Audiological and Demographic Factors that Impact the Precision of Speech Categorization in
Cochlear Implant Users

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Abstract

Objectives: The ability to adapt to subtle variation in acoustic input is a necessary skill for successful speech perception. Cochlear implant (CI) users tend to show speech perception benefits from the maintenance of their residual acoustic hearing. However, previous studies often compare CI users in different listening conditions within-subjects (i.e., in their typical Acoustic + Electric configuration compared to Acoustic-only or Electric-only configurations) and comparisons among different groups of CI users do not always reflect an Acoustic + Electric benefit. Existing work suggests that CI users with residual acoustic hearing perform similarly to Electric-only listeners on phonetic voicing contrasts and unexpectedly poorer with fricative contrasts which have little energy in the range of the Acoustic + Electric listeners' acoustic hearing. To further investigate how residual acoustic hearing impacts sensitivity to phonetic ambiguity, we examined whether device configuration, age, and device experience influenced phonetic categorization in a large individual differences study.

Design: CI users with various device configurations (Electric-only N = 41; Acoustic + Electric N = 95) categorized tokens from five /b-p/ and five /s-f/ minimal pair continua (e.g., bet-pet; sock-shock). We investigated age, device experience, and when applicable, residual acoustic hearing (pure tone hearing thresholds) as predictors of categorization. We also examined the relationship between phonetic categorization and clinical outcomes (CNC, AzBio) in a subset of our sample.

Results: Acoustic + Electric CI users were better able to categorize along the voicing contrast (steeper categorization slope) compared to Electric-only users, but there was no group-level difference for fricatives. There were differences within the subgroups for fricatives: bilateral users showed better categorization than unilateral users and bimodal users had better categorization than hybrid users. Age was significant factor for voicing, while device experience was significant for fricatives. Critically, within the Acoustic + Electric group, hybrid CI users with better residual acoustic hearing (better pure tone hearing thresholds) had shallower slopes than those with poorer residual hearing.

Conclusions: Our findings suggest residual acoustic hearing is beneficial for categorizing stop voicing, but not frication. Age impacts the categorization of voicing, while device experience matters for fricatives. For CI users with ipsilateral residual acoustic hearing, those with better hearing thresholds may be over-relying on their acoustic hearing rather than extracting as much information as possible from their CI, and thus have worse fricative categorization.

Introduction

Cochlear implants restore sound to profoundly deaf individuals by bypassing damaged hair cells in the cochlea to directly stimulate the auditory nerve. However, the signal received from the implant is degraded compared to the acoustic input of a normal hearing listener. This is largely because the entire range of acoustic frequencies must be transmitted across a small number of electrode channels (typically around 22), though there are other sources of degradation (e.g., limited frequency range). Consequently, post-lingually deaf Cochlear Implant (CI) users must adapt auditory and speech perception systems that were previously developed to handle high fidelity acoustic input to the novel patterns of electrical stimulation from the CI. This adaptation can take up to a year or more, as reflected in improving speech recognition performance in the time since implantation (Dorman et al., 2006).

In recent years, standards of cochlear implantation have changed to embrace bilateral implantation, and candidacy has expanded to include people with less than profound hearing loss. Consequently, there is wide variation in the types of hearing devices used by many CI users. This depends on the type and nature of the hearing loss, and the standards of care in the clinical units that treat them. Some users will only receive electric stimulation through a full-length implant, either in a single ear or in both (traditional *unilateral* and *bilateral* implants). Others receive both acoustic and electric (A+E) stimulation, in which some acoustic hearing is preserved to combine with the implant. Classically, this A+E stimulation has been achieved via *bimodal* configurations, in which the listener has a CI on one ear and uses hearing aid to amplify any residual hearing in the contralateral ear (Wilson & Dorman, 2008). However, in recent years, newer (*hybrid*) implantation strategies leverage residual acoustic hearing in the implanted (ipsilateral) ear (Gantz et al., 2005; Woodson et al., 2009). These hybrid configurations use a CI that is constructed to maintain ipsilateral low-frequency acoustic hearing (and are sometimes shorter than a standard electrode).

These differences in device configuration lead to unique challenges for different types of

CI users. While all CI users must adapt to novel stimulation through their implant, A+E users must also learn to integrate electric stimulation with acoustic hearing to take advantage of all the information available to them, and this in turn may differ depending on whether acoustic hearing is arriving in the contra- or ipsilateral ear. Despite these challenges it is clear that most A+E users do benefit from the acoustic hearing (Dorman et al., 2008; Gantz et al., 2005; Turner et al., 2004, 2008). However, a recent study suggests that this may not be uniformly true across all speech sounds, particularly voiceless fricatives (McMurray et al., 2016); this rather special case could reveal limits to how A+E users adapt to their listening configuration. The goal of the present study is to examine this more closely with a large and variable sample of CI users.

Benefits and limits of A+E Listening

Generally, there is a benefit for maintaining residual acoustic hearing in some form, as seen in gross outcome measures of word and sentence recognition. Substantial work compares A+E listeners in such measures with and without acoustic hearing. Monosyllabic word recognition is usually improved in combined A+E listening compared to unilateral E-only stimulation (Dorman et al., 2008), although some individuals do not show an acoustic benefit for word recognition in quiet (Dunn et al., 2005; Mok et al., 2006). Tests that directly compare types of listeners are more limited, but also show a benefit. Listeners in an A+E configuration often have better speech recognition in noise compared to E-only CI users (Dorman & Gifford, 2010). For example, when Hybrid CI are matched with E-only CI users on their speech in quiet performance, speech in noise performance showed benefit of up to around 9 dB SNR (Gantz et al., 2005; Turner et al., 2004). Combined A+E stimulation also benefits pitch discrimination and melody recognition in CI users. For example, Gfeller et al. (2007) showed that hybrid CI users performed similarly to NH when determining the direction of a pitch change (high-to-low or low-to-high) while standard CI users performed worse. This was especially true at lower frequencies (i.e., where the hybrid listeners are more likely to have residual acoustic hearing).

At the level of perception of individual speech sounds, however, A+E CI users do not always perform better than E-only users. McMurray et al. (2016) presented continua of stops and fricatives to groups of CI users and NH listeners in an analogue of traditional phoneme identification tasks. These contrasts were chosen to highlight information that would primarily be transmitted by CIs (high-frequency spectral information for /s-/j/) or primarily by acoustic hearing (low-frequency voicing information for /b-p/). Stops were categorized similarly among both A+E and E-only CI users, though both showed shallower categorization slopes than NH listeners (indicating noisier or more gradient categorization). Importantly, for fricatives, A+E CI users had unexpectedly *shallower* categorization slopes than E-only CI users. That is, they appeared to perform worse. While the sample size was modest (N = 30), this was true for both hybrid and bimodal CI users. Residual acoustic hearing, in this case, was not advantageous for stop perception and seemed to be detrimental to fricative perception.

These results are surprising for two reasons. First, any simple reading of the extant literature would suggest that A+E users should have sharper categorization across both contrasts, but an even more fine-grained reading would suggest a benefit for a voicing contrast (where the acoustic stimulation should help), and no benefit for fricatives (where it should not). Zhang et al. (2010), for example, found that most of the benefit from combined A+E stimulation came from the low frequency region around the F0 of the voice. This should predict a benefit for a stop voicing continuum, where this acoustic range is critical. In contrast, fricatives—where the differences were observed—do not have any meaningful information in the range of a A+E listeners' residual acoustic hearing and should be entirely transmitted through their CI. This is particularly the case for bimodal users, who receive a full-length implant like unilateral users, and any amplified acoustic hearing is likely to be irrelevant (since there is no information in that range). Thus, there is no audiological reason why bimodal users' implant is different from a unilateral user. Given these facts, this study appears to suggest that A+E users may be getting less information from their implant than E-only listeners, or that they may be over-relying on

79 their acoustic hearing (which cannot help them with these fricatives).

