ($r = 0.73$, $p = 0.01$), as well as the magnitude of the head shadow and CROS benefit from the front (Figure 2F; $r = 0.91$, $p < 0.001$). For speech in noise, we also see a strong, positive correlation between the magnitude of the face shadow (Figure 2G; $r = 0.85$, $p = 0.004$) and head shadow (Figure 2H; $r = 0.75$, $p = 0.02$) with CROS benefit.

Subjective Report

The average ratings from the SSQ12 are shown in Figure 4. Error bars represent the 95% confidence

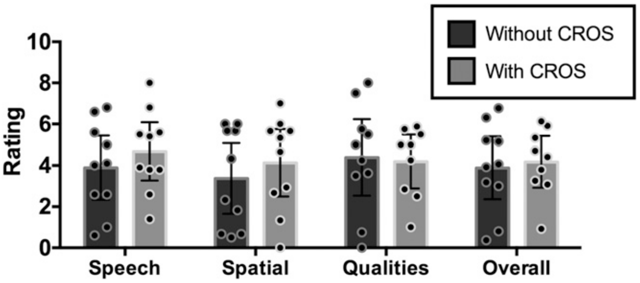

Figure 4. Mean SSQ12 ratings for the ten participants are displayed here. Error bars represent the 95% confidence interval of the mean.

interval. A Wilcoxon signed-rank test indicated that median ranks in the speech domain with the CROS device (median = 4.65, SD = 1.97) were significantly higher than the median ranks without the CROS device (median = 4.05, SD = 2.17; $Z = -2.103, p = 0.035$). No other significant differences were observed.

DISCUSSION

This study quantified subjective and objective benefit of a CROS device used with a unilateral CI in nine different sound level and source location listening combinations. Our overarching hypothesis was that CROS benefit would depend on both the location of the target signal and the presentation level.

Effect of Level and Talker Location

In this study, we manipulated listening difficulty by testing quiet speech (50 dB), conversational-level speech (65 dB), and speech in noise (+5-dB SNR), and as expected, there was a large main effect of level reflecting that performance was significantly impacted as a function of these sound levels. We also found a large location × CROS interaction effect revealing that talker location was significantly impacting performance with the CROS device. This interaction appeared to be driven by performance at the 0° speaker, suggesting that all listening conditions benefit by CROS addition when speech is presented from the front. We compared performance by locations after collapsing across levels and no individual location reached statistical significance after correcting for multiple comparisons. We later determined that this was likely due to the noise condition from the 0° location alone driving the location × CROS interaction. Indeed, Figure 3 illustrates that little if any benefit on average is derived in the quiet or conversational levels from the 0° location.

Initially, we had hypothesized that benefit would arise for conditions in which speech was presented to the CROS ear at a low presentation level (50 dBA) and in noise (+5-dB SNR). Although we did not observe a significant effect of CROS in these conditions, mean benefit for low-level speech presented to the CROS ear was 8.4% points and in the presence of noise, mean CROS benefit was 13.2% points (Figure 3).

Unexpectedly, the only listening condition that demonstrated statistically significant improvement with the CROS device was speech recognition in noise with the signal presented at 0°. This result is different from what we had hypothesized; however, Wimmer et al (2017) also reported significant CROS-related improvement for speech understanding in noise with speech at 0°. Unlike the present study, Wimmer et al (2017) used a directional microphone on the CROS device, which likely explains their finding. Interestingly, even while using a directional microphone setting on the CROS ear, Wimmer et al (2017) reported benefit for conditions in which speech was presented to the CROS ear. In addition, Wimmer et al (2017) reported that when noise was presented to the CROS ear (speech to CI side), performance compared with the CI-alone condition was not appreciably different. These findings are clinically important as a directional CROS could provide benefit where we would expect—with speech presented to the CROS ear or to the front of the listener—but would also minimize CROS input in potentially detrimental listening conditions such as when noise is presented to the CROS ear. Thus, these findings by Wimmer et al (2017) suggest that the CROS device can be worn effectively in any situation (i.e., regardless of spatial location of the speaker). Even though we did not see a statistically significant detriment to speech understanding with the addition of the CROS device, we did observe an 11% point decrease in speech understanding, on average, for noise conditions in which speech was presented to the CI ear (Figure 3). In theory, when speech is presented to the CI ear and noise is directed toward the CROS ear, directional microphones should better attenuate the contralateral noise. Thus, future studies investigating the impact of microphone directionality on speech understanding with CROS devices may explain differences in the present study to those of Wimmer et al (2017).

