Bimodal Benefit for Music Perception and Appreciation: Effect of acoustic bandwidth and resolution of low-frequency acoustic stimuli

By

Kristen L. D'Onofrio

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Approved:

René H. Gifford, Ph.D.

Daniel H. Ashmead, Ph.D.

Reyna L. Gordon, Ph.D.

Spencer B. Smith, Ph.D., Au.D.

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CI	cochlear implant
CNC	consonant-nucleus-consonant
dB HL	decibels hearing level
dB SL	decibels sensation level
dB SPL	decibels sound pressure level
DR	dead region
F0	fundamental frequency
FFR	frequency following response
HFPTA	high-frequency pure-tone average
Hz	Hertz
LF	low-frequency
LFPTA	low-frequency pure-tone average
NH	normal hearing
OMSI	Ollen Musical Sophistication Index
PTA	pure-tone average
SNHL	sensorineural hearing loss
TFS	temporal fine structure
WB	wideband

Chapter 1

INTRODUCTION

1.1 Background

Cochlear implants (CI) have been remarkably successful in improving quality of life and enabling high levels of speech perception. However, signal processing and design limitations continue to make the perception of complex stimuli challenging. This is particularly true for inputs that demand faithful representation of pitch (e.g., music) (Chatterjee et al., 2017; Chatterjee & Peng, 2008; Hsiao & Gfeller, 2012; Luo, Fu, & Galvin, 2007). As such, music perception tends to be poorer in CI users than in normal-hearing (NH) individuals (e.g., D'Onofrio et al., 2020; Gfeller et al., 2007; Kang et al., 2009; Kong et al., 2004).

The challenges associated with CI-listening are well-documented; however, they can be mitigated through the provision of aided acoustic hearing in the contralateral ear – a configuration termed "bimodal hearing". Indeed, current estimations indicate that approximately 60-72% of adult CI patients have some degree of useable residual hearing in the contralateral ear (Dorman & Gifford, 2010; Holder et al., 2018). Bimodal benefit for music listening – that is, the benefit obtained via the addition of acoustic hearing (via hearing aid) in the non-CI ear – has been demonstrated in a myriad of ways, including tasks of melody perception (Dorman et al., 2008; El Fata et al., 2009; Kong et al., 2005; Sucher & McDermott, 2009), pitch perception (Cheng et al., 2018; Crew et al., 2015; Cullington & Zeng, 2011), timbre perception (Kong et al., 2012), musical sound quality (El Fata et el., 2009; Plant & Babic, 2016; Sucher & McDermott, 2009), and musical emotion perception (D'Onofrio et al., 2020; Giannantonio et al., 2015; Shirvani et al., 2016). For many, the benefit of contralateral acoustic hearing can be substantial;

however, there is considerable inter-subject variability, as well as intra-subject variability across various test measures. Further, there is no standard hearing aid fitting procedure for bimodal stimulation. As the number of patients with residual hearing continues to increase, establishing data-driven guidelines for the bimodal patient is of increased importance.

1.2 Effect of acoustic bandwidth on bimodal listening

A number of studies have investigated hearing aid parameters with respect to the speech domain, most commonly by varying low-frequency acoustic bandwidth in the non-CI ear. Zhang, Dorman, & Spahr (2010) examined bimodal benefit for acoustic stimuli presented to the non-CI ear low-pass filtered at 125, 250, 500, 750 Hz, and unfiltered (wideband). Significant improvement was reported for all conditions, including < 125 Hz. Further, speech understanding in noise improved systematically as the acoustic bandwidth increased from < 125 Hz to the wideband condition, thereby suggesting that amplification should be provided at all aidable frequencies for maximum benefit. Consistent with Zhang et al. (2010), Sheffield & Gifford (2014) indicate that the minimum acoustic bandwidth necessary for significant bimodal benefit was < 125 Hz for male talkers in noise and < 250 Hz for female talkers in noise and male talkers in quiet. Additionally, bimodal benefit was found to increase significantly with increasing acoustic bandwidth up to < 500 Hz for male talkers in noise, and up to < 750 Hz for female talkers in noise and male talkers in quiet. Importantly, an increase in performance beyond 750 Hz was noted, however, this improvement failed to reach statistical significance. Data from Neuman et al. (2019) add further support that providing the broadest acoustic bandwidth yields maximum bimodal benefit. Thus, in light of these results for speech perception, converging evidence suggests that traditional, wideband amplification should be recommended for patients with bimodal hearing.

In contrast, Messersmith, Jorgensen, and Hagg (2015) demonstrated that for select individuals, amplification over a restricted bandwidth (< 2000 Hz) resulted in optimal performance. These results are based on a very small, highly selective sample of participants (n = 6) who were chosen to participate because of their poor performance with wideband amplification. In fact, 3 of the 6 participants had thresholds greater than 110 dB HL above 2000 Hz, and thus, cochlear dead regions (DRs)—regions of the cochlea with minimal to no functional inner hair cells and/or neurons—were presumed to be present. Similarly, data from Zhang et al. (2014) suggest that a restricted bandwidth should be applied in cases where high-frequency DRs are present. Specifically, they demonstrated significant improvement in speech recognition in quiet and noise as well as improved subjective speech sound quality with a restricted HA bandwidth for individuals with confirmed cochlear DRs. In contrast, individuals without cochlear DRs demonstrated best performance with a wide HA bandwidth (Zhang et al., 2014). These two studies are in agreement with the hearing aid literature, which has likewise shown little-to-no benefit from amplifying frequencies beyond approximately 1.7 times the DRs edge frequency (Baer, Moore, & Kluk, 2002; Mackersie, Crocker, & Davis, 2004; Vickers, Moore, & Baer, 2001).

Taken together, the existing literature suggests that for *most* patients, amplifying the broadest range possible generally yields optimal speech perception performance. However, for some, there can be diminishing returns with increased bandwidth, or even a decrement in performance for which a restricted acoustic bandwidth would be recommended (Davidson et al., 2015; Zhang et al., 2013).

To my knowledge, there has been no systematic evaluation of the effect of acoustic bandwidth in the music domain for bimodal listeners; however, both Zhang et al. (2014) and El Fata et al. (2009) shed light on this issue indirectly. In the study by Zhang et al. (2014), music sound quality was judged to be optimal when a restricted bandwidth was utilized for listeners with DRs – a finding that is consistent with results in the speech domain. El Fata et al. (2009) investigated the effect of degree of hearing loss in the non-implanted ear on bimodal benefit for song identification. The authors divided their participants into two groups according to degree of hearing loss. Group I included individuals with low-frequency thresholds better than a median of 85 dB HL, and Group II included those with median thresholds worse than or equal to 85 dB HL. Group I participants performed significantly better in the bimodal condition compared with the CI-alone condition. For Group II participants, however, there was no difference between the two listening conditions. Although DRs were not explicitly evaluated, these findings likewise indicate that bimodal benefit may be affected by degree of residual acoustic hearing, and further, may impact optimal acoustic bandwidth.

