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Integration of speech information (or not) across electric and acoustic modes in hearing impaired listeners.

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ABSTRACT

Many people with hearing loss use two cochlear implants (bilateral CIs), or combine a CI with a hearing aid (bimodal). While the addition of a second CI or acoustic input improves speech perception (particularly in noise), it is not clear how listeners fuse these disparate inputs. We used a duplex perception paradigm to investigate this. Listeners heard the four vowels from six talkers. In one condition, the first formant was presented to the CI, and the second to the other CI or hearing aid (and vice versa). In normal listeners, accuracy under dichotic presentation (across ears) did not differ from combined presentation (both formants, both ears). However, performance dropped to near chance with isolated formants. We then tested a range of CI users including bilateral (N=8); acoustic+electic listeners (CI and a hearing aid; N=11) and single-side-of-deafness (SSD; N=9) listeners. CI users also performed well in combined listening, and poorly for isolated formants. However, duplex presentation was much poorer than combined. Thus, CI users may not fuse inputs well at an auditory level, instead treating input from each mode or each ear as distinct auditory objects. This suggests the benefits of acoustic+electric hearing may derive from central integration not from fusion.

Keywords: Cochlear Implantation, Binaural Listening, Acoustic+Electric Processing, Speech Perception, Duplex Perception

1. INTRODUCTION

Hearing loss affects 16% of adults and almost 50% of people at some point (1). As remediation technology gets better, outcomes continue to improve. Yet variability between listeners is not fully explained by input quality (2-4). People with similar hearing profiles vary in speech perception (particularly in noise) (2-5); and people with similar speech perception in the lab differ in real-world outcomes (6, 7). This suggests that some of the variation in outcomes may relate to variation in cognitive mechanisms that weight and combine acoustic cues (8), map input to meaning (9, 10), or segregate objects in from background noise (11) (to name a few). That is, good outcomes of hearing remediation are likely to be the simultaneous product of good peripheral input (e.g. audibility, frequency precision) and good downstream cognitive processes that map the input to language.

This manuscript examines one such mechanism: the ability to integrate or fuse inputs from two ears, or from two modalities (acoustic and electric hearing) within a single ear. Until recently, remediation options were limited: for profoundly deaf individuals (who sought remediation), a single Cochlear Implant (CI) was the norm. However, in recent years, a diverse array of configurations have become standard, offering new sources of auditory information, and greater sensitivity to individual hearing profiles, and better outcomes. For example, many profoundly deaf people people receive bilateral CIs (12) (CIs in each ear). Further, for individuals with some hearing there are other options. Bimodal CIs pair a standard electrode in one ear with a hearing aid on the contralateral ear. This permits users to take advantage of any acoustic hearing in that ear (13, 14). Similarly, hearing preservation or hybrid CIs allow listeners to take advantage of residual hearing on the implanted ear in much the same way (15, 16) (and these may allow an additional CI or hearing aid on the other ear). Finally, increasing numbers of individuals with normal hearing in one ear, but severe-to-profound hearing loss on the other (Single Side of Deafness or SSD) are receiving CIs.

The benefits of these approaches are thought to derive from the ability to integrate or fuse inputs.

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Depending on the device, fusion may have overcome two problems. First, in bilateral CIs, listeners must fuse electric (CI) hearing from each ear. Second, in hybrid implants, listeners must fuse qualitatively distinct inputs from the *same* ear: higher frequency electric hearing (which loses temporal fine structure and fine grained frequency distinctions), and lower frequency acoustic hearing which is higher fidelity, but perhaps less audible and which may span only small frequency range. Bimodal and SSD listeners must solve both problems.

There are clear benefits to these multimodal hearing configurations. However, it is unclear whether these benefits derive from truly fusing the inputs. Here, we operationally define *fusion* as the ability to form a composite auditory "image" using inputs from both mode or CIs, an image on which further processing (e.g., speech perception) is based. The alternative is some form of *integration*, when listeners use information from each ear in some way, but without forming a composite. To address this, we present preliminary results from a new "duplex" perception paradigm (17, 18) which offers a more definitive way to characterize the degree to which CI users fuse inputs from each ear or mode.

1.1 Performance gains (or costs) from integrating across ears and modes.

In assessing the integration of multiple CIs or CIs and a hearing aid, the dominant approach is to compare performance in the same subject with and without the additional CI or hearing aid. This offers great control, but it is important to note that compares performance in a listener's typical configuration to one they are unused to. Further, it should not be construed as a long term benefit to one type of configuration or another, since this approach does not compare two types of CI users.