Partial Head Shadow or "Face Shadow"

Contradictory to our results and the results reported by Wimmer et al (2017), Van Loon et al (2014) reported a statistically significant 1.4-dB *detriment* to speech reception threshold in noise in ten unilateral CI recipients after adding the CROS to the CI ear when speech was presented in front of the listener (0°). Others have reported no significant differences in speech understanding with CROS use and speech at 0° (Grewal et al, 2015; Taal et al, 2016). If the addition of the CROS did not affect the SNR at the CI ear, we would expect performance to remain unchanged. However, in the present study, performance *was* impacted with the addition of the CROS. Although the presence of a full head shadow effect has been well-documented in the literature, our study and others (Kolberg et al, 2015) suggest the presence of a partial head shadow effect that we refer to here as a *face shadow*. We quantify face shadow as the difference in an individual's speech understanding when speech is presented to the front of the listener (0°) and when speech is directed toward the CI ear (±90°), see Figure 2A. Not surprisingly, the magnitude of this effect is smaller than the head shadow effect, yet for both, the contralateral microphone may significantly counteract the physical attenuation of the signal to the CI ear alone (i.e., by routing signals from bilateral microphones). Interestingly, we found significant correlations between both face shadow and head shadow with the degree of CROS-derived benefit for both low-level speech (50 dBA) and speech in noise but not for louder, conversational-level speech. In summary, the presence and magnitude of face and/or head shadow may prove useful as a clinical measure in helping the clinician to identify those patients who would most benefit from use of a CROS system (i.e., those with the largest shadow effects).

Subjective Report

Of the three domains that we tested for subjective measures of CROS benefit—speech, spatial, and sound quality—only the speech domain of the SSQ questionnaire was significantly improved with CROS use. This finding is consistent with the purpose of the CROS device, which is to improve speech understanding regardless of the spatial location of the sound source. For the clinician, assessing subjective benefit using the speech domain of the SSQ may be helpful for gauging benefit. User satisfaction is likely to also be influenced by how well the audiologist can educate the patient on when and where a CROS device will be beneficial, such as in challenging listening environments.

Limitations and Future Directions

A potential caveat of this study is that our relatively small sample (n = 10) may not generalize to the broader population of CI users. Measures of effect size—in our case, partial eta squared (η_p^2)—are useful indicators of how much variance in an outcome variable is explained by an independent variable. Because we found effect sizes explaining as much as 45% of the variability in word recognition scores ($\eta_p^2 = 0.45$), we have greater confidence in the generalizability of these findings than if the *p* value was extraordinarily small (i.e., highly significant) for a small effect ($\eta_p^2 = 0.01$). Greater statistical power via a larger sample size may help to confirm whether several trends that we identified (Figure 3) are statistically significant in the broader population.

An additional limitation of the present study is that speech recognition testing was completed after acute use of the CROS device. There is always the potential for performance to change after acclimating to device use. Thus, future investigations should be completed with a larger cohort following chronic CROS use as well as a comparison to the acute condition. Future work may consider a within-subjects design with bilateral CI users to investigate the differences in outcomes for these two interventions. Another area of investigation might focus on the high versus low performers and whether there is a relationship between CROS-derived benefit and CI-alone performance. Last, no signal processing, such as directional microphone technology, was applied to participant programs. Eight of ten participants enrolled in this study used ClearVoice™ medium in their sound coding strategy. Two participants did not employ any level of noise reduction (i.e., ClearVoice™). Thus, the impact of these technologies on CROS-derived benefit should be evaluated.

Large variability in the present study may result from several factors. First, we confirmed that participants' programs were stable per audiologist report, and mean CI-aided audiometric thresholds were 25.6-dB HL from 250 through 6000 Hz. We believe this provides further support of the CROS benefit as no programming effort was required to provide significant auditory benefit for the user in this sample of ten participants. We did not make any programming adjustments or investigate differences in benefit as a function of programming; however, if a patient's map is not providing sufficient audibility—in terms of either absolute detection and/or audible bandwidth—we may not expect the addition of a CROS system to provide maximum potential benefit.

CONCLUSION

For CI recipients with moderate-to-profound sensorineural hearing loss in the non-implanted ear who are unable to pursue a second CI, a CROS device can provide subjective and objective benefit in certain listening situations. It is important for the audiologist to effectively educate the user as to which conditions are best suited for CROS benefit as well as those conditions for which CROS may be detrimental. Our main study findings were as follows:

- Speech understanding in noise was significantly improved with the addition of the CROS device for speech originating at 0° azimuth.
- There was a significant correlation between face and head shadow and CROS benefit for low-level speech (50 dBA) and speech in noise.

- Subjective CROS-derived benefit was observed in the speech domain of the SSQ.
- The magnitude of face or head shadows might serve useful as a clinical measure in helping the clinician to identify those patients who would most benefit from the use of a CROS system.

Acknowledgments. We would like to thank Drs. Linsey Sunderhaus and Adrian Taylor for their assistance with participant fittings and data collection. We would also like to thank Carol Murad and Dr. Lindsey Early of Advanced Bionics who visited and trained us on how to fit the CROS system. We also would like to thank the study participants for volunteering their time and effort to this research.

REFERENCES

Arora R, Amoodi H, Stewart S, Friesen L, Lin V, Nedzelski J, Chen J. (2013) The addition of a contralateral routing of signals microphone to a unilateral cochlear implant system—a prospective study in speech outcomes. *Laryngoscope* 123(3): 746–751.

Buss E, et al. (2008) Multicenter U.S. bilateral MED-EL cochlear implantation study: speech perception over the first year of use. *Ear Hear* 29(1):20–32.