With respect to the earlier speech perception literature, it should be noted that all 12 participants in the Sheffield & Gifford (2014) study had auditory thresholds better than or equal to 80 dB HL at or below 500 Hz. Similarly, in the study by Neuman et al. (2019), nearly all (20 out of 23 participants) had thresholds better than or equal to 80 dB HL at or below 500 Hz. In contrast, this was true of only 5 of the 14 total participants in the study by El Fata et al. (2009). Because of the reduced peripheral auditory fidelity often associated with severe-to-profound thresholds, it is possible that for the other 9 listeners, a narrower bandwidth may actually yield improved performance, as suggested by Zhang et al. (2014) and Messersmith et al. (2015).

Further investigation into the effect of acoustic bandwidth is needed in order to establish evidenced-based clinical guidelines for optimal music perception in a bimodal configuration.

1.3 Key structural features of music

While it is clear that CI performance tends to improve with access to acoustic hearing, we must further explore how this benefit relates to specific musical features which differ from that of speech. A strong understanding of the acoustic cues contributing to music perception and appreciation could help in predicting bimodal benefit and offer additional utility in explaining the variability across patients – even among those with similar auditory thresholds.

There are 5 key structural features of music, including: rhythm (a regular, repeated pattern of sounds), pitch (the perceptual correlate of frequency), melody (pitches played sequentially), harmony (pitches played concurrently), and timbre (the physical attribute used to differentiate sounds of the same pitch, loudness, and duration). With respect to rhythm perception, CI listeners generally perform comparably to NH listeners on basic rhythmic tasks (Gfeller et al., 1997; Hsiao & Gfeller, 2012; Kong et al., 2004), though performance tends to diminish with increased task complexity (Jiam and Limb, 2019; Kong et al., 2004). For example, Phillips-Silver et al. (2015) demonstrated that CI listeners were better at identifying a Latin Merengue beat with unpitched drum tones, as opposed to piano notes. Reynolds and Gifford (2018) also demonstrated poorer performance by CI users on the Beat Alignment Test (BAT) compared to previous testing with normal hearing participants (Iverson and Patel, 2008). Using the Montreal Battery of Evaluation and Amusia (MBEA), Cullington and Zeng (2011) demonstrated that both bimodal and bilateral CI recipients performed poorer than NH listeners on the rhythm subtest. Although a bimodal group was included in this study, no CI-alone testing was completed to allow for a within-subject analysis of bimodal benefit. Further research is warranted to determine how much benefit, if any, CI listeners may receive from residual acoustic hearing on more complex rhythm perception tasks.

In contrast to rhythm, perception of pitch, melody, and harmony often improves significantly with the addition of acoustic hearing (Brockmeier et al., 2010; Cheng et al., 2018; Crew et al., 2015; Cullington & Zeng, 2011; Dorman et al., 2008; El Fata et al., 2009; Gantz, 2005; Gfeller et al., 2006; Gfeller et al., 2007; Gfeller et al., 2008; Gfeller et al., 2012; Kong et al., 2005; Parkinson et al., 2019; Sucher & McDermott, 2009). Similarly, timbre perception tends to improve via the addition of acoustic hearing – albeit to a lesser degree (Kong et al., 2012; Parkinson et al., 2019; Yüksel, Meredith, & Rubinstein; 2019). These findings are consistent with the current state of CI signal processing; that is, temporal cues are well-preserved, yet spectral cues are diminished (Limb & Roy, 2014). The addition of acoustic hearing benefits those musical features that are spectral in nature (i.e., pitch, melody, harmony, timbre), and the assumption is that this benefit is largely due to improved access to fundamental frequency (F0) and low-frequency temporal fine structure (TFS) representation via the acoustic hearing ear – features not well-transmitted via the CI (Limb & Roy, 2014; Moore, Glasberg, Flanagan, & Adams, 2006). Indeed, F0 and TFS can still be perceived by listeners with some degree of sensorineural hearing loss (SNHL), and thus, contribute to improved performance in listeners with bimodal hearing (Dincer D'Alessandro, 2018; Sheffield and Zeng, 2012; Sheffield & Gifford, 2014; Zhang, Dorman, & Spahr, 2010); that is, normal hearing sensitivity is not required for perception of and benefit from F0 and TFS.

We would be short-sighted however, if our assessments were limited solely to those features of music in isolation. In practice, several structural features are combined and integrated in meaningful and strategic ways to impact sound quality, musical emotion perception, and ultimately overall music appreciation. For example, musical mode (the subset of pitches utilized) and tempo (speed of the music) are two primary cues that contribute to the emotion that is conveyed by a musical excerpt. Additional factors include but are not limited to articulation, dynamics, consonance/dissonance, timing, melodic/harmonic complexity, and rhythmic complexity (Balkwill & Thompson, 1999; Gabrielsson & Juslin, 1996) – all of which build on the structural features in isolation, and which contribute uniquely to the perception of musical emotion and overall appreciation (Bachorowski, 1999; Eerola & Vuoskoski, 2013; Scherer, 2003). Several studies have demonstrated that CI listeners incorporate little to no pitch information when completing judgments of musical emotion, and instead rely predominantly on temporal cues (Caldwell et al., 2015; D'Onofrio et al, 2020; Giannantonio et al., 2015). Further, CI recipient reports of dissatisfaction with music listening or unpleasant sound quality underscore the shortcomings of current CI processing for music appreciation (Lassaletta et al., 2007; Mirza et al., 2003). For the same reasons discussed above, residual acoustic hearing can yield improved musical emotion perception, sound quality, and overall music appreciation, as listeners are able to incorporate greater use of spectral information from the acoustic hearing ear – namely greater access to F0 and TFS (D'Onofrio et al, 2020; Giannantonio et al., 2015; Plant & Babic, 2016; Shirvani et al., 2016).

While there are certainly a number of musical and technological factors that contribute to overall sound quality and music appreciation, it is important to acknowledge that sound quality judgments are also influenced by individual factors, including but not limited to musical training and experience, familiarity with musical style and/or genres (Ginocchio, 2009), personality characteristics (Robinson, Weaver, Zillman, 1996), and demographic variables (e.g., gender, age, ethnicity) (LeBlanc, Stamou, & McCrary, 1999; Nater, Abbruzzese, Kreb, & Elhert, 2006; Robinson et al., 1996). Ginocchio (2009) found that listeners with more musical training tended to provide higher overall musical preference ratings. They also reported that type of musical experience (e.g., band, choir, piano lessons) may influence ratings, such that involvement in band had a greater impact on ratings of non-popular styles of music. Nater et al. (2006) demonstrated gender differences in physiological responses (i.e., reactivity patterns) to music stimuli. Specifically, women tended to show greater hypersensitivity to music that was aversive. Similarly, Robinson et al. (1996) reported that women rated soft/non-rebellious rock music more positively than men, and conversely, men rated hard/rebellious rock music more positively than women. Thus, any examination of subjective sound quality must also consider non-musical, individual factors as an integral component to one's judgment.

1.4 Fundamental frequency (F0) and temporal fine structure (TFS)

Pitch, the building block of musical melody and harmony, requires access to F0 directly, or indirectly, via the perception of harmonics (as in, the missing fundamental – see Clarkson & Clifton, 1985; He & Trainor, 2009; Houtsma & Smurzynski, 1990; Lau & Wener, 2012; Micheyl & Oxenham, 2004; Schouten, 1940; Smith, Marsh, Greenberg, & Brown, 1978). Similarly, timbre, or the "tone quality" of a sound, relates to the temporal envelope shape, the distribution of spectral energy across frequencies, and amplitude changes of the harmonics over time. Thus, timbre perception requires sensitivity to both the signal's TFS and temporal envelope (Looi et al., 2008).