Bilateral CIs offer several potential benefits to listeners. First, bilateral CI users show benefits in speech perception in noise, when the noise and speech are not co-localized (19-21). However, the largest benefits are seen when the noise is at 90° relative to the listener, suggesting the benefits may derive from head shadow (not true localization) (19). However smaller benefits can be observed when speech and noise are closer in space suggesting CI users may be localizing the speech relative to the noise. Even beyond the benefits of localization, bilateral CIs benefit speech perception in quiet (19-21). This may be a form of redundancy gain: the additional CI offers an additional glimpse at a noisy input. Thus, it is not clear that any of these gains not require true fusion of inputs from the two CIs – they can largely occur due to ancillary benefits of two ears (head shadow, redundancy).

Bilateral CI users can localize sounds using interaural time and level differences, though level differences are more robustly used (22). Localization likely entails true fusion, since timing and level must be integrated from the two ears in order to compute location. However, localization is a fairly low level and specialized skill. Consequently, fusion in this domain does not necessarily mean that CI users can fuse inputs from each ear for more general functions like speech perception.

Bimodal CI users use a hearing aid on the contralateral ear to the CI. Similarly, ***Hybrid or Hearing Preservation CI*** users use a CI designed to preserve residual acoustic hearing in the implanted ear (usually amplified by a hearing aid) (23, 24). Both are commonly described as Acoustic+Electric (A+E) hearing. In both configurations, the residual acoustic hearing is not typically sufficient to enable accurate word recognition by itself. However, the typically low frequency acoustic input they provide can be used in a variety of ways. It can provide information to support word segmentation, and prosody. It can also enable better talker identification (25), which can help stream an attended speech stream from the background. Finally, the residual low frequency input can transmit low frequency phonetic cues like F0 (for voicing) or the first formant (for vowels). As a result of this, the addition of acoustic hearing to the CI provides better speech perception in both bimodal (13, 14, 26, 27) and hybrid (24, 27-29) configurations, particularly in noise.

The gains associated with adding acoustic input to the CI for the most part can be accounted for without positing true fusion. Instead they may derive from redundancy, the accessibility of new cues (F0), or improvements in processes like streaming. Indeed this may explain why both A+E configurations tend to show similar profiles of performance despite facing different fusion problems.

While an A+E benefit has been universally observed, one recent study challenges this showing at least one situation in which there may be a cost. We recently tested standard electric CI users (unilateral and bilateral) and A+E CI users (bimodal and hybrid) in a phoneme categorization task using speech continua. On a voicing (b/p) continuum, A+E listeners showed sharper categorization than CI_E users, likely due to their better access to low frequencies (the pitch and voicing). In contrast, on a fricative continuum (s/ʃ), A+E listeners showed substantially worse categorization. This was surprising as sibilant fricatives contain little input in the low frequency acoustic-hearing range. Given this, A+E listeners should have performed equivalently to electric only. This raises the possibility that A+E listeners are not properly integrating A and E. Specifically, A+E listeners may overweight the acoustic input. While this may be useful in typical situations (where the acoustic input is generally helpful), in fricatives it is not (since there is no signal in the acoustic range), leading them astray. It is not clear whether this is a failure of fusion or integration, but it led us to think about how to more directly assess fusion across hearing modes.

1.2 Fusion vs. Integration

As we have described, many of the benefits for A+E hearing and for bilateral implantations may reflect a loose form of integration, not fusion. Factors like head shadow, redundancy gains, or using pitch for word segmentation do not require true fusion across ears and modes into a unified auditory percept, but simply the use of information from both modes or ears to accomplish separate goals, whose outputs can b integrated later.

So how would one know if fusion had been achieved? The ideal test would be a situation in which the input coming into each ear (or mode) is individually not sufficient for a robust percept; however, the listener can succeed when they are combined. This rules out redundancy gains, and if the information in each ear is fairly minimal, it rule out ancillary processes like segmentation or attention.

One paradigm that potentially meets this criterion is ***duplex perception*** (17, 18). In this classic paradigm, speech cues (e.g., a formant transition) are synthesized individually and sent to each ear separately. Individually, such cues often sound like non-speech (e.g., a chirp), but when combined they create the percept of a speech sound[2]. This offers a potentially strong test for fusion, as only when the cues are combined *prior to speech categorization* are they useful.