80 Evidence from Mok et al. (2006) supports the idea that bimodal users may not always
81 take full advantage of their CI. They tested bimodal listeners with and without their hearing aid
82 to compute a bimodal benefit (A+E minus E-only). They unexpectedly found that bimodal CI
83 users with poorer residual hearing showed a greater bimodal benefit. Individuals with better
84 residual hearing did not improve as much in the combined hearing aid + CI listening condition
85 as those with poorer residual hearing. For these bimodal users, Mok et al. (2006) suggests that
86 their residual mid- to high-frequency acoustic hearing may provide conflicting information that is
87 hard to integrate with the CI. While not tested by Mok et al., the same premise could be true of
88 hybrid CI users. For hybrid users, residual low-frequency hearing from their implanted ear could
89 be difficult to integrate with information from their CI. This could explain why A+E users in
90 McMurray et al. (2016) did not see a benefit during stop voicing categorization.

91 Second, the McMurray et al. (2016) result is surprising because it calls into question the
92 assumption that acoustic hearing will always outperform electric stimulation. The evidence base
93 for this assumption is not as strong as one might think. Most investigations of residual acoustic
94 hearing in CI users do not compare performance of A+E users to different E-only CI users.
95 Rather, these studies use within-subjects designs that compare performance by CI users with
96 residual acoustic hearing in their day-to-day A+E configuration to performance in an E-only
97 configuration (Dorman & Gifford, 2010; Dunn et al., 2005; Gantz et al., 2005; Mok et al., 2006;
98 Turner et al., 2004). However, in such studies, the A+E condition is the configuration they use
99 every day—the E-Only condition (where subjects often performed worse) is a less familiar
100 listening configuration.

101 True comparisons between groups are rare (though see: Dorman & Gifford, 2010; Gantz
102 et al., 2005; Turner et al., 2004). This is in part because it is quite difficult to properly match
103 groups on things like age, device use, and most importantly pre-implantation audiological
104 capacities. A randomized control trial is not possible. Different kinds of listener will be eligible for

a hybrid or bimodal CI and who gets a standard electrode: those with better residual hearing and thus, better neural health, can receive the shorter electrode to maintain their acoustic hearing, while someone with more substantial hearing loss (and likely also poorer neural health) generally receive a full electrode. Differences between groups may also be confounded with age—people who were implanted decades ago (and are therefore older) may have only had the option of an E-only configuration, or older individuals who received an A+E configuration years earlier may have lost their residual hearing. These effects are also confounded with device experience: older adults, for example, may have worse residual hearing but longer experience with their CI depending on when they received it. These confounds make it difficult to construct well matched groups to execute a true between-subjects comparison.

Beyond these issues, there are also concerns about collapsing different A+E listening configurations. While McMurray et al. (2016) did not find differences between bimodal and hybrid listeners, these devices are often tuned differently. At the time of that study, hybrid implants at the University of Iowa were generally tuned to avoid overlap in frequency with the listener's residual acoustic hearing. As a result, low frequencies (below approximately 1000 Hz) may be transmitted only via acoustic hearing, and not via the CI. In contrast, bimodal listeners typically receive an implant tuned to the full spectrum (since their residual hearing will be from the contralateral ear). A larger sample with greater audiological diversity may be able to tease this apart.

The Present Study

The present study set out to address these questions by testing a large sample of CI users, including E-Only users (unilateral and bilateral), along with both bimodal and hybrid A+E listeners. This was intended to permit a multiple regression approach better investigate the role of residual acoustic hearing for phonetic perception while controlling for age, device experience, etc. We tested the same phonetic contrasts as McMurray et al. (2016). As in that study,

listeners heard tokens from a stop-voicing and fricative-place continuum spanning two words (e.g., *beach/peach*, *sip/ship*), and selected the corresponding picture. While McMurray et al. (2016) also used eye-tracking as a more sensitive measure of sensitivity to within-category structure (and not just categorization), we used only the overt identification measure, as that was sufficient to show group differences in the prior task, and the number of participants we intended to test called for a shorter experiment than would be appropriate for eye-tracking.

Critically, in this 2AFC / speech continuum task “better” categorization is reflected in steeper categorization slopes. This pattern of data is often associated with categorical perception (Liberman et al., 1957), in which sharp categorization is thought to be the ideal and is achieved by ignoring within category variation. We make no such assumptions here; in fact, it is now well understood that gradient sensitivity to within category detail is the norm (Andruski et al., 1994; McMurray et al., 2002; Miller, 1997); and that higher within-category sensitivity can be linked to steeper categorization slopes (McMurray et al., 2018). However, in this case, we see steeper categorization not as indicative of an underlying mechanism of perception, but rather as indicative that listeners simply more consistent in how they categorize the sounds. We return to this theoretical and methodological debate in the general discussion.

We examined several factors that might influence phonetic categorization. First, we compared A+E and E-Only CI users and further broke down these groups into more specific device configurations (unilateral, bilateral, bimodal, hybrid, and single-sided deafness). In addition to the standard subgroups of A+E and E-Only listeners (hybrid, bimodal, unilateral, and bilateral CI users), we also included single-sided deafness listeners (SSD), who represent a rather extreme case of A+E listening. In these listeners, one ear has complete access to the full spectrum (i.e., has hearing thresholds within the normal range) while the other ear has a CI.

Second, to explain the variability within CI users, we also examined age and device experience as predictors of categorization. All of the tested CI users had at least one year device experience and should be well-adapted to their CI, thus we did not expect large effects of

experience (since overall speech perception usually plateaus at around a year). However, it may capture slower and more subtle differences past the initial learning period. Age was included because older adults tend to have poorer acoustic hearing thresholds, but age also impacts central auditory processing (e.g., Bidelman et al., 2014) and may thus especially impact timing cues for stop perception.

Third, we examined degree of residual hearing (for A+E listeners). Our hypothesis was that individuals with better residual hearing over-rely on their acoustic hearing even when they could receive more information through their implant (As in Mok et al. (2006)). If this is the case, then individuals with poorer residual hearing in the mid- to high-range will show greater acoustic-electric performance than those with better residual hearing, an effect that should be highlighted by the fricatives, which functionally isolate the CI only. We specifically address this by asking how residual hearing thresholds (as measured by pure-tone audiometry) impact perception of acoustic cues in stops and fricatives in a group of A+E CI users.

Finally, we sought to relate phonetic categorization to standard clinical measures of speech perception. For a subset of our participants, we obtained assessment scores from tests of word and sentence recognition. The ability to perceive fine-grained acoustic detail is likely beneficial to the process of recognizing words, so we expected listeners with better categorization to also perform better in standard clinical assessments. Steeper categorization of phonetic continua, in this case, reflects more definitive (i.e., less noisy) perception, which in turn could benefit the mapping of speech sounds to words.

Unlike prior studies, we did not test listeners in different listening configurations (e.g., with and without their hearing aid). This was for three reasons. First, the huge variety of device configurations made standardization of this difficult; for example, some hybrid listeners have residual acoustic hearing in both ears, while others use only one. Second, we wanted to ensure that all listeners were performing the task in their usual, most familiar configuration. Finally, our primary goal was a between-subjects comparison among people who are all using their

Table 1. Summary of participant demographics.

Group	N	Mean Age (SD)	Mean Device Experience (SD) in years
Electric-Only			
Unilateral	18	58.5 (11.2)	12.8 (9.1)
Bilateral	23	57.0 (13.2)	7.8 (5.2)
Acoustic + Electric			
Bimodal	43	60.4 (10.0)	3.4 (3.4)
Hybrid	25	62.5 (10.2)	2.0 (1.6)
Single-Sided Deafness (SSD)	27	54.3 (12.4)	2.9 (1.7)

everyday listening configuration.

Materials and Methods

Participants

CI users were recruited through the Cochlear Implant Research Center at the Department of Otolaryngology, University of Iowa Hospitals and Clinics. 147 post-lingually deafened CI users completed this task as part of a longer visit to the lab. 11 participants were excluded because their data were incomplete, which leaves 136 participants (69 female, 67 male). All recruitment and experimental protocols were approved by the Institutional Review Board at the University of Iowa.