Current CI signal processing strategies preserve the signal's temporal envelope, but largely discard TFS information. While the envelope-based strategies upon which CIs operate are sufficient for speech recognition in quiet, the complexity of music demands access to TFS. Bimodal stimulation, via aidable residual hearing in the non-implanted ear, allows greater access to TFS cues, and thus, the inherent limitations of CI design and signal processing can be mitigated. While it is known that TFS diminishes with poorer auditory thresholds, this can be highly variable across patients (e.g., Lorenzi et al., 2006; Strelcyk & Dau, 2009) and may contribute significantly to the variability in benefit demonstrated in previous literature.

1.4.1 Pitch discrimination

Several studies have investigated perception of F0 among listeners with contralateral acoustic hearing via behavioral pitch perception tasks. Cullington & Zeng (2011) found performance on pitch perception tasks to be superior among bimodal listeners compared with bilateral listeners, although this difference failed to reach statistical significance. Both Crew et al. (2015) and Cheng et al. (2018) examined the effect of residual acoustic hearing in the contralateral ear with respect to melodic contour identification (MCI) – a measure of "functional pitch" perception. Results demonstrated superior performance in the bimodal condition compared with CI-alone, thus yielding further support for the benefit of contralateral acoustic hearing for music tasks. Yüksel et al. (2019) examined pitch direction discrimination in children with combined unilateral CI and low-frequency acoustic hearing in the contralateral ear. Consistent with previous literature, performance was comparable to NH listeners and substantially better than previous work with CI-only listeners (Jung et al., 2012; Kang et al., 2009).

Despite the existing evidence indicating the benefit of acoustic hearing, it remains unclear as to how pitch perception relates to overall music perception and appreciation. In other words, pitch perception has yet to be utilized as a potential predictor of bimodal benefit. As a foundational element of music, the perception of pitch may be expected to relate to magnitude of bimodal benefit on music tasks. Further, pitch perception may be useful in predicting optimal acoustic bandwidth.

1.4.2 Timbre perception

As with pitch perception, timbre perception is also impacted by residual acoustic hearing (Kong et al., 2012; Yüksel et al., 2019). In an investigation of children with bimodal hearing, Yüksel et al. (2019) found timbre perception performance to be about 14-percentage points better when compared with a previous study in children using CI-only listening (48% vs. 34%, from Jung et al., 2012). A notable limitation of this study is that they did not complete a within-subject analysis (e.g., CI-alone vs. bimodal performance), and thus, it is possible – albeit unlikely – that the difference in scores was due simply to a difference in samples. Still, any improvement with residual hearing could be expected to correlate with strength of TFS representation in the non-CI ear. To that end, Kong, Mullangi, & Marozeau (2012) aimed to determine the relative contribution of spectral and temporal envelope cues for timbre perception in a group of bimodal and bilateral CI recipients. As expected, results of their study indicate strong reliance on the temporal envelope cue by both groups, whereas spectral envelope was less salient. Surprisingly, no significant improvement in performance was evident with either the addition of a 2nd CI for the bilateral participants, or the addition of contralateral acoustic hearing for bimodal listeners. Importantly, the authors do report that 3 of the 7 total bimodal participants demonstrated increased reliance on the spectral envelope cue. This is in contrast to only 1 bilateral participant, which suggests a possible advantage of the bimodal condition over CI-alone on this task.

However, with such a small sample size and without additional literature for comparison, it is difficult to draw a strong conclusion from this single study. Further research is clearly warranted to parse out the added contribution of TFS and envelope cues in the contralateral ear, and their relationship with music perception benefit.

Importantly, the internal representation of timbre is reportedly similar between NH listeners and listeners with CI (Macherey et al., 2013; Parkinson et al., 2019). In other words, the same underlying acoustic cues are utilized by both populations; however, the relative weighting of these cues can vary based on a number of factors, including but not limited to contributions from residual acoustic hearing as discussed above, the frequency range of the stimuli, and music listening habits (Kong et al., 2012; Macherey et al., 2013). Indeed, Kong et al. (2012) found that CI users tend to rely less on spectral cues, and more on temporal envelope for timbre recognition tasks. Further support for this type of relative weighting comes from existing studies showing better overall performance on timbre tasks among CI users, when compared to other features of music (e.g., pitch or melody perception) – a finding believed to be due to the potential salience of temporal envelope cues via current CI signal processing (Arehart et al., 2014; Jung et al., 2012; Kang et al., 2009; Yüksel et al., 2019).

1.4.3 Frequency following response

TFS representation, including F0, can also be measured via objective methods. The frequency following response (FFR) is an auditory-evoked potential that has recently gained increased traction in the music domain as an objective means by which processing of F0 and TFS can be quantified. F0 (the lowest frequency of a periodic stimulus), TFS (the rapid oscillations that vibrate at a rate near the center frequency of the sound wave; Rosen, 1992), and to some degree the signal's temporal envelope (i.e., slowly fluctuating changes in amplitude over time) are transmitted in the auditory system via synchronous neural firing in line with the phase of the signal (i.e., phase locking). The FFR reflects this neural synchrony to a given stimulus primarily represented at the level of the brainstem, and thus, this measure is uniquely positioned to track specific acoustic properties of the signal, including its spectral and temporal characteristics.

D'Onofrio et al. (2020) obtained FFR recordings for 9 postlingually deafened adult cochlear implant recipients and demonstrated that neural representation of F0 in the non-CI ear was significantly correlated with bimodal benefit for musical emotion perception ($r = 0.67$, $p < 0.05$). Importantly, bimodal benefit for musical emotion perception was not significantly correlated with audiometric thresholds, suggesting that the FFR provides additional value beyond the audiogram. Although further study is warranted, early indications suggest that FFR recordings from the non-implanted ear may hold significant promise for estimating bimodal benefit for music (D'Onofrio et al., 2020), as well as for speech (Kessler et al., 2020) – and ultimately, these measures may help inform clinical decision-making regarding pursuit of a second cochlear implant or maintaining a bimodal hearing configuration. Moreover, an objective measure utilized for this purpose would have particular utility in difficult-to-test populations.

1.5 The present study

In order to provide evidence-based services to bimodal patients, we must systematically investigate the acoustic information that is both minimally, and optimally, beneficial for bimodal listening. Using music as a stimulus provides a uniquely advantageous mechanism for the examination of fitting optimization, particularly for complex signal processing. The current study extends earlier work by Sheffield & Gifford (2014) to examine the effect of low-frequency acoustic bandwidth for music perception and appreciation, in addition to the influence of behavioral pitch perception and neural representation of pitch.

The primary aims of the study are two-fold: (1) to determine the minimum and optimum acoustic bandwidth necessary to obtain bimodal benefit for music perception, music appreciation, and speech perception, (2) to determine whether optimal acoustic bandwidth is correlated with resolution of acoustic, low-frequency stimuli via behavioral (pitch discrimination) and objective (FFR) measures. Our primary hypotheses are that bimodal benefit for perception and appreciation will increase with audible acoustic bandwidth in the non-implanted ear, and secondly, bimodal benefit will be directly related to behavioral pitch discrimination, as well as neural representation of F0 for each low-pass filter cutoff frequency tested. The two aims are addressed in Experiments I and II, respectively.