We thus implement a duplex perception experiment using two-formant vowels. Formant tracks were extracted from four vowels (/ɪ, æ, ɑ, ʊ/) spoken by several talkers, and resynthesized. We compared several conditions including dichotic listening (one formant in each ear or mode), combined (both formants in both ears or modes) and each formant individually (presented to both ears or modes). Listeners categorized each vowel in a 4AFC task. Critically, if listeners are exhibiting perfect fusion, we should find performance in the dichotic condition to be similar to performance in the combined/ However, if listeners are not fusing, dichotic listening should be comparable to performance on individual formants. Experiment 1 validates the paradigm with NH young adults. Experiment 2 then tests a variety of CI users including bilateral, bimodal, hybrid and SSD listeners. Note that Experiment 2 represents a preliminary report, as we have not yet reached our planned sample size.

2. Experiment 1

2.1 Methods

Subjects. 14 NH listeners participated. Subjects were typical college students, screened for normal hearing. They were received course credit or a nominal compensation for their participation.

Stimuli. Stimuli were resynthesized from natural recordings. The entire stimulus set comprised four vowels from six speakers of Midwest American English. Rather than using point vowels, we used /ɪ/ and /ʊ/ (which are one step lower than the point vowels /i/ and /u/) as these have durations that were more similar to /æ/ and /ɑ/. Further we used six talkers of mixed gender to create some difficulty in vowel identification (particularly as there would be no F0) and keep performance off ceiling.

To generate the stimuli, we first recorded several exemplars of each vowel from each speaker. We selected the clearest exemplar whose duration was closest to the mean duration of the set. Next, we extracted formant tracks for the first and second formants. These were then input into the KlattWorks interface (30), to the Klatt88 synthesizer (31), and the results were smoothed using a series of sigmoidal fits to the formant frequencies. The amplitude of voicing (AVS) parameter was set to approximate the envelope of the original sounds, but equated on duration. We then synthesized each formant individually (with no pitch) using the parallel tract of the synthesizer. These were then recombined into stereo soundfiles in five different configurations: 1) the combined condition, in which both formants were present in both the left and right channels; 2) a dichotic condition with F1 on the left and F2 on the right; 3) a second dichotic condition with F1 on the left and F2 on the right; 4) F1 alone (on both sides); and 5) F2 alone (on both sides).

Design. There were 6 talkers, 4 vowels and 5 conditions for a total of 120 total stimuli. Each was

[2] The term duplex derives not from the fact that the information is sent to two ears, but rather, that many listeners report hearing two things simultaneously – the “chirp” and the speech sound.

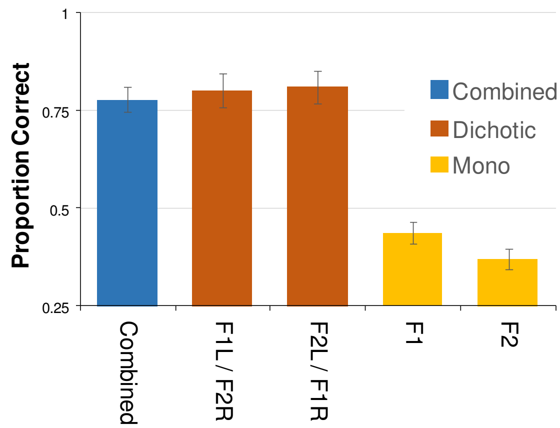

Figure 1: Vowel identification performance as a function of condition for NH subjects.

presented 3 times for a total of 360 trials. Stimuli were tested in completely random order.

Procedure. Stimuli were delivered over high quality circumaural headphones in a sound proof booth. Subjects were allowed to adjust the volume to a comfortable listening level prior to the experiment. On each trial, subject clicked on a start button at the center of the screen to hear the stimulus. They then heard the auditory stimulus, they responded by clicking on one of four response options labeled with example words containing each of the four vowels (*lick, lock, look, lack*). Periodically the locations of each word on the screen were shuffled.

2.2 Results

Figure 1 shows the results. In the combined condition, listeners achieved 77.6% correct, showing good (but not perfect) identification of the vowels. In the two duplex conditions performance was similar (if not slightly better) at around 80%. Finally performance dropped to near chance (25%) in the two mono conditions suggesting that the formants alone were not sufficient for a vowel percept.