Compton-Conley CL, Neuman AC, Killion MC, Levitt H. (2004) Performance of directional microphones for hearing aids: real-world versus simulation. *J Am Acad Audiol* 15(6):440–455.

Dorman MF, Loiselle LH, Cook SJ, Yost WA, Gifford RH. (2016) Sound source localization by normal-hearing listeners, hearing-impaired listeners and cochlear implant listeners. *Audiol Neurotol* 21(3):127–131.

Dorman MF, Loizou PC, Spahr A, Dana CJ. (2003) Simulations of combined acoustic/electric hearing. In: Engineering in Medicine and Biology Society, 2003. *Proceedings of the 25th Annual International Conference of the IEEE*, Cancun, Mexico, September 17–21*,* Vol. 3, pp. 1999–2001. IEEE.

Dorman MF, Spahr AJ, Loizou PC, Dana CJ, Schmidt JS. (2005) Acoustic simulations of combined electric and acoustic hearing (EAS). *Ear Hear* 26(4):371–380.

Gifford RH, Grantham DW, Sheffield SW, Davis TJ, Dwyer R, Dorman MF. (2014) Localization and interaural time difference (ITD) thresholds for cochlear implant recipients with preserved acoustic hearing in the implanted ear. *Hear Res* 312:28–37.

Grantham DW, Ashmead DH, Ricketts TA, Haynes DS, Labadie RF. (2008) Interaural time and level difference thresholds for acoustically presented signals in post-lingually deafened adults fitted with bilateral cochlear implants using CIS processing. *Ear Hear* 29:33–44.

Grewal AS, Kuthubutheen J, Smilsky K, Nedzelski JM, Chen JM, Friesen L, Lin VYW. (2015) The role of a new contralateral routing of signal microphone in established unilateral cochlear implant recipients. *Laryngoscope* 125(1):197–202.

Guevara N, Grech C, Gahide I, Gallego S. (2015) Assessment of the contralateral routing of signal system in unilateral cochlear implantation. *Clin Otolaryngol* 40(6):535–544.

Kokkinakis K, Pak N. (2014) Binaural advantages in users of bimodal and bilateral cochlear implant devices. *J Acoust Soc Am* 135(1):EL47–EL53.

Kolberg ER, Sheffield SW, Davis TJ, Gifford H. (2015) Cochlear implant microphone location affects speech recognition in diffuse noise. *J Am Acad Audiol* 58:51–58.

Lamel LF, Kassel RH, Seneff S. (1989) Speech database development: design and analysis of the acoustic-phonetic corpus. In *Speech Input/Output Assessment and Speech Databases.* Vol. 2, pp. 161–170.

Litovsky RY, Johnstone PM, Godar SP. (2006) Beneftis of bilateral CIs and/or HAs in children. *Int J Audiol* 45(Suppl 1):1–22.

Litovsky RY, Parkinson A, Arcaroli J, Peters R, Lake J, Johnstone P, Yu G. (2004) Bilateral cochlear implants in adults and children. *Arch Otol Head Neck Surg* 130:648–655.

Loiselle LH, Dorman MF, Yost WA, Cook SJ, Gifford RH. (2016) Using ILD or ITD cues for sound source localization and speech understanding in a complex listening environment by listeners with bilateral and with hearing-preservation cochlear implants. *J Speech Lang Hear Res* 59:810–818.

Loizou PC, Dorman M, Poroy O, Spahr T. (2000) Speech recognition by normal-hearing and cochlear implant listeners as a function of intensity resolution. *J Acoust Soc Am* 108(5):2377–2387.

Noble W, Jensen NS, Naylor G, Bhullar N, Akeroyd MA. (2013) A short form of the Speech, Spatial and Qualities of Hearing scale suitable for clinical use: the SSQ12. *Int J Audiol* 52(6):409–412.

Revit LJ, Killion MC, Compton-Conley CL. (2007) Developing and testing a laboratory sound system that yields accurate real-world results. *Hear Rev* 14(11):54.

Schleich P, Nopp P, D'Haese P. (2004) Head shadow, squelch, and summation effects in bilateral users of the MED-EL COMBI 40/40+ cochlear implant. *Ear Hear* 25(3):197–204.

Taal CH, van Barneveld DC, Soede W, Briaire JJ, Frijns JHM. (2016) Benefit of contralateral routing of signals for unilateral cochlear implant users. *J Acoust Soc Am* 140(1):393.

Van Loon MC, Goverts ST, Merkus P, Hensen EF, Smits C. (2014) The addition of a contralateral microphone for unilateral cochlear implant users: not an alternative for bilateral cochlear implantation. *Otol Neurotol* 35:e233–e239.

Weder S, Kompis M, Caversaccio M, Stieger C. (2015) Benefit of a contralateral routing of signal device for unilateral cochlear implant users. *Audiol Neurotol* 20(2):73–80.

Wimmer W, Kompis M, Stieger C, Caversaccio M, Weder S. (2017) Directional microphone contralateral routing of signals in cochlear implant users. *Ear Hear* 38:368–373.