Chapter 2

METHODS

2.1 Participants

Participants included 12 adult bimodal listeners (7 males, 5 females) and 12 NH adult controls (2 males, 10 females). The Ollen Musical Sophistication Index (OMSI) (Ollen, 2006) was completed by all participants to quantify individual musical training and aptitude. The OMSI consists of 10-items and indicates the probability that a music expert would consider the individual as “more” or “less musically sophisticated.” Scores over 500 are considered “more musically sophisticated”; less than 500 are considered “less musically sophisticated”. Participants from both groups were largely considered “less musically sophisticated,” and an independent samples *t*-test confirmed that there was no significant difference in musical background between groups ($t_{22} = -0.809$, $p = 0.43$). Tables 1 and 2 include additional demographic information for the NH and bimodal participants, respectively. Serial audiograms leading up to implantation were not available for most participants, and thus, duration of deafness is an approximation, ranging from 5 months to 50 years.

Table 1. NH participant demographic information

Participant	Age (years)	OMSI
1	24	299
2	24	127
3	28	139
4	23	323
5	23	97
6	56	998
7	62	208
8	56	165
9	63	953
10	22	99
11	25	432
12	22	46
Mean	36	323.83
SD	17.60	323.81

Table 2. Bimodal participant demographic information.

Participant	Age (yrs)	Manufacturer	Internal	Implant Ear	Etiology	Strategy	OMSI
1	52	Cochlear	CI512	R	Mumps	ACE	105
2	80	Cochlear	CI512	L	Sudden SNHL	ACE	400
3	65	AB	Mid-Scala	R	Meniere's Disease	Optima-S	16
4	80	Cochlear	CI24RE (CA)	L	Unknown	ACE	300
5	36	AB	Mid-Scala	L	Unknown	Optima-S	184
6	70	AB	Mid-Scala	R	Unknown	Optima-S	110
7	49	AB	SlimJ	L	Meniere's Disease	Optima-S	988
8	57	AB	Mid-Scala	L	Unknown	Optima-S	250
9	59	AB	Mid-Scala	R	Meniere's Disease	Optima-S	21
10	26	AB	Mid-Scala	L	Unknown	Optima-S	61
11	80	AB	Mid-Scala	L	Unknown	Optima-S	169
12	44	AB	Mid-Scala	L	Unknown	Optima-P	108
Mean	58						226
SD	18						266

Normal hearing was defined as audiometric thresholds ≤ 25 dB HL between 250-4000 Hz, bilaterally. A Grason Stadler GSI 61 audiometer was used for all hearing evaluations. ER-3A insert earphones were used for all acoustic ear testing. CI-aided thresholds were tested in the soundfield, and thresholds were between 20-30 dB HL from 250-6000 Hz for all qualifying participants. Audiometric thresholds for both the NH and bimodal group are shown in Figure 1. For the NH group, the right and left ears were averaged together, and for the bimodal group, thresholds are shown for the non-implanted ear only.

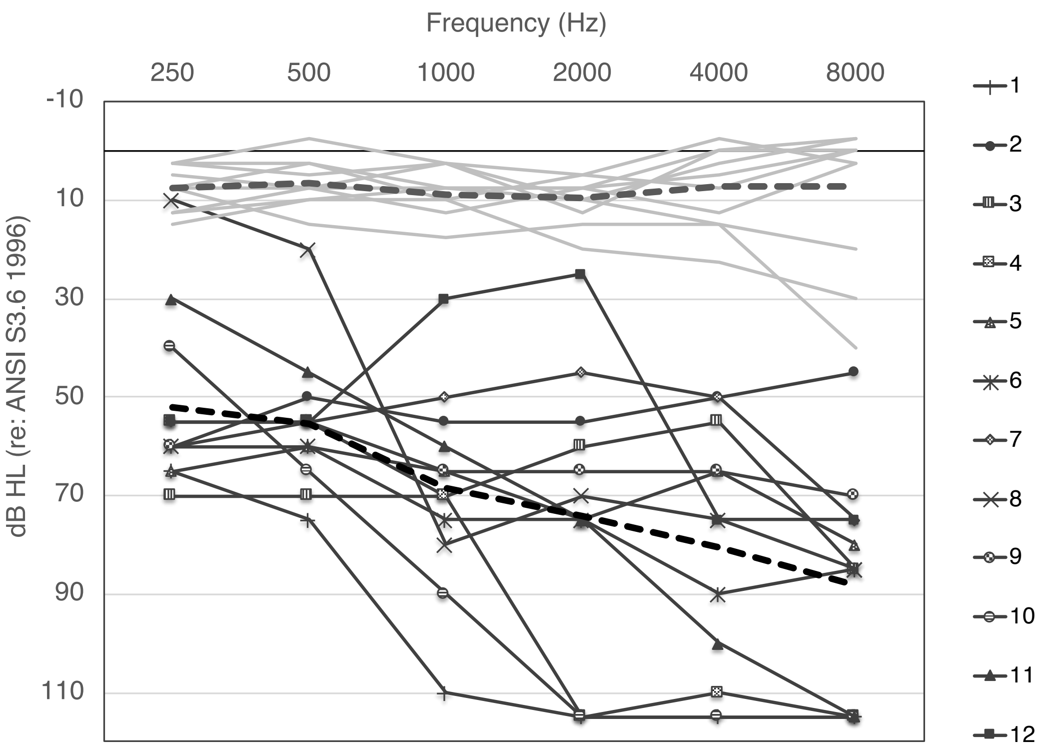


Figure 1. Audiometric thresholds for NH (right and left ears averaged, solid light gray lines) and bimodal listeners (non-implanted ear only, solid dark gray lines with symbols). Group means for NH and bimodal listeners are shown in light and dark gray, respectively. *NH defined as thresholds ≤ 25 dB HL through 4 kHz.

Low-frequency pure-tone average (LFPTA), pure-tone average (PTA), and high-frequency PTA (HFPTA) for individual bimodal participants are shown in Table 3. LFPTA is defined as the average of thresholds at 125, 250, and 500 Hz. PTA is the average of 500, 1000, and 2000 Hz, and HFPTA is the average of 4000, 6000, and 8000 Hz.

Table 3. LFPTA, PTA, and HFPTA for individual bimodal participants. All values are represented in dB HL.

Participant	LFPTA	PTA	HFPTA
1	67	100	115
2	57	53	48
3	70	67	70
4	53	80	113
5	63	67	72
6	55	70	87
7	55	50	63
8	15	57	83
9	57	62	70
10	45	90	115
11	37	60	110
12	53	37	80
Mean	52	66	86
SD	15	18	23

All testing was completed with the participant's CI programmed to user settings. When testing the CI ear, the contralateral ear was plugged with a 3M Classic foam earplug to prevent the non-CI ear from responding. In addition, DRs in the non-CI ear were assessed using the Threshold Equalizing Noise (TEN) Test (Moore et al., 2000), and were characterized using a shift criterion of ≥ 10 dB. Testing determined that 2 participants had a DR at 750 Hz (Participants 1 and 8), 2 at 1500 Hz (Participants 4 and 10), and 1 at 4000 Hz (Participant 11).

All test procedures were explained to the participants and written informed consent was obtained. At the conclusion of the study, participants were compensated for their time spent participating.

2.2 Test environment

All testing was completed in a single-walled sound-attenuation chamber.