For statistical purposes, we collapsed the two dichotic conditions into a single one, and the two isolated formants into a single mono condition. These were submitted to a one-way ANOVA examining the effect of listening condition. The main effect of condition was significant ($F(2,26)=170.4$, $p<.0001$). Follow-up tests confirmed no significant difference between combined and dichotic ($F(1,13)=2.44$, $p=.14$), but a difference between dichotic and mono ($F(1,13)=185.0$, $p<.0001$).

The mono condition—while substantially lower than the other conditions—was nonetheless significantly above chance (0.25; $t(13)=8.08$, $p<.0001$). An analysis of the specific errors in the mono condition suggested this was because listeners were often able to extract at least one feature from the isolated formants. For example, a low F1 could indicate either of the high vowels (/ɪ/ or /ʊ/), while a high F1 would indicate one of the low vowels (/æ/ or /ɑ/). For example, with F1 alone, listeners were 81.7% accurate at identifying the height of the vowel (e.g., both /ɪ/ and /ʊ/ are high vowels), but only 52.9% accurate at identifying the frontness (e.g., /ɪ/ and /æ/ are front vowels). Here chance is 50%, suggesting they could not identify frontness at all from F1. Conversely, with F2 alone, they were 70.4% correct for frontness but 52.0% correct with backness.

We used this logic to generate predicted performance if dichotic performance was solely based on a redundancy-gain. Imagine that listeners were not fusing the inputs at all, but merely using F1 (from the left ear, for example) to identify height, and F2 (from the right) to identify frontness. They could then combine these abstract features at a central level to identify the vowel without fusing the auditory percept into a single percept. In this case, the predicted accuracy would be simply the product of height accuracy using F1 and backness accuracy in F2. Across the sample, this was 57.5%, far less than the average in the duplex condition (80.3%). To evaluate this statistically, this predicted accuracy was computed for each subject, and compared to their own dichotic listening accuracy. The redundancy gain score was significantly lower ($t(13)=4.91$, $p<.0001$), suggesting that the excellent dichotic performance derived substantially from fusion.

2.3 Discussion

These results validate the basic paradigm. NH listeners performed well in the combined condition and equally well for both dichotic modes. However, performance suffered a large decline between dichotic and mono presentations. This suggests listeners' strong dichotic performance condition was not likely the result of redundancy between the two ears; rather they were doing something that can be described as fusion. The fact that listeners retained some ability to identify the vowels in the mono condition suggests that each formant individually was not truly non-informative. Nonetheless, our analysis of the errors suggests that this performance cannot be accounted for by simply extracting one vowel feature (frontness or height) from each ear and combining the results. Rather, listeners had to fuse the inputs to attain this level of performance. We next apply this logic to a variety of CI users.

3. Experiment 2

3.1 Methods

Subjects. Subjects consisted of 28 CI users of various configurations (Bilateral: N=8; Bimodal: N=9; Hybrid: N=2; SSD: N=9). Subjects were classified as bimodal or hybrid if they had better than 75 dB (unaided) at least two frequencies in the contralateral (bimodal) or implanted (hybrid) ear. Subjects were classified as SSD if they had NH (PTA < 20 dB) on the unimplanted ear. Subject demographics and hearing status are provided in Table 1. Our planned sample size is 15 subjects / group; thus analyses are preliminary. Given the small sample of hybrid CI users (so far), hybrid and bimodal CI users were collapsed into a single A+E group.

Stimuli and Design. Stimuli and design were identical to Experiment 1.

Procedure. Prior to the experiment, the listener's hearing devices were connected directly to the audio output of the computer via custom direct-connect cables, or in some case via Bluetooth (for some hearing aids). For hybrid CI users, sounds were only presented to the hybrid CI (and hearing aid) – the other ear was not used. For SSD subjects, audio was presented by soundfield to the NH ear, and by direct connect to the CI (with the microphone off). This ensured that the left or right channel was only presented to the intended ear or modality. Other procedures were the same as Experiment 1.

3.2 Results

In examining dichotic performance the left ear/right ear distinction was not the most important in CI users. More important was which ear had a hearing aid (or implant). Thus, for considering performance in the dichotic condition, for A+E listeners we classified the condition as a preferred dichotic condition when F1 was sent to the acoustic mode and F2 to the CI (and the converse was dispreferred). This was done regardless of which ear had the hearing aid. Hybrid patients used a similar criterion (but on the same ear). We adopted the same scheme for SSDs for consistency (though there is no reason to think that F1 would be preferred for the NH ear over F2). For bimodals, we used the ear they favored (if the subject reported one) or the first-implanted ear otherwise as the preferred ear (again, this was largely for consistency's sake and was not predicted to make a large difference).