The CI users included a range of device configurations. Because an individual's residual acoustic hearing could deteriorate over time, we used the participant's PTA on the test day to determine which device configuration A+E subjects should be classified in. We used 85 dB HL as a cut-off for recategorizing participants. Hybrid users with a low frequency PTA poorer than 85 dB on their ipsilateral side would be recategorized depending on the status of their contralateral ear. If they were a bilateral hybrid user, they would remain categorized as a hybrid user as long as one ear passed our PTA criterion. If the hybrid user had a contralateral hearing aid (and that ear still passed our PTA cut off), they would be categorized as bimodal. Based on this criterion, we recategorized 17 hybrids as bimodal CI users and 1 bilateral hybrid as a bilateral (traditional) CI user. Table 1 summarizes the demographic breakdown of each

participant group. The average age of the included participants was 58.7 years old, with a mean device experience of 5.0 years. A complete list of participant characteristics, including information about their hearing and their demographic details, is provided in the OSF repository associated with this paper (<https://osf.io/z5e3y/>).

Design

We used five minimal pairs for each contrast (10 total). From each pair, we constructed an 8-step continuum. Fricative minimal pairs were *shack-sack*, *shave-save*, *shelf-self*, *ship-sip*, *shock-sock*. Stop voicing minimal pairs were *beach-peach*, *bear-pear*, *bet-pet*, *bin-pin*, *bug-pug*.

Each continuum step was presented 5 times for a total of 400 trials (2 contrasts x 5 continua/contrast x 8 steps x 5 repetitions). The trials were randomized so that stimuli from different continua were interleaved. The visual display contained the two images representing the endpoints of the continuum for that trial and two images for a minimal pair from the other contrast. Thus, images for fricative minimal pairs served as the unrelated images for stop trials and vice versa. The pairing between fricative and stop continua was randomized across subjects, but was fixed within a subject's session (i.e., *shock-sock* might be consistently paired with *beach-peach* for one subject, but with *bet-pet* for another). Image positions were randomized across the four quadrants of the computer screen, such that all the possible combinations of target, competitor, and two distractors appeared equally often in each position.

Stimuli

We used the same auditory and visual stimuli as in McMurray et al. (2016). Briefly, auditory stimuli were spoken by a male speaker of American English. Fricative continua were created by extracting the long-term spectra of the fricatives, aligning them by their spectral means, and creating intermediate steps that varied in spectral shape. These were then shifted by spectral mean from /s/ to /ʃ/ (see Figure 2, McMurray et al., 2016). Stop voicing continua

were created by successively cross-splicing the minimal pairs to make voice onset time (VOT) steps. That is, a section from the onset of the voiced token (e.g., *beach*) was cut and replaced by the onset of the voiceless token (e.g., *peach*).

Visual stimuli were images from a clipart database that had been selected from several options as the most prototypical image for a given target word. Images were edited for clarity and visual style to minimize distractions. All images received final approval by a senior member of the lab with extensive experimental experience.

Procedure

Participants were seated in a sound-attenuated booth in front of a 19" computer screen with a resolution of 1024×1280. Auditory stimuli played over loudspeakers approximately 1 meter from the participant. Participants were first familiarized with the picture-word pairings that would appear in the experimental task. Each image was presented in the middle of the computer screen with its label printed in all capital letters below. Participants were instructed to move through each image at their own pace by pressing the space bar. The experimental task was explained following the picture familiarization.

During the experimental task, four images were displayed (two for a stop continuum, two for a fricative continuum) with a red circle in the center. After 500 msec, the circle turned blue, and the participant clicked on it to play a word over the loudspeakers. Participants were instructed to click on the picture that best matched what they heard. The entire task took approximately 30 minutes.

Data Processing

Responses were coded separately for each contrast. For the stops, /p/ responses were coded as 1 and /b/ responses were coded as 0. For the fricatives, /s/ responses were coded as 1 and /ʃ/ responses were coded as 0. Any responses that were for the other contrast (i.e.,

selection of a fricative image to a stop auditory target) were excluded.

To account for differences in the *placement* of the category boundary along the continua, rather than the *slope* of the boundary, we relativized the continua steps to each participant's boundary. This allows us to focus on how listeners are dealing with the ambiguity of the stimuli by setting everyone's category boundary to zero. Positive steps represent movement towards the /p/ or /s/ end of the continua and negative steps represent movement towards the /b/ or /j/ end for stops and fricatives respectively. We fit a series of logistic regressions using the *glmer* function (family=binomial) in R (lme4 version 1.1-26; Bates et al., 2015; R version 4.0.4; R Core Team, 2021) to find the boundary crossing for each subject. This boundary value was then subtracted from each continuum step to relativize step to each listener's category boundary. If a listener's category boundary was estimated to be too extreme (i.e., fell outside of steps 2 through 7), their data were excluded from further analysis (n = 13).

Analyses

We started with an initial analysis that examined only the effect of hearing configuration, in order to better understand the overall group differences. We next present our primary analyses that include demographic and hearing factors as moderators. After that, we examine the effect of residual acoustic hearing as a moderator for the A+E group only. Finally, we related audiological outcomes (performance in two standard tests of speech perception) to individual differences in stop and fricative categorization.

Effect of Hearing Configuration. First, we analyzed stop-voicing and fricative categorization as a function of hearing configuration. We ran separate logistic mixed effects models for stop and fricative categorization. Both models used the same structure given in (1), in the notation of the *glmer()* function in R.

$$\text{response} \sim r\text{Step} * \text{hearing configuration} + (1 + r\text{Step} || \text{participant}) + (1 + r\text{Step} || \text{item}) \quad (1)$$

Here, rStep refers to the relative continuum step (after adjusting for the subject's own boundary). This was further centered. Hearing configuration was coded with a set of four contrast codes, each individually designed to test specific comparisons of interest: a) SSD users (+1) to the rest of the subjects (-0.25), b) E-only (-0.25) users to A+E (+0.25), c) Unilaterals (-0.5) to Bilaterals (+0.5, with all other groups set to 0), and d) Hybrids (-0.5) to Bimodals (+0.5, with all other groups set to 0). The interaction between rStep and the Hearing configuration contrasts were the crucial predictors in this model, as these can reveal if the slope of the categorization function (the effect of rStep) differed across hearing configurations. We included the maximal random effects structure for all models: random intercepts and slopes for rStep by subjects and items (distinct continua).

Effect of Participant Characteristics. As we described in the introduction, a variety of demographic and audiological factors must be accounted for, before we can be confident in differences among listening configurations. We thus ran two additional logistic mixed-effects models, again examining stop-voicing and fricatives separately. These models were based on the prior models and included age and device experience as main effects. As there were difficulties getting this model to converge, we dropped the four-way interaction. This model is given in (2).

$$\begin{aligned} \text{response} \sim & \text{rStep} * \text{hearing configuration} * \text{age} + \\ & \text{rStep} * \text{hearing configuration} * \text{device experience} + \\ & (1 + \text{rStep} || \text{participant}) + (1 + \text{rStep} || \text{item}) \end{aligned} \quad (2)$$

We excluded the SSD listeners from these models to focus on individuals who had a more typical pattern of hearing loss. Hearing configuration was coded with a set of three contrast codes: a) E-only (-0.25) users to A+E (+0.25), b) Unilaterals (-0.5) to Bilaterals (+0.5, with all other groups set to 0), and c) Hybrids (-0.5) to Bimodals (+0.5, with all other groups set to 0). We centered rStep, age, and device experience. We included the three-way interactions between rStep, age, and hearing configuration and between rStep, device experience, and hearing configuration, along with their component two-way interactions. Again, the crucial

interactions are with rStep as these would suggest that the slope of the categorization function is affected by the other predictors. We included random intercepts and slopes by rStep on participants and items.