2.3 Experiment I

Music perception and appreciation were assessed via measures of timbre perception and subjective sound quality of real-world music samples. Speech perception was assessed via monosyllabic word recognition in quiet. For NH listeners, all stimuli were presented both binaurally and monaurally (via insert earphones). For monaural presentation, the test ear chosen was counterbalanced across participants and remained the same for a given individual throughout testing in both Experiments I and II. For the bimodal group, all stimuli were presented CI-alone (via direct audio input (DAI)) and bimodally (via DAI to the CI and via insert earphone to the non-CI ear).

For presentation to the non-CI ear, and in accordance with methods described by Sheffield & Gifford (2014), all stimuli were presented in the following filter conditions: < 125, < 250, < 500, < 750 Hz, and wideband (full, non-filtered bandwidth). Thus, for each stimulus, there were a total of 6 different listening conditions (CI-alone, CI + 125, CI + 250, CI + 500, CI + 750, CI + WB). Filtering was completed using MATLAB software with a finite impulse response filter with a specific order (256, 512, or 1,024) allowing for a 90-dB/octave roll-off in each filter condition. All stimuli were processed through each filter condition. To account for each participant's hearing loss, individual frequency shaping was completed in accordance with the NAL-NL2 hearing aid prescriptive formula for a 65 dB SPL input level.

For presentation to the CI ear, unfiltered stimuli were presented via DAI. All AB participants utilized a Naida processor regularly; however, a Harmony processor was utilized for testing in the lab to allow for a DAI connection via DirectConnect earhook. A picture of the Harmony processor with DAI connection via DirectConnect earhook is shown in Figure 2A. All Cochlear recipients were tested using N6 (CP910) processors equipped with DAI port. A picture of the N6 processor with DAI connection is shown in Figure 2B. The environmental microphone input was disabled during testing using an AUX only microphone setting.

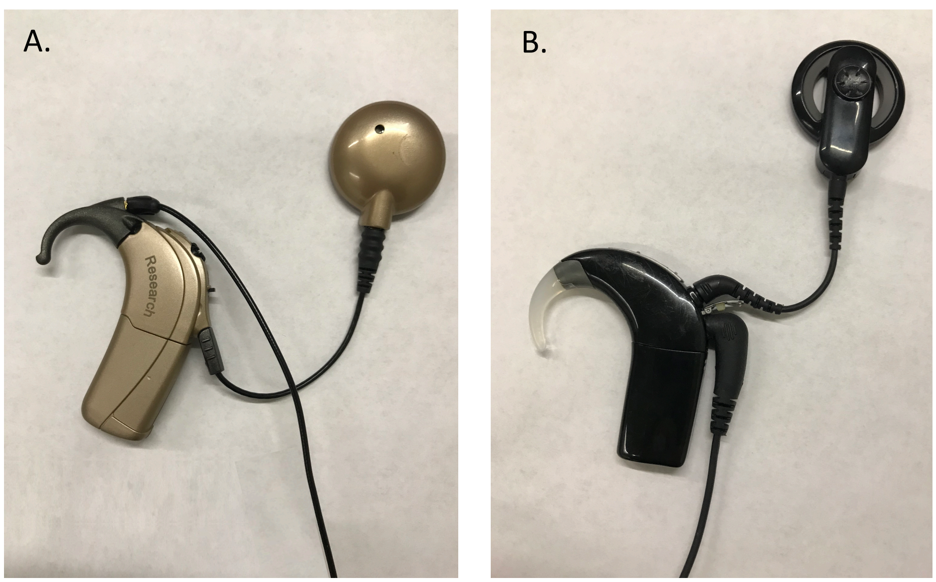


Figure 2A-B. A. Harmony processor with DAI connection via DirectConnect earhook. B. N6 processor with DAI connection.

All stimuli were delivered at the participant's "loud, but comfortable" level. For each stimulus, participants listened to a sample trial in one ear (CI ear for bimodal participants; R or L ear to NH participants) and were asked to rate perceived loudness on a categorical scale with the following descriptors: “barely audible”, “soft”, “comfortable”, “loud, but comfortable”, and “too loud”. Stimuli were then played in the opposite ear, and participants were asked to match loudness. For the bimodal group, stimuli to the non-implanted ear were always frequency-shaped in accordance with NAL-NL2, as previously described. Once perceived loudness was matched, the experimenter then played the sample to both ears simultaneously, and participants were asked if the stimulus sounded balanced. In the bimodal group, loudness matching was always completed using the wideband condition in the non-implanted ear. The level decided upon was used for all remaining filter conditions. We acknowledge that this may result in the filtered conditions being perceived as softer. However, there are two reasons that preclude the ability to match loudness for each filtered condition: (i) For the narrowest conditions, the gain needed would likely exceed the limits of the equipment, and (ii) The output for specific frequencies would vary substantially across the filtered conditions, thereby confounding the question of interest. Absolute presentation levels ranged from 70 to 85 dB SPL for NH listeners and from 85 to 105 dB SPL for bimodal listeners.

2.3.1 Measure of timbre perception

Timbre perception was measured using the Timbre Identification subtest of the UW-CAMP (Kang et al., 2009). Each stimulus presentation was presented as the same 5-note sequence of C4-A4-F4-G4-C5, played at 82 beats per minute (bpm), recorded at a mezzo forte dynamic marking. The participant’s task was to choose which instrument was played from a closed-set of 8 instruments, resulting in an overall percent correct score. The 8 instruments include: cello, clarinet, flute, guitar, piano, saxophone, trumpet, and violin, and represent the four major instrument classes (strings, woodwinds, brass, and percussion). Prior to testing, each instrument was played for the participant 3 times with the associated name of the instrument visible for familiarization.

2.3.2 Measures of sound quality

Two tasks were used to assess subjective sound quality of real-world music. The first consisted of experimenter-chosen music selections. Song samples were chosen from a pre-selected library of songs consisting of various genres categorized in accordance with the record label's description. The genres for selection included: Alternative, Blues, Disco/Electronic, Hip-Hop/Rap, Jazz, Pop, Rhythm & Blues (R&B), and Rock. Two songs were chosen from each genre for task presentation, resulting in a total of 16 songs. The clips were 20-seconds in duration, and each participant was instructed to rate sound quality directly following stimulus presentation on an 11-point scale ranging from 0 to 10, with the following descriptive anchors: 1 = very bad, 3 = rather bad, 5 = midway (neutral), 7 = rather good, 9 = very good. The mean overall rating, per trial, was used for subsequent analyses. This task has been previously validated in 10 NH listeners and 10 individuals who used combined electric and acoustic stimulation (EAS) (Gilbane & Gifford, 2018).

The second assessment included participant-chosen music selections. Participants were asked to choose 2 of their favorite songs, and provide them to the experimenter prior to the test session. The participant-chosen music task was added in an effort to test listeners on music representative of what they listen to in the real world. Because music sound quality ratings can be influenced by individual factors (i.e., musical training, familiarity with musical style and/or genres, demographic variables, personality characteristics) (Ginocchio, 2009; LeBlanc et al., 1999; Nater et al., 2006; Robinson et al., 1996), participant-chosen songs were also included to control for any bias that may otherwise be present when making sound quality judgements of songs for which a participant may not enjoy or is lacking in familiarity. The test procedure for the participant-chosen selections was identical to that previously described for the experimenter-chosen selections.