Figure 2 shows the results averaged over all groups. In the combined condition, all three groups showed similarly strong performance to the NH listeners in Experiment 1. Similarly, CI users performed roughly the same as the NH listeners for the mono condition. However, in contrast to Experiment 1, all three groups showed a marked decrement in performance in dichotic listening from the combined condition. Dichotic performance was not always as poor as in the mono condition. In bilateral CI users, this was seen for both dichotic conditions; for A+E and SSD listeners it was seen for the "preferred" conditions in which F1 was presented to the acoustic ear. It is not surprising that A+E listeners were much poorer in the dispreferred dichotic conditions as for many of them, F2 presented to the acoustic side would be inaudible (it was too high frequency).

We did not wish to make strong comparisons between CI users and the NH listeners of Exp 1 (since NH listeners are not age-matched to the CI sample). However, we wanted to determine if performance in the combined and mono conditions was comparable between CI and NH subjects, to determine if the CI users performed similarly to NH when listening did not require fusion. This was done with an ANOVA examining condition (combined vs. mono) and group (all four). There was no main effect of

Table 1 – Summary of CI users in Experiment 2

Configuration	N	Age	Age of Deafness	PTA (<1500 Hz)	PTA
Bilateral	8	56.3	34.3	-	-
Bimodal	9	61.0	33.3	61.7 dB	69.4 dB
Hybrid	2	54.9	42.0	78.8 dB	90.0 dB
SSD	9	54.6	45.8	14.8 dB	23.8 dB

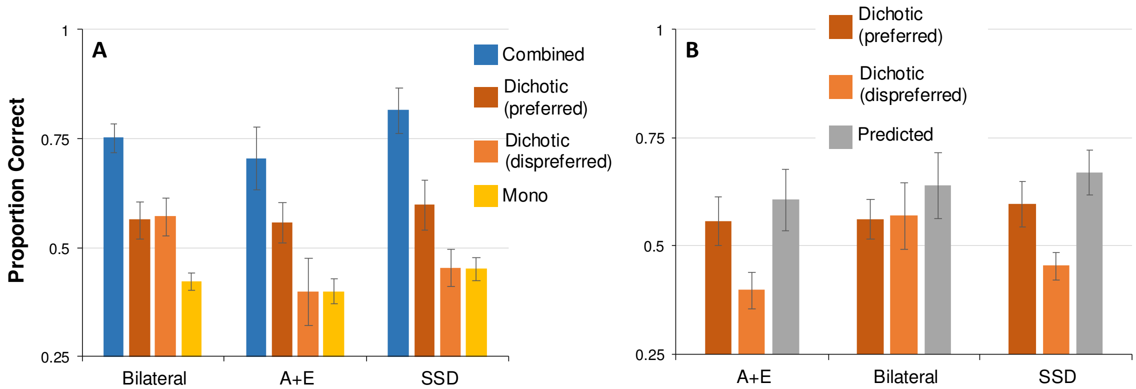

Figure 2: A) Vowel identification as a function of condition for three groups of CI subjects. B) Vowel identification in the two dichotic listening conditions compared to predicted performance based on the two mono conditions.

group (F<1) or no group × condition interaction (F<1). Individual t-tests confirmed that each CI group did not differ from NH. This suggests that CI users and NH listeners performed similarly in the two conditions that did not require fusion.

Next, we analyzed just the CI users with a mixed ANOVA examining condition (within-subject) and listener group (between). There was a no effect of listener group but a significant main effect of condition (F(3,75)=76.9, p<.0001). The latter was driven by significant differences between combined and both dichotic conditions (vs. preferred: F(1,25)=87.9, p<.0001; vs. dispreferred: F(1,25)=121.9, p<.0001); and between each dichotic condition and the mono condition (preferred: (F(1,25)=55.5, p<.0001; dispreferred: F(1,25)=4.34, p=.047). The condition × listener group interaction was significant (F(6,75)=2.46, p=.032). This was driven by the fact that the bilateral users showed no difference between the two dichotic listening conditions (t(7)=0.16, p>.2) and both other groups did (A+E: t(10)=2.78, p=.02; SSD: t(8)=3.75, p=0.006).