Effect of Residual Hearing. We restricted this analysis to bimodal and hybrid CI users who have residual acoustic hearing on the contralateral and ipsilateral ear, respectively. We again ran separate mixed-effects logistic regression for stop voicing and fricatives using the model shown in (3).

$$\begin{aligned} \text{response} \sim & \text{rStep} * \text{hearing configuration} * \text{better PTA} + \\ & \text{rStep} * \text{age} + \text{rStep.std} * \text{devExp} + \\ & (1 + \text{rStep} || \text{participant}) + (1 + \text{rStep} || \text{item}) \end{aligned} \quad (3)$$

We have contrast coded hearing configuration; this time to compare hybrid (-0.5) to bimodal (+0.5) CI users. We used better ear pure tone average (PTA) as our measure of residual acoustic hearing. This means that for subjects who had residual hearing in both ears, we took the better (lower) of the two as their threshold of hearing. PTA was centered and included as a predictor along with centered rStep in both logistic mixed effects models. We included age and device experience (both centered) and their interactions with rStep. Both models included random intercepts and slopes by rStep for participants and items.

Relationship to Clinical Outcomes. One concern is that the effects on phonetic categorization are small and may not generalize to everyday performance. Thus, our final analysis sought to determine the degree to which performance in these speech categorization tasks is related to individual differences in standard clinical assessments of speech perception for CI users. We obtained several measures of word and sentence recognition for a large subset of these users. Measures included the Consonant-Nucleus-Consonant (CNC) test of word recognition (Peterson & Lehiste, 1962) and the AzBio test of sentence recognition (Spahr et al., 2012) in both quiet and noise (+5 dB SNR). We were not able to obtain these scores for our full sample, so analyses will be carried out on a subset of the data (CNC N = 109, AzBio in quiet N = 61, AzBio in noise N = 62).

We ran separate linear regressions that predicted performance in each test (CNC, AzBio quiet, AzBio noise) as a function of categorization of each phonetic contrast (stops, fricatives). To quantify the slope of each contrast for each subject, we ran two logistic mixed effects models predicting either /p/ response for the stops or /s/ response for the fricatives. We included rStep as a main effect and random intercepts and slopes by rStep by subject and by item. We then used each subject's random effect of rStep as an estimate of their stop or fricative categorization (which we term *categorization slope*). The random slope of rStep for each subject reflects how much an individual varies around the estimate of rStep, and thus provides a measure of their categorization slope. A positive random slope for a given participant reflect a larger effect of rStep (steeper slope), while negative slopes reflect a smaller effect of rStep (shallower slope) than the group average. Note that these models did not include any of the fixed effects from the above models as this would have converted our measure of speech categorization to a relative measure (how much better was a listener doing than they would be predicted by their age, device experience, PTA, etc.).

The categorization slope from stop voicing and fricatives were only moderately correlated ($r = 0.42$, $p < 0.001$), so we did not calculate a composite effect and instead ran separate regressions for each phonetic contrast. We included these slopes as predictors in the linear regressions, along with the Hearing configuration comparison between E-only (-0.5) and A+E (0.5) listeners, and age (centered). The model formulae are given in (4).

$$Accuracy \sim categorization\ slope * hearing\ configuration + age \quad (4)$$

Results

We present the results from our analyses of the stop-voicing contrast followed by the analyses of frication.

Stop Voicing

Figure 1. Proportion /p/ response to all /b-p/ continua for each listening configuration by (A) original continuum step and by (B) relative continuum step.

Effect of Hearing Configuration. Figure 1 shows the mean proportion responses for the voicing contrasts as a function of hearing configuration (Unilateral, Bilateral, Bimodal, Hybrid, and SSD). Panel A shows the raw data, and panel B shows the data after alignment by the subjects' crossover (the basis of the analysis). As is evident in Figures 1, SSD users displayed the sharpest categorization. This is perhaps not surprising, as they have a completely NH ear. Within the more canonical CI users, A+E users appear to have sharper categorization for stop-voicing than E-only users (solid lines compared to dotted lines in Figure 1B).

Table 2 shows the results for the mixed-effect model investigating hearing configuration for stop-voicing categorization. We found the expected main effect of rStep ($B = 5.98$, $z = 15.36$, $p < .001$): as subjects moved from the negative rSteps to the positive rSteps, they were more likely to respond with /p/. There were two main effects of listener group, implying differences in the overall bias to /b/ or /p/. SSD subjects showed lower /p/ responses than the other groups ($B = -0.16$, $z = -2.25$, $p = .02$) and A+E subjects also showed lower /p/ responding than the E-only subjects ($B = -0.36$, $z = -2.21$, $p = 0.03$). In both cases, the presence of acoustic information seemed to bias listeners to hear more /b/. Note that because of the way that rStep was adjusted

Table 2. Summary of the mixed effects logistic regression (Equation 1) assessing stop voicing categorization, predicted by rStep and hearing configuration. * $p < .05$

Estimate	B	SE	z	p	
rStep	5.98	0.39	15.36	< .001	*
Hearing config (SSD vs everyone else)	-0.16	0.07	-2.25	0.02	*
Hearing config (A+E vs E-only)	-0.36	0.16	-2.21	0.03	*
Hearing config (Bi- vs Unilateral)	-0.11	0.13	-0.9	0.37	
Hearing config (Bimodal vs Hybrid)	0.06	0.10	0.61	0.54	
rStep x Hearing config (SSD vs everyone else)	1.98	0.39	5.13	< .001	*
..... x Hearing config (A+E vs E-only)	2.91	0.86	3.37	< .001	*
..... x Hearing config (Bi- vs Unilateral)	0.79	0.67	1.17	0.24	
..... x Hearing config (Bimodal vs Hybrid)	-0.56	0.54	-1.02	0.31	

on a per subject basis, this bias does not reflect a shift in the category boundary, but rather an overall higher likelihood of responding /b/.

Of particular interest, the interaction between rStep and Hearing configuration was significant for SSD subjects compared to everyone else ($B = 1.98$, $z = 5.13$, $p < .001$) and for A+E compared to E-only ($B = 2.91$, $z = 3.37$, $p < .001$). This means that SSD CI users had a steeper slope than the other subjects (a larger effect of rStep) and the A+E CI users had a steeper slope than E-only users. This suggests that the failure to observe the A+E benefit by McMurray et al. (2016) was likely due to reduced power.

Effect of Participant Characteristics. We next examined the same effects after accounting for demographic factors that maybe confounded with performance (Table 3, Equation 2 for model). Subjects were more likely to respond with /p/ with increasing rSteps ($B = 5.51$, $z = 13.17$, $p < 0.001$). There were two main effects of hearing configuration: A+E listeners were less likely to respond with /p/ compared to the E-only listeners ($B = -0.57$, $z = -3.17$, $p = 0.002$) and Bimodal CI users were more likely respond with /p/ compared to the Hybrid CI users ($B = 0.31$, $z = 2.64$, $p = 0.008$). There was also a main effect of age ($B = 0.18$, $z = 2.34$, $p = 0.02$) and device experience ($B = -0.18$, $z = -2.22$, $p = 0.03$), meaning that older subjects were more likely to respond with /p/, as were those with less device experience. The interaction

between device experience and bimodal vs. hybrid hearing configuration was also significant ($B = 0.80$, $z = 3.21$, $p = 0.001$), meaning that the hybrid CI users had a larger effect of device experience (more overall /p/ responding) compared to the bimodal users.

The critical interactions are with rStep. As with the initial model, the effect of rStep was significantly different between A+E and the E-only listeners ($B = 3.85$, $z = 3.82$, $p < 0.001$; Figure 2A) with steeper categorization slopes for A+E listeners. There was also a significant interaction between rStep and age ($B = -1.86$, $z = -4.46$, $p < 0.001$; Figure 2B): as age increased, subjects showed shallower categorization slopes. No other interactions with rStep

Table 3. Summary of a logistic mixed effects model (Equation 2) assessing stop voicing categorization, predicted by rStep, hearing configuration, age, and device experience.