2.3.3 Measure of speech recognition

In an attempt to replicate a portion of the study by Sheffield & Gifford (2014), consonant-nucleus-consonant (CNC) monosyllabic words (Peterson and Lehiste, 1962) were used to assess speech recognition in quiet. This measure also served as a within-subject comparison of the cues contributing to bimodal benefit for speech recognition and music perception. The CNC test battery includes 10 phonemically balanced lists, each containing 50 words. The words are spoken by a male talker with a mean F0 around 123 Hz and standard deviation of 17 Hz, as reported by Zhang et al. (2010).

2.4 Experiment II

2.4.1 Pitch discrimination

Pitch perception was tested using a pitch discrimination task. Stimuli were delivered monaurally to both groups – to the non-implanted ear of bimodal participants (CI was removed during testing) or to the test ear of NH participants. The task was an adaptive, three interval, two alternative forced choice task, which consisted of a reference tone, and two subsequent tones. This method has been utilized in similar tasks developed for the cochlear implant population (e.g., spectral modulation detection (SMD); Gifford, Hedley-Williams, & Spahr, 2014; Zhang, Spahr, Dorman, & Saoji, 2013). The listener was instructed to indicate which of the two subsequent tones was different from the reference by pressing the appropriate selection on a touchscreen monitor. The stimulus was a harmonic complex with 20 components starting at the fundamental, and was designed to represent a synthetic piano. The amplitudes of the harmonics were proportional to 1/F, and decreased in accordance with the sequence: 1, 1/2, 1/3, 1/4, etc. Base frequencies chosen for testing were real-world music notes from the Western tonal system with F0s closest to the low-pass filter cutoffs discussed above. These therefore included: B2 (123 Hz), B3 (247 Hz), B4 (494 Hz), and F#5 (740 Hz). Presentation levels for each frequency were the same as those utilized for FFR testing (this process is described in the following section). It is possible that significantly poor auditory thresholds at one or more of these frequencies would preclude pitch discrimination testing at that particular frequency. Exclusion criteria included thresholds in the profound hearing loss range (90 dB HL or greater). Presentation order was counterbalanced across participants. Results from this task were expressed as a threshold in Hz for each of the 4 base frequencies.

2.4.2 Frequency following response

F0 and TFS representation were assessed via the FFR generated for 200-ms musical notes with F0s closest to the low-pass filter cutoffs, and which matched the base frequencies utilized in the pitch discrimination task: B2 (123 Hz), B3 (247 Hz), B4 (494 Hz), and F#5 (740 Hz). Figure 3A-D show the original stimulus spectra for B2, B3, B4, and F#5, respectively. A 170-ms /da/ speech stimulus (F0 = 100 Hz, F1 = 700 Hz) was also used for testing. Figure 4 shows the original stimulus spectrum for /da/.

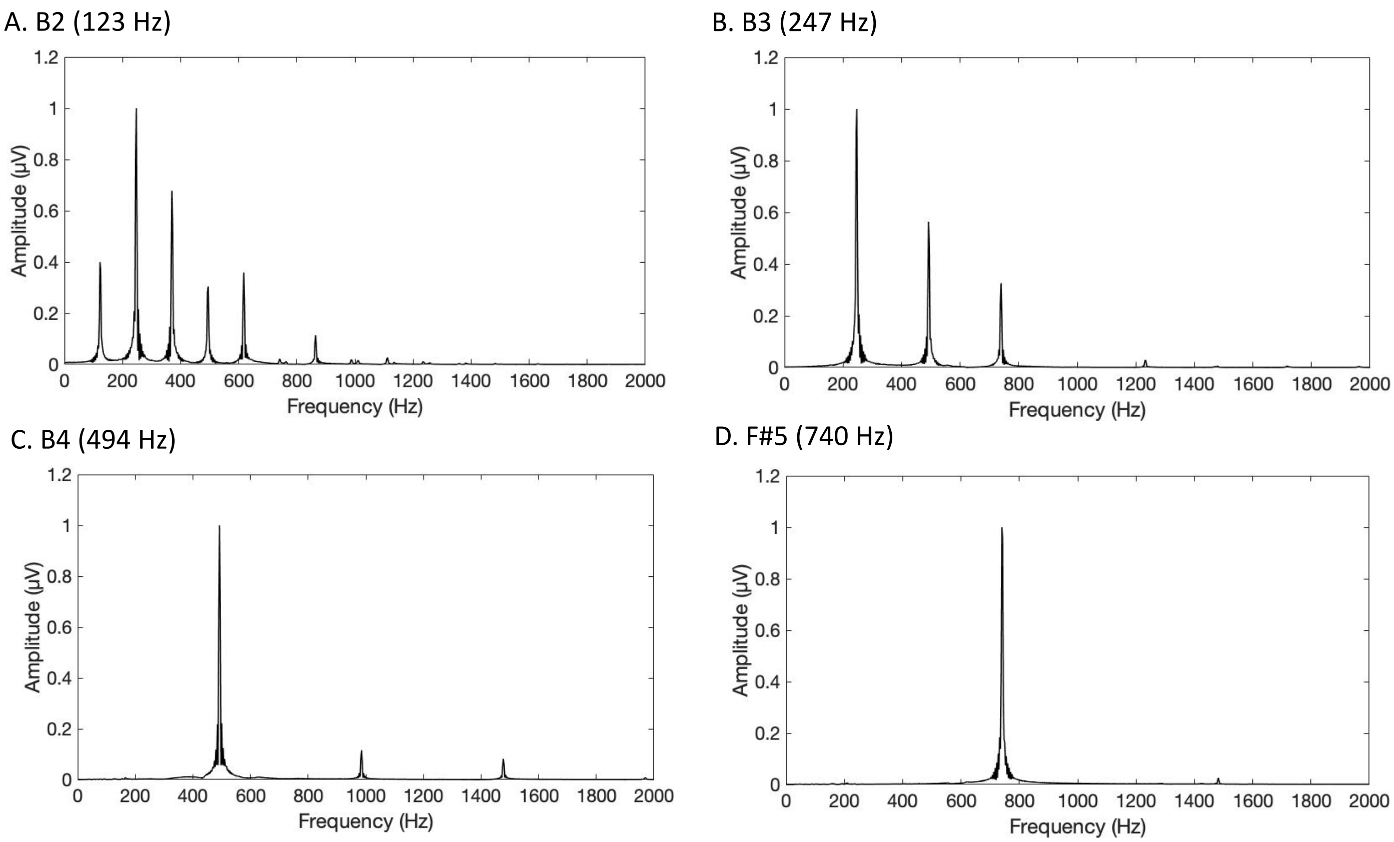


Figure 3A-D. Original spectra for the B2, B3, B4, and F#5 stimuli.