To determine if true fusion was occurring, we again computed the predicted dichotic performance assuming only redundancy. For all three groups, predicted performance equaled or *exceeded* performance in each dichotic condition (Figure 2B) . This contrasted with the NH listeners where predicted performance was lower than the observed dichotic performance. This suggests that any above-threshold performance in the dichotic listening conditions is likely to be due to late stage combination of vowel features (height and backness) that are identified separately in each ear or mode.

Finally, there is marked variability among CI users. This is particularly true in bimodal and hybrid users where residual hearing thresholds and ranges differ markedly, but there is also variation among bilateral users depending on factors like simultaneous or sequential implantation. While group level averages suggest that CI users as a whole do not fuse inputs from both ears or modes, we inspected individual level data to determine if anyone showed integration (Figure 3). Of the 28 listeners, only two showed dichotic performance that was equal to combined: Subjects 38 (bilateral) and 24 (bimodal). Notably both hybrid users showed a failure to fuse despite the fact that they had to fuse between inputs in the same ear, and all SSD listeners failed to fuse despite normal hearing on the contralateral ear.

3.3 Discussion

Experiment 2 shows no support for the hypothesis that CI users are capable of fusing inputs across ears or modes. Unlike the NH listeners in Experiment 1, they showed a marked decrement in dichotic listening conditions (Figure 2A). This was observed in 26 of the 28 listeners. Further, dichotic listening never exceeded what would be predicted by a purely additive model that performed speech perception on each ear individually and combined the results. While these results should be treated as preliminary since data collection is not complete (particularly with respect to hybrid listeners where only two listeners have been tested), they nonetheless show a surprisingly consistent lack of fusion.

4. Conclusions

Preliminary data from our experiments suggest that CI users do not fuse inputs across multiple ears, or possibly across different kinds of inputs from the same ear. This does not appear to differ across configurations – even SSD listeners show the effects. It unclear why they are failing at this,

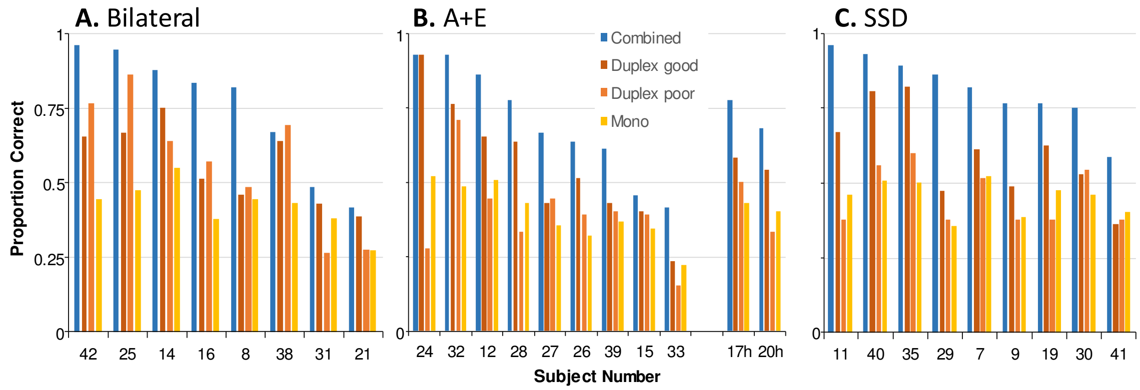

Figure 3: Accuracy as a function of condition for individual bilateral (A), A+E (B) and SSD (C) listeners. The two hybrid users are set to the right in panel B and indicated with an "h" in their subject number.

and future work (potentially with NH listeners) should evaluate things like the relative timing of the signal from each implant (or the hearing aid), the level of spectral degradation, or whether this is a result of long-term exposure to CI input (or if it can be ameliorated by adaptation).

Importantly, however, it suggests that the frequently reported gains for bilateral and A+E configurations do not derive from true fusion. That is listeners do not form an integrated auditory percept and then perform speech perception (or other auditory processing) on this unified image. Rather, our results are more consistent with a more heuristic form of integration. Listeners may, for example, form two auditory percepts, perform speech perception twice, and integrate the results (for a redundancy gain). Or they simply may take advantage of cues that are not available without these modes, for example A+E listeners can use pitch to segment, or bilateral users may utilize head shadow to parse speech from noise. It remains to be seen if there are auditory rehabilitation or signal processing techniques that can help them achieve true fusion.

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