Effect	B	SE	z	p	
rStep	5.51	0.42	13.17	< .001	*
Hearing configuration (A+E vs E-only)	-0.57	0.18	-3.17	0.002	*
Hearing configuration (Bi- vs Unilateral)	0.05	0.14	0.32	0.75	
Hearing configuration (Bimodal vs Hybrid)	0.31	0.12	2.64	0.008	*
Age	0.18	0.08	2.34	0.02	*
Device Experience	-0.18	0.08	-2.22	0.03	*
Age x Hearing configuration (A+E vs E-only)	-0.67	0.3	-2.23	0.03	*
x Hearing configuration (Bi- vs Unilateral)	-0.18	0.22	-0.8	0.43	
x Hearing configuration (Bimodal vs Hybrid)	-0.01	0.2	-0.07	0.95	
Device Experience x Hearing configuration (A+E vs E-only)	-0.53	0.33	-1.59	0.11	
x Hearing configuration (Bi- vs Unilateral)	-0.37	0.22	-1.69	0.092	
x Hearing configuration (Bimodal vs Hybrid)	0.80	0.25	3.21	0.001	*
rStep x Hearing configuration (A+E vs E-only)	3.85	1.01	3.82	< .001	*
..... x Hearing configuration (Bi- vs Unilateral)	0.24	0.79	0.31	0.76	
..... x Hearing configuration (Bimodal vs Hybrid)	-1.21	0.62	-1.94	0.05	
..... x Age	-1.86	0.42	-4.46	< .001	*
..... x Device Experience	0.43	0.46	0.94	0.35	
rStep x Age x Hearing configuration (A+E vs E-only)	2.11	1.61	1.31	0.19	
..... x Hearing configuration (Bi- vs Unilateral)	0.93	1.21	0.77	0.44	
..... x Hearing configuration (Bimodal vs Hybrid)	0.60	1.12	0.54	0.59	
rStep x Device Exp. x Hearing configuration (A+E vs E-only)	0.59	1.81	0.33	0.74	
..... x Hearing configuration (Bi- vs Unilateral)	1.10	1.21	0.91	0.36	
..... x Hearing configuration (Bimodal vs Hybrid)	-1.60	1.34	-1.19	0.23

Figure 2. Proportion /p/ response by relative continuum step for A) Acoustic + Electric and E-only hearing configurations and B) median split by age.

were significant.

Effect of Residual Acoustic Hearing. For the model investigating residual hearing for stop-voicing categorization (Table 4), we again found the expected main effect of rStep ($B = 6.48$, $z = 15.17$, $p < 0.001$). There is also a significant main effect of PTA ($B = -0.19$, $z = -2.02$, $p = 0.04$): as PTA increased (i.e., residual hearing becomes worse), subjects are more likely to respond with /p/. There is also a significant interaction between Hearing configuration (Hybrid vs. Bimodal) and PTA ($B = 0.41$, $z = 2.13$, $p = 0.03$), suggesting that the Hybrid CI users have a larger effect of PTA overall. That is, the Hybrid listeners with poorer PTA are more likely to respond with /p/.

We are again most interested in the interactions with rStep. The only significant interaction with rStep was age ($B = -1.50$, $z = -2.31$, $p = 0.02$). This is consistent with our previous analysis: older CI users have shallower slopes while categorizing stop voicing compared to younger CI users. The lack of an interaction of rStep and PTA is consistent with the idea that as long as listeners have some residual hearing, they can reap the benefits of acoustic hearing, but it may not matter how much.

Table 4. Summary of a logistic mixed effects model (Equation 3) assessing stop voicing categorization, predicted by rStep, residual acoustic hearing, age, and device experience for A+E CI users.

Effect	B	SE	z	p	
rStep	6.48	0.43	15.17	< 0.001	*
Hearing configuration (Hybrid vs Bimodal)	0.17	0.1	1.73	0.08	
Age	0.08	0.10	0.79	0.43	
Device Experience	-0.04	0.10	-0.42	0.67	
Better ear PTA	-0.19	0.09	-2.02	0.04	*
Hearing configuration (Hybrid vs Bimodal) x Better ear PTA	0.41	0.19	2.13	0.03	*
rStep x Hearing configuration (Hybrid vs Bimodal)	-0.64	0.59	-1.10	0.27	
..... x Age	-1.45	0.65	-2.24	0.03	*
..... x Device Experience	-0.2	0.63	-0.31	0.75	
..... x Better ear PTA	0.25	0.56	0.44	0.66	
rStep x Hearing config. (Hybrid vs Bimodal) x Better ear PTA	-1.92	1.14	-1.69	0.09	

Stop-Voicing Summary. Our first analysis suggests that SSD users perform better than other CI users in stop categorization—even A+E CI configurations (hybrid and bimodal). This is unsurprising given that they have a fully NH ear. Unlike McMurray et al. (2016), we found that A+E CI users showed steeper stop-voicing categorization than E-only users.

We also confirm the benefit of acoustic hearing for stop-voicing – even after controlling for confounding factors like age and device experience, A+E listeners have steeper categorization slopes compared to E-only listeners. In addition, these analyses point to the importance of age for stop-voicing categorization. We consistently find that increasing age impacts the categorization slope for stop voicing. We did not find any evidence that the *amount* of residual hearing impacts stop-voicing categorization, suggesting that the presence of residual acoustic information is enough to provide some benefit.

Fricative Categorization

Effect of Hearing Configuration. As with voicing, we started by examining the overall

Figure 3. Proportion /s/ response to all /f/-/s/ continua for each listening configuration by (A) original continuum step and by (B) relative continuum step.

effect of hearing configuration for fricative categorization (Table 5). We again found the expected main effect of rStep ($B = 5.96$, $z = 14.71$, $p < 0.001$), subjects responded more with /s/ as they moved from the negative to the positive ends of the continuum. We also saw some group level differences in response bias. The SSD subjects responded with /s/ more overall compared to everyone else ($B = 0.36$, $z = 3.43$, $p < .001$) and the bimodal users responded more with /s/ compared to the hybrid CI users ($B = 0.37$, $z = 2.46$, $p = .01$). Both groups with full spectrum acoustic input showed more /s/ responses.

The crucial effects were the interaction between rStep and Hearing configuration. Not surprisingly, SSD subjects had a steeper slope than other CI users ($B = 1.90$, $z = 4.68$, $p < .001$). There was no significant difference between A+E and E-only users, but within those groups, the bimodal CI users had a steeper slope than the hybrids ($B = 1.15$, $z = 1.94$, $p = .05$), and bilateral users had a steeper slope than unilateral ($B = 1.79$, $z = 2.50$, $p = .01$).

Effect of Participant Characteristics. Table 6 presents the summary of the model examining the effect of hearing configuration after accounting for demographic factors. The expected main effect of rStep was significant ($B = 4.92$, $z = 11.35$, $p < 0.001$); again, subjects were more likely to respond with /s/ as the stimulus moved from the negative to the positive

Table 5. Summary of a mixed effects regression assessing fricative categorization (Equation 1), predicted by rStep and hearing configuration.

Estimate	B	SE	Z	p	
rStep	5.96	0.41	14.71	< .001	*
Hearing config (SSD vs everyone else)	0.36	0.10	3.43	< .001	*
Hearing config (A+E vs E-only)	0.25	0.24	1.07	0.28	
Hearing config (Bi- vs Unilateral)	0.19	0.18	1.03	0.30	
Hearing config (Bimodal vs Hybrid)	0.37	0.15	2.46	0.01	*
rStep x Hearing config (SSD vs everyone else)	1.90	0.41	4.68	< .001	*
..... x Hearing config (A+E vs E-only)	0.61	0.92	0.66	0.51	
..... x Hearing config (Bi- vs Unilateral)	1.79	0.72	2.50	0.01	*
..... x Hearing config (Bimodal vs Hybrid)	1.15	0.59	1.94	0.05	*

steps of the continua. There are also significant main effects of hearing configuration for the comparison between A+E and E-only listeners ($B = 0.69$, $z = 2.52$, $p = 0.01$), age ($B = -0.25$, $z = -2.09$, $p = 0.04$), and device experience ($B = 0.31$, $z = 2.47$, $p = 0.01$). This means that the A+E listeners were more likely to respond with /s/, as were the younger participants and the participants with more device experience. The effect of age and device experience both interact with the A+E vs. E-only hearing configuration contrast. E-only listeners have a bigger effect of age on overall /s/ responding ($B = 1.01$, $z = 2.15$, $p = 0.03$), while A+E listeners have a bigger effect of device experience on overall /s/ responding ($B = -1.08$, $z = -2.16$, $p = 0.03$).