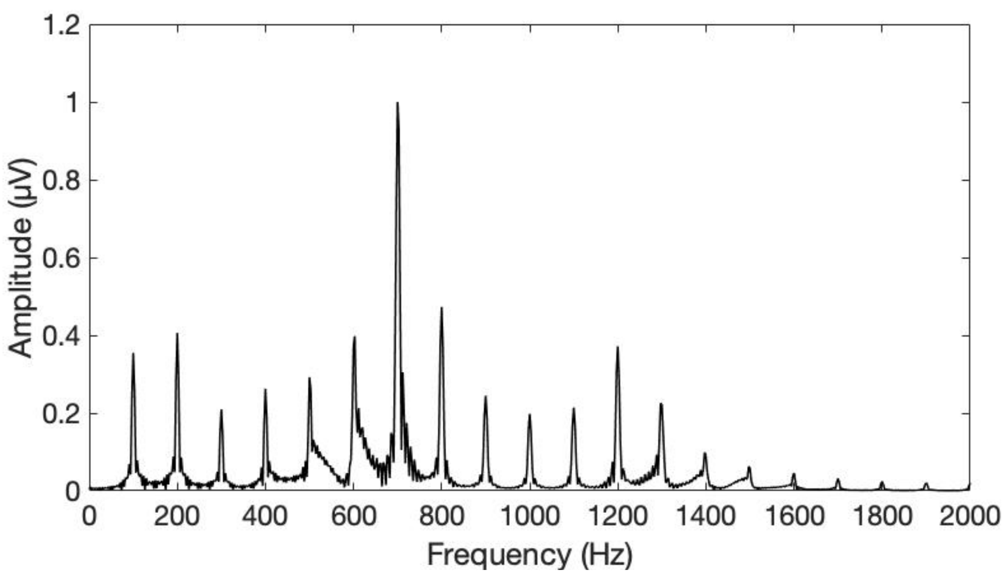


Figure 4. Original spectrum for the /da/ stimulus (F0 = 100 Hz, F1 = 700 Hz).

All FFR stimuli were delivered monaurally – to the non-implanted ear of bimodal participants (CI was removed during testing) or to the test ear of NH participants. Presentation order was counterbalanced across participants. Consistent with our pitch discrimination exclusion criteria, FFR testing was not completed if thresholds for a given test frequency were in the profound hearing loss range (90 dB HL or greater).

Recordings were conducted using a vertical electrode montage with a three Ag-AgCl electrode array (Cz active, Fpz ground, earlobe reference). Participants sat in a reclining chair with room lights off and were instructed to remain awake throughout testing, but as relaxed as possible while refraining from movement in order to reduce myogenic artifact. Participants viewed a muted nature documentary (episodes from the Planet Earth II series) during testing to facilitate an awake, but relaxed state. An Intelligent Hearing System (IHS) Duet System (Smart EP, Miami FL, USA) was used for stimulus presentation, with all stimuli presented through magnetically shielded Etymotic ER-3A insert earphones. Stimuli were delivered at a rate of 4.35 Hz and with alternating polarity, thereby allowing for both TFS and envelope analysis by either subtracting or adding the output from each polarity, respectively (see Aiken & Picton, 2008). Each FFR was taken as an average of 2000 stimulus repetitions (for the music stimuli) and 3000 stimulus repetitions (for the speech stimulus), with artifact rejection set to ±35 μV. Fewer stimulus repetitions were utilized for the music stimuli, as each stimulus was longer in duration (200-ms vs. 170-ms). High-pass and low-pass filters were set to 1 Hz and 5000 Hz, respectively, which allowed for further post-hoc filtering. Two runs were completed per stimulus. Post-acquisition, the two recordings were averaged, bandpass filtered from 70-3000 Hz, and transformed into the spectral domain using a fast Fourier transform (FFT).

For NH listeners, stimuli were presented at 80 dB SPL to the test ear. This presentation level was chosen as it has been used routinely in FFR literature and is consistent with previous work in our lab (D'Onofrio et al., 2020; Kessler et al., 2020). For bimodal listeners, presentation levels were determined based on the participant's "loud, but comfortable" level for each stimulus. The level at which the stimulus was "barely audible" was also documented, allowing for individual sensation levels (dB SL) to be reported. This presentation level technique for the bimodal listeners was chosen in an effort to control for audibility across participants and to be consistent with presentation level procedures for the music and speech testing. The levels of presentation used for testing in the bimodal group are shown in Table 4.

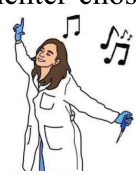
Table 4. Individual presentation levels for the music (B2, B3, B4, F#4) and speech (/da/) stimuli for bimodal participants. Absolute level is shown in dB SPL, and sensation level is shown in dB SL.

Participant	123 Hz		247 Hz		494 Hz		740 Hz		/da/	
	dB SPL	dB SL	dB SPL	dB SL	dB SPL	dB SL	dB SPL	dB SL	dB SPL	dB SL
1	90	----	92	----	97	----	DNT	DNT	95	----
2	85	7	85	7	75	15	80	16	80	----
3	100	12	100	12	100	20	99	20	100	----
4	85	30	90	30	90	30	95	30	95	25
5	103	20	103	20	95	25	104	25	101	----
6	85	25	90	25	90	30	95	30	85	----
7	90	30	95	35	95	35	90	30	95	45
8	75	55	85	60	85	55	85	20	80	40
9	95	25	95	25	90	20	90	20	95	25
10	93	43	102	47	100	30	100	15	97	32
11	85	40	80	30	75	25	75	15	70	10
12	70	20	70	20	70	25	65	20	65	35
Mean	88.0	27.9	90.6	28.3	88.5	28.2	88.9	21.9	88.2	30.3
SD	9.4	14.0	9.6	15.1	10.2	10.6	11.8	5.9	12.0	11.6

*Participant 1 was not tested on the 740 Hz stimulus due to thresholds in the profound range. This is notated by "DNT" (did not test).
*Some participants were tested prior to the decision to record the "barely audible" level. Thus, a measure of dB SL could not be determined in those cases. This is notated by "----".

The tasks and listening conditions from Experiments I and II for both groups are summarized in Table 5.

Table 5. Tasks from Experiments I and II.

	Tasks	Stimulus	Listening Conditions	
			Bimodal	NH
Experiment I	Timbre Perception	UW-CAMP – Timbre Identification subtest 	CI-alone (DAI) CI + 125 Hz CI + 250 Hz CI + 500 Hz CI + 750 Hz CI + WB	Binaural Monaural
	Sound Quality	Experimenter-chosen music  Participant-chosen music 		
	Word Recognition	CNC monosyllabic words 		
	Tasks	Stimulus	Test Frequencies	
Experiment II	Pitch Discrimination	Harmonic complex 	123 Hz 247 Hz 494 Hz 740 Hz	
	FFR	Rhodes piano  Speech 	123 Hz 247 Hz 494 Hz 740 Hz /da/ (*FFR only)	

Chapter 3

DATA ANALYSIS

3.1 Statistical tests

A power analysis was completed for a sample size justification. We have conducted a study of a continuous, yet categorically classified response variable (acoustic bandwidth) from matched pairs of study subjects (CI-alone and bimodal). Our pilot data for this study indicated that the difference in the response between conditions was normally distributed with standard deviation 10.9. If the true difference in the mean response of matched pairs is 12.5 as shown in our pilot data, we would need to study 8 participants (CI and bimodal) to be able to reject the null hypothesis that this response difference is zero across the conditions with probability (power) 0.8. The Type I error probability associated with the test of this null hypothesis is 0.05. To account for the potential effects of attrition, we increased our enrollment by 50% to 12 total participants. We have included an equal number of subjects in our NH control group.