Turning to the critical interactions with rStep, we found a significant interaction between rStep and device experience ($B = 1.1$, $z = 2.13$, $p = 0.03$), suggesting that those with longer device experience have steeper fricative categorization. Both age and device experience also interact with rStep for the A+E vs. E-only listener comparison. Younger E-only listeners have steeper slopes than older E-only listeners, while A+E listeners do not show a large effect of age

Table 6. Summary of a logistic mixed effects model assessing fricative categorization (Equation 2), predicted by rStep, hearing configuration, age, and device experience.

Effect	B	SE	z	p	
rStep	4.92	0.43	11.35	< .001	*
Hearing configuration (A+E vs E-only)	0.69	0.27	2.52	0.01	*
Hearing configuration (Bi- vs Unilateral)	0.14	0.21	0.66	0.51	
Hearing configuration (Bimodal vs Hybrid)	0.26	0.17	1.5	0.13	
Age	-0.25	0.12	-2.09	0.04	*
Device Experience	0.31	0.13	2.47	0.01	*
Age x Hearing configuration (A+E vs E-only)	1.01	0.47	2.15	0.03	*
..... x Hearing configuration (Bi- vs Unilateral)	-0.03	0.33	-0.10	0.92	
..... x Hearing configuration (Bimodal vs Hybrid)	-0.59	0.34	-1.73	0.08	
Device Experience x Hearing configuration (A+E vs E-only)	-1.08	0.5	-2.16	0.03	*
..... x Hearing configuration (Bi- vs Unilateral)	0.41	0.34	1.22	0.22	
..... x Hearing configuration (Bimodal vs Hybrid)	-0.65	0.37	-1.75	0.08	
rStep x Hearing configuration (A+E vs E-only)	2.1	1.11	1.89	0.06	
..... x Hearing configuration (Bi- vs Unilateral)	1.64	0.86	1.90	0.06	
..... x Hearing configuration (Bimodal vs Hybrid)	0.86	0.71	1.22	0.22	
..... x Age	-0.45	0.49	-0.92	0.36	
..... x Device Experience	1.1	0.52	2.13	0.03	*
rStep x Age x Hearing configuration (A+E vs E-only)	5.42	1.84	2.95	0.003	*
..... x Hearing configuration (Bi- vs Unilateral)	-0.8	1.30	-0.61	0.54	
..... x Hearing configuration (Bimodal vs Hybrid)	-2.16	1.37	-1.57	0.12	
rStep x Device Exp. x Hearing configuration (A+E vs E-only)	-4.90	1.98	-2.47	0.01	*
..... x Hearing configuration (Bi- vs Unilateral)	1.44	1.36	1.06	0.29	
..... x Hearing configuration (Bimodal vs Hybrid)	-2.39	1.49	-1.61	0.11	

on their slopes ($B = 5.42$, $z = 2.95$, $p = 0.003$; Figure 4A). E-only listeners with longer device experience also have steeper slopes than E-only with less experience, while A+E listeners do not show a large effect of device experience on their slopes ($B = -4.90$, $z = -2.47$, $p = 0.01$; Figure 4B).

Effect of Residual Acoustic Hearing. Finally, we investigated the role of residual acoustic hearing for fricative categorization (Table 7). This showed the expected main effect of rStep ($B = 5.69$, $z = 11.55$, $p < 0.001$). There is also a main effect of hearing configuration ($B =$

Figure 4. Proportion /s/ response by relative continuum step for each hearing configuration (Acoustic + Electric vs. Electric-only) and median split by A) age and B) device experience.

0.49, $z = 3.24$, $p = 0.001$), suggesting that bimodal CI users are overall more likely to respond with /s/. The interaction between Hearing configuration and PTA ($B = -0.73$, $z = -2.40$, $p = 0.02$). This suggests that the effect of PTA on overall bias to respond /s/ flips between the two Hearing configuration groups: hybrid listeners with poorer PTA are more likely to respond with

/s/, while the opposite is the case for bimodal listeners.

Crucially, there were several significant interactions with rStep. Bimodal listeners had steeper slopes than hybrid listeners (rStep x Hearing configuration: $B = 1.71$, $z = 2.85$, $p = 0.004$). As we found in the prior analysis, listeners with longer device experience also had steeper slopes (rStep x Device experience $B = -1.17$, $z = -1.99$, $p = 0.05$). Critically, there was a three-way interaction between rStep, Hearing configuration, and PTA ($B = -3.05$, $z = -2.51$, $p = 0.01$), suggesting that the relationship between PTA and rStep is different for hybrid and bimodal CI users. In particular, hybrid users with *poorer* residual hearing have steeper slopes (better categorization), while PTA did not play a large role for bimodal listeners (Figure 5).

Table 7. Summary of a logistic mixed effects model assessing fricative categorization (Equation 3), predicted by rStep, residual acoustic hearing, age, and device experience for A+E CI users.

Effect	B	SE	z	p	
rStep	5.69	0.49	11.55	< 0.001	*
Hearing configuration (Hybrid vs Bimodal)	0.49	0.15	3.24	0.001	*
Age	-0.03	0.15	-0.20	0.84	
Device Experience	-0.24	0.15	-1.68	0.09	
Better ear PTA	-0.2	0.14	-1.37	0.17	
Hearing configuration (Hybrid vs Bimodal) x Better ear PTA	-0.73	0.30	-2.40	0.02	*
rStep x Hearing configuration (Hybrid vs Bimodal)	1.78	0.61	2.92	0.003	*
.....x Age	0.5	0.6	0.83	0.41	
.....x Device Experience	-1.17	0.59	-1.99	0.05	*
.....x Better ear PTA	-0.92	0.58	-1.57	0.12	
rStep x Hearing config. (Hybrid vs Bimodal) x Better ear PTA	-3.05	1.21	-2.51	0.01	*

Figure 5. Proportion /s/ response by relative continuum step for the Hybrid and Bimodal CI users median split by PTA.

Summary. In fricatives, we did not find a large group difference based on the availability of acoustic input (A+E vs. E-only). However, we did find differences within the subgroup comparisons (SSDs and bimodals were better than hybrids, bilaterals were better than unilaterals). This is inconsistent with McMurray et al.'s prior work but partially consistent with the baseline assumption that acoustic hearing would not contribute substantially to fricative performance.

When investigating demographic factors, we found that device experience affects slope for fricatives. The fricative perception of E-only CI users is impacted by both age and device experience: younger E-only listeners have steeper slopes, as do E-only listeners with longer device experience.

We also found an effect of residual acoustic hearing for fricatives. For the hybrid listeners, better residual acoustic hearing seems to be detrimental. Thus, maintaining acoustic hearing on the ipsilateral side may result in CI users over-relying on their acoustic hearing

(where there is no meaningful information for fricatives) instead of taking full advantage of their CI. Here we demonstrate that this effect may be primarily driven by hybrid, not bimodal, A+E listeners, a point we return to in the general discussion.

Relationship to Clinical Outcomes

Finally, we related the categorization slopes from the models above to standardized outcomes of speech perception. The models predicted outcomes from categorization slope, hearing configuration and age.

For **CNC word recognition in quiet** (Table 8), only the interaction between hearing configuration and either categorization slope was significant (Hearing config. x Stop categorization slope: $B = -8.21$, $t(104) = -3.07$, $p = 0.003$; Hearing config. x Fricative categorization slope: $B = -9.36$, $t(104) = -4.94$, $p < 0.001$). For both stop-voicing and fricatives, E-only listeners with steeper slopes performed better at CNC word recognition compared to those with shallower slopes, while opposite was true for A+E listeners (Figure 6).

The same relationship was seen for **AzBio in quiet** (Table 9). E-only listeners with a

Table 8. Summary of linear regressions investigating CNC scores (Equation 4), predicted by the random effect of stops or fricatives, hearing configuration, age, and device experience.

A) CNC score x Stops					
Effect	B	SE	t	p	
Intercept	69.89	2.82	24.8	< 0.001	*
Categorization slope (Stop voicing)	2.32	1.41	1.64	0.10	
Hearing configuration (E-only vs A+E)	-9.2	5.69	-1.62	0.11	
Age	5.05	4.76	1.06	0.29	
Hearing config. (E-only vs A+E) x Cat. Slope (Stop voicing)	-8.21	2.67	-3.07	0.003	*
B) CNC score x Fricatives					
Intercept	67.35	2.34	28.78	< 0.001	*
Categorization slope (Fricative)	1.49	0.96	1.57	0.12	
Hearing configuration (E-only vs A+E)	-3.80	4.65	-0.82	0.42	
Age	5.83	4.37	1.33	0.19	
Hearing config. (E-only vs A+E) x Cat. Slope (Fricative)	-9.36	1.89	-4.94	< 0.001	*

Figure 6. Accuracy on the CNC word recognition task for A+E and E-only CI users by A) the random effect of stops and B) the random effect of fricatives.

larger effect of rStep for both stops ($B = -12.63$, $t(56) = -4.30$, $p < 0.001$) and fricatives ($B = -13.18$, $t(56) = -4.25$, $p < 0.001$) scored higher at sentence recognition in quiet compared to those with shallower slopes, while the opposite was true for A+E listeners (Figure 7).

Finally, for **AzBio in noise** (Table 10), there was a main effect of the stop categorization slope ($B = 6.44$, $t(57) = 4.39$, $p < 0.001$) and of hearing configuration ($B = 11.83$, $t(57) = 2.36$, p

Table 9. Summary of linear regressions investigating AzBio in quiet (Equation 4), predicted by the random effect of stops or fricatives, hearing configuration, age, and device experience.

A) AzBio in quiet x Stops					
Effect	B	SE	t	p	
Intercept	81.89	3.22	25.45	< 0.001	*
Categorization slope (Stop voicing)	1.32	1.62	0.81	0.42	
Hearing config. (E-only vs A+E)	-12.21	6.26	-1.95	0.06	
Age	6.12	5.9	1.04	0.30	
Hearing config. (E-only vs A+E) x Cat. Slope (Stop)	-12.63	2.94	-4.30	< 0.001	*
B) AzBio in quiet x Fricatives					
Intercept	80.73	3.10	26.02	< 0.001	*
Categorization slope (Fricative)	-0.7	1.55	-0.45	0.66	
Hearing config. (E-only vs A+E)	-2.22	6.14	-0.36	0.72	
Age	5.19	5.38	0.96	0.34	
Hearing config. (E-only vs A+E) x Cat. Slope (Fricative)	-13.18	3.10	-4.25	< 0.001	*

Figure 7. Accuracy for AzBio in quiet for A+E and E-only CI users by A) Stop categorization slope and B) Fricative categorization slope.

515 = 0.02), suggesting that the CI users with steeper stop slopes also performed better at sentence
 516 recognition in noise and A+E listeners performed better than E-only listeners. In the fricative
 517 model, the same main effects were significant (fricative categorization slope: $B = 3.38$, $t(57) =$
 518 3.47 , $p = 0.001$; hearing configuration: $B = 21.95$, $t(57) = 4.45$, $p < 0.001$). There was also an
 519 interaction between hearing configuration and fricative categorization slope ($B = -5.36$, $t(57) = -$
 520 2.75 , $p = 0.008$), suggesting that the E-only listeners have a larger effect of fricative random
 521 slope (Figure 8).

Figure 8. Accuracy in AzBio in Noise (+5 dB SNR) for A+E and E-only CI users by A) Stop categorization slope and B) Fricative categorization slope.

Summary. These analyses provide evidence that the resolution of phonetic

categorization matters for standard clinical assessments, particularly for E-only CI users. E-Only

listeners with steeper slopes (i.e., clearer categorization) perform better on standard clinical

measures of word and sentence recognition. On the other hand, the A+E listeners show a less

clear relationship between their phonetic perception and clinical outcomes. A+E listeners with

Table 10. Summary of linear regressions investigating AzBio in noise (Equation 4), predicted by the random effect of stops or fricatives, hearing configuration, age, and device experience.

A) AzBio in noise x Stops					
Effect	B	SE	t	p	
Intercept	51.48	2.48	20.73	< 0.001	*
Categorization slope (Stop voicing)	6.44	1.46	4.39	< 0.001	*
Hearing config. (E-only vs A+E)	11.83	5.03	2.36	0.02	*
Age	3.39	4.74	0.72	0.48	
Hearing config. (E-only vs A+E) x Cat. Slope (Stop voicing)	-5.26	2.83	-1.86	0.07	
B) AzBio in noise x Fricatives					
Intercept	48.45	2.49	19.48	< 0.001	*
Categorization slope (Fricative)	3.39	0.97	3.47	0.001	*
Hearing config. (E-only vs A+E)	21.95	4.93	4.45	< 0.001	*
Age	0.41	4.93	0.08	0.93	
Hearing config. (E-only vs A+E) x Cat. Slope (Fricative)	-5.36	1.95	-2.75	0.008	*

steeper (i.e., clearer, more defined) slopes in both fricative and stop perception do not necessarily perform better in word and sentence recognition tasks. The lack of a clear effect of categorization slope for both the word and sentence recognition tasks in quiet suggests that when presented with unambiguous tokens, CI users are able to perform well regardless of their attention to fine-grained acoustic ambiguity.

Discussion

The present study examined a large heterogenous group of CI users—both electric-only CI users and those with residual acoustic hearing—to unpack the relationship between acoustic hearing and fine-grained phonetic perception. This led to a number of key findings.

The A+E Benefit

For both stop-voicing and fricative categorization, SSD subjects had steeper categorization than the other groups of CI users. This is unsurprising but it confirms that having one normal-hearing acoustic ear regularly outperforms listeners with reduced residual acoustic hearing in one or both ears. However, as we discuss, our findings with hybrid listeners suggest that an overreliance on acoustic input in some circumstances could prevent listeners from fully adapting to their implant. Thus, it may be fruitful for future work to compare electric-only listeners to SSD hearing with the CI only in similar tasks.

Within the more canonical CI users (those with bilateral hearing loss), we found mixed evidence for a A+E benefit. A+E CI users performed better than E-only users with stop voicing. This benefit was observed even controlling for demographic factors. Unlike prior studies that largely compared A+E listeners with and without their acoustic hearing, this between subject comparison suggests a robust, between-subject benefit. The cue to stop voicing is transmitted at the low frequencies of hybrid and bimodal CI user's residual hearing, thus these listeners are benefitting from the maintenance of their acoustic hearing. Importantly, this benefit was not

moderated by the amount of low frequency acoustic hearing (the PTA). Thus, it may be present even with minimal acoustic hearing (as long as there is some).

In contrast, for fricative categorization, there was no clear benefit for A+E listeners, both as a whole and when demographic factors were accounted for. On the one hand, this was expected—the cues to fricative place of articulation are largely in high-frequency spectral regions. Consequently, the low-frequency residual acoustic hearing retained by hybrid CI users was not expected to be beneficial. On the other hand, this was unexpected given the widespread view that A+E stimulation is universally better. Importantly, we do not replicate earlier work showing *worse* performance on fricatives for A+E listeners (McMurray et al., 2016). As we observe here, there is substantial variability in performance in this task which is in part due to demographic and hearing factors (e.g., length of device use, age). Thus, the smaller sample of A+E listeners in this earlier study may not have been a close match to the electric only users in that study.

Nonetheless, our analyses partially support the broader hypothesis generated by that study: that over reliance on residual acoustic hearing may lead CI users to fail to fully utilize their CI. This is seen most clearly in our analysis of residual hearing where hybrid CI users with better residual hearing showed worse categorization performance. This was not observed for bimodal listeners suggesting that this mis-weighting may be less challenging when combining highly distinct acoustic and electric input across two ears than when doing so within an ear.

Other effects of device type

Nonetheless, in the fricatives we did find some differences between sub-groups of CI users: bilateral CI users performed better than unilateral, and bimodal users performed better than hybrids. We see two factors that may contribute. First, the cues to fricative place of articulation are largely in high-frequency spectral regions. Consequently, the low-frequency residual acoustic hearing retained by hybrid CI users was not expected to be beneficial. In contrast, bimodal CI users have a contralateral HA that may give them some access to the full

range of acoustic hearing and could contribute to fricative perception. Future work should thus consider the role of the relative coverage in the electric and acoustic hearing devices. Second, this cannot account for the fact that among the E-only users, bilateral input leads to better performance than the unilateral users. Here we note that fricatives are often quite a bit lower in amplitude than vowels and stop consonants. In this case, binaural hearing offers a well-known benefit of about 6 dB for detecting quiet sounds (Shaw et al., 1947). This could be particularly helpful for lower amplitude fricatives¹.

Demographic and Other Effects

Beyond the effects of hearing configuration, we uncovered a number of other relevant effects. First, we found a strong effect of age on stop-voicing categorization: older CI users had shallower stop categorization regardless of their device configuration. Though we did not test NH listeners, this may reflect normal aging processes. One possibility is that this reflects an effect of cognitive aging on the general perceptual/cognitive processes of categorization. However, if this were the case, we might have expected to see similar effects for fricatives (which were not observed).

Alternatively, this may reflect some more specific perceptual processes that underlie voicing perception. Age affects the use of timing cues, like stop voicing (Toscano & Lansing, 2017), and older adults with age-typical hearing have more asynchronous neural responses to stop voicing cues (i.e., VOT), which is thought to reflect poorer time-locking to the acoustic signal (Bidelman et al., 2014). It follows that older CI users would display the same influence of age on the perception of stop voicing as this seems to be driven by an aging process separate from peripheral hearing ability.

For fricative categorization, we also found that longer device experience predicted

¹ This may play a role in the bimodal vs. hybrid benefit as well, though we note that some hybrid listeners wear a contralateral hearing aid.

steeper categorization. It takes time to learn to distinguish the different turbulent, noisy fricative sounds through electric stimulation. Bearing in mind that all the participants in this study had at least 1 year of device experience, this suggests an even more protracted period of adaptation to finding this cue. Intriguingly, it was largely the E-only listeners who drove this effect. One possibility is that the A+E listeners' over reliance on the acoustic input may lead them reach an early plateau in adapting to their CI, while the E-only listeners continue to improve with further experience. This seems to be especially true for sounds that may be difficult to characterize through electric stimulation as we found this relationship only for fricatives and not for stop voicing.

Finally, we found unexpected differences in the overall response rate of the targets across different listener groups. While this would normally be treated as uninteresting noise, it may actually reflect listener biases that may be useful. For example, A+E listeners with poorer residual hearing were more likely to respond with /p/ overall. In NH listeners, there is a trade-off between VOT and frequency at the onset of voicing, such that a higher onset frequency requires a shorter VOT to be perceived as voiceless (Summerfield & Haggard, 1977). In these A+E listeners, the absence of low-frequency information for those with poorer PTA might be taken as evidence for a /p/. In this case, it is not the signal itself that is missing low-frequency information, but the listener's own hearing which keeps them from perceiving the low-frequency information that is present in the signal. We found a similar situation with the fricatives. Bimodal listeners (who have access to the full spectrum through a hearing aid) were more likely to respond with /s/, suggesting that hybrid listeners (who only have access to low-frequency acoustic hearing) over-rely on their residual hearing and take the absence of high-frequency acoustic information as cuing /f/. This is further supported by the hybrid listeners with poorer residual hearing having steeper slopes than those with better residual hearing – those with better hearing are relying on their acoustic hearing when it is not appropriate, to the detriment of their fricative perception. This seems like a misattribution of the missing information.

Relation Between Categorization and Standard Outcomes

Finally, we found evidence for a relationship between categorization slope and performance on standard clinical measures of speech perception, especially in noise. The E-only CI users who have steep categorization slopes also perform well in word and sentence recognition tasks. This validates the utility of strong speech categorization skills as an underpinning of success with standard CI approaches.

However, these relationships were less clear for the A+E listeners. In fact, both outcome measures in quiet, A+E listeners' poorer categorization was related to better speech perception or sentence recognition. This was unexpected but we see several potential explanations that are worth further consideration. First, it may be that underutilization of the CI leads listeners to down weight individual segmental cues all together in favor of broader envelope or prosodic cues (to sentences). This could then disrupt the relationship between individual phoneme categorization and word or sentence recognition. The dissociation between categorization slope and recognition accuracy for A+E listeners in quiet may thus provide further evidence to the unconventional relationship between these listeners' hearing ability and how they process speech.

Second, it is now well known that both NH listeners (Andruski et al., 1994; McMurray et al., 2002; Miller, 1997) and CI users (McMurray et al., 2016) are not striving for a discrete representation of phonemes, but a gradient one that may enable them to be more flexible (c.f., Kapnoula et al., 2021; McMurray et al., 2009). In this case, the shallower categorization slope of the A+E listeners may mean something completely different than that of the Electric-only listeners. In the former group, their more fine-grained skills enable them to achieve this gradient representation, whereas in the latter, the shallower slope reflects inconsistency and/or noise. As we describe, this will require more sophisticated measures to detect.

For the sentence recognition in noise task, we found an expected effect for both CI

groups. Listeners with steeper categorization slopes also performed better at sentence recognition in noise. It should be noted that this may not be a causal relationship by which better categorization directly contributes to sentence recognition. The perceptual skills that improve phonetic categorization likely also underly talker streaming skills that help with sentence in noise perception. Thus, in this case, improved categorization may simply reflect better perceptual skills, which help with sentence perception (for other reasons).

Categorical Perception

Lastly it is important to consider the fundamental mechanisms of categorization that CI users may be deploying. The 2AFC speech continua task used here is classically interpreted under the assumption that categorization should be reasonably sharp and that any deviation from that is suboptimal and will appear as a shallower slope. Indeed, those were the operating assumptions adopted here.

This view is classically linked to categorical perception (Liberman, 1957) which further posits that categorization warps the perception of continuous cues like VOT or frication spectra. As a model of perception this has not held up to empirical scrutiny (Massaro & Cohen, 1983; Schouten et al., 2003; Toscano et al., 2010); indeed, it is now thought that a more gradient mode of perception may be more functional for listeners by allowing them to preserve flexibility (Kapnoula et al., 2021; McMurray et al., 2009; Miller, 1997).

How does this more modern understanding impact our interpretation of the present study? It is important to point out that even if perception is gradient, some listeners may nonetheless be more inconsistent or noisy than others. Indeed, that is the most likely cause of the electric vs. A+E differences observed in stop-voicing categorization. Importantly, a crucial limitation of this paradigm is that a shallow slope could arise from a situation in which the listener is striving for a steep categorization but is inconsistent near the boundary, or one in which the listener is truly gradient.

Several alternative paradigms may help. For example, eye-tracking in the visual world paradigm can examine commitment to each option (/b/ vs. /p/) conditioned on the final response (e.g., all the trials where the listener chose /b/). This has shown that CI users are in fact similarly sensitive to fine-grained differences in VVOT (relative to NH listeners), despite showing shallower categorization slopes. This suggests these shallow slopes may be due to noise. Second, newer continuous rating scale tasks may be able to disentangle these. In these tasks, listeners make a continuous rating as to the degree to which a speech token is a /b/ or /p/. Here, the variation around the mean can be informative: listeners who are truly gradient may show individual trial responses tightly clustered around the mean, whereas listeners who are noisier may show much more variation (Kapnoula et al., 2017).

Future work may be able to harness these theoretical and methodological advances to better understand the way that A+E hearing alters speech categorization. Critically, fricatives, which uniquely do not contain substantial information in the range of the acoustic hearing may be a fertile ground for such investigations.

Conclusions

Listeners must be able to cope with phonetic ambiguity in the speech signal to successfully map sounds to words. CI users must adapt to novel electric stimulation, and for those with residual acoustic hearing, they must integrate acoustic and electric stimulation. Our results suggest that CI users with residual acoustic hearing can more clearly resolve phonetic ambiguity than listeners who receive only electric stimulation in some situations, such as stop-voicing. However, other times, they may rely on acoustic hearing when it is not appropriate to do so, such as in fricatives. Ensuring that CI users with residual acoustic hearing adapt as much as possible to their CI and are able to integrate acoustic and electric stimulation may lead to improved language outcomes for these listeners.

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