The IBM SPSS Statistics Version 25 (Armonk, NY) and GraphPad Prism 7.0 (San Diego, CA) software programs were utilized for statistical analyses. For Experiment I, data analysis focused on within-subject and between-group performance and rating differences. Among bimodal listeners, these within-subject conditions of comparison included CI-alone, CI + 125, CI + 250, CI + 500, CI + 750, CI + WB, and an additional condition for analysis purposes termed CI + OPT. CI + OPT was defined as the filter condition for which the participant obtained highest performance. For example, if participant 1's scores on a given measure were the following: CI-alone = 20%, CI + 125 = 25%, CI + 250 = 30%, CI + 500 = 35%, CI + 750 = 55%, CI + WB = 45%, the CI + 750 condition would be considered this individual's CI + OPT condition for that particular stimulus. Analyses were completed using mixed model and repeated measures ANOVAs and paired comparisons based on a priori hypotheses for bimodal benefit.

For Experiment II, data analysis similarly focused on within-subject and between-group performance differences. Additional analyses focused on correlations between behavioral pitch discrimination and neural representation of F0 vs. bimodal benefit for timbre perception, sound quality ratings, and word recognition scores. The strength of the correlations was described according to Cohen's (1988) conventions quantifying effect size. In all cases, bimodal benefit was defined as the difference between scores in the bimodal condition and scores in the CI-alone condition.

Chapter 4

RESULTS

4.1 Experiment I

4.1.1 Measure of timbre perception

Figure 5 shows results from the timbre perception task. NH listeners achieved mean scores of 88.9%, 95% confidence interval (CI) [81.9, 96.0] and 87.4%, 95% CI [79.0, 95.8] in the binaural and monaural conditions, respectively. A paired samples *t*-test revealed no significant difference in performance between the binaural and monaural conditions (t_{11}= 1.123, $p = 0.29$).

With respect to performance in the bimodal group, first a few general observations can be made. Performance generally improved with the addition of more acoustic information; however, performance in all 6 listening conditions (CI-alone, CI + 125 Hz, CI + 250 Hz, CI + 500 Hz, CI + 750 Hz, and CI + WB) remained poorer than NH performance. Mean timbre perception for CI-alone was 46.5%, 95% CI [32.4, 60.7], mean for CI + 125 Hz was 50.3%, 95% CI [36.4, 64.3], mean for CI + 250 Hz was 47.2%, 95% CI [38.1, 56.3], mean for CI + 500 Hz was 49.0%, 95% CI [35.8, 62.0], mean for CI + 750 Hz was 52.5%, 95% CI [39.5, 65.4], and mean for CI + WB was 59.0%, 95% CI [50.9, 67.2]. At the group level, best performance among bimodal listeners was achieved in the CI + WB condition, with a score of 59% – though that was still 28- to 30-percentage points poorer than NH performance in the monaural and binaural conditions, respectively.

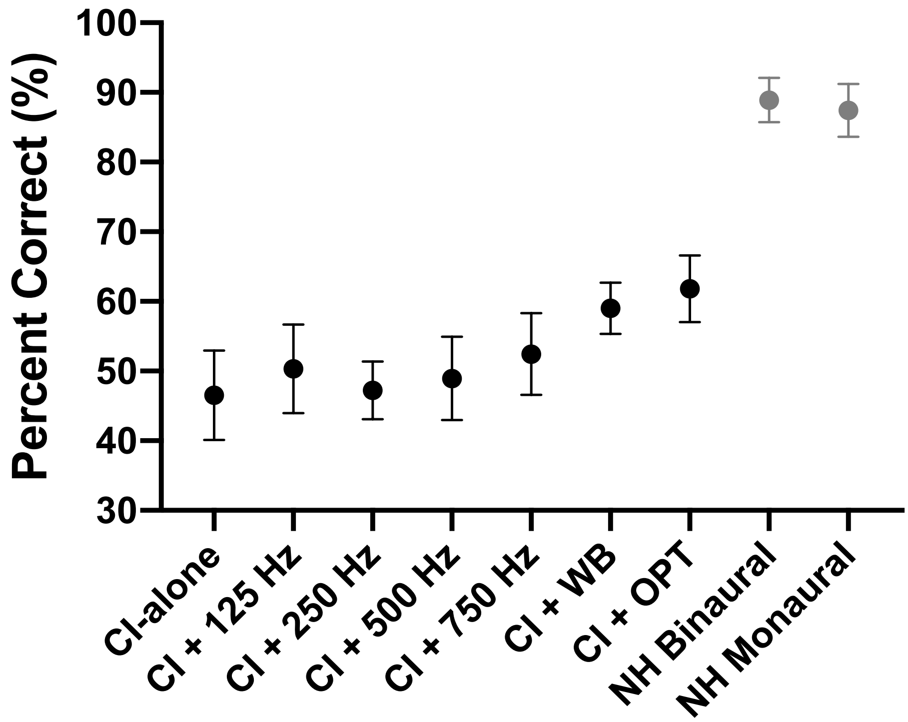


Figure 5. Mean timbre identification scores in percent correct. Error bars represent ±1 SEM.

A closer examination of the individual bimodal data shows that optimal performance (CI + OPT) was obtained in the CI + WB condition for 8 listeners, in the CI + 750 Hz condition for 2 listeners, and in the CI + 125 Hz condition for 2 listeners. Mean timbre perception for CI + OPT was 61.8%, 95% CI [51.3, 72.3]. The bimodal benefit for each individual's CI + OPT score ranged from 4- to 42-percentage points when compared to the CI-alone condition. Mean performance differences across the 6 listening conditions and CI + OPT were examined using a repeated measures ANOVA and revealed a significant effect of listening condition, $F(6, 66) = 6.476$, $p < 0.01$, $\eta_p^2 = 0.37$. Follow-up pairwise comparisons using Bonferroni adjustment for multiple comparisons revealed a significant difference between the CI-alone and CI + OPT condition ($p < 0.02$, $d = 1.339$). CI + OPT performance was also significantly greater than performance in the CI + 125 ($p < 0.04$, $d = 1.157$), CI + 250 ($p < 0.01$, $d = 1.484$), and CI + 500

($p < 0.01$, $d = 1.598$) conditions. The difference between CI + OPT and both CI + 750 and CI + WB failed to reach statistical significance. Taken together, despite a trend toward improvement with increasing bandwidth at the group level, significant acoustic benefit was observed only for the conditions yielding optimal individual performance.

4.1.2 Measures of sound quality

Figure 6 shows results from the sound quality task. For experimenter-chosen selections, mean sound quality ratings for NH listeners were 6.8, 95% CI [5.8 , 7.7] and 6.5, 95% CI [5.7, 7.4] in the binaural and monaural conditions, respectively. For participant-chosen selections, mean sound quality ratings for NH listeners were 7.9, 95% CI [6.9, 8.8] and 7.5, 95% CI [6.7, 8.4] in the binaural and monaural conditions, respectively. Among NH listeners, sound quality ratings were examined using a two-way repeated measures ANOVA with the two factors being listening condition (binaural, monaural) and stimulus type (experimenter-chosen, participant-chosen). Analysis revealed a significant main effect of stimulus type, $F(1,11) = 25.691$, $p < 0.01$, $\eta_p^2 = 0.70$, but no significant effect of listening condition, $F(1,11) = 1.536$, $p = 0.24$, $\eta_p^2 = 0.12$, and no significant interaction effect, $F(1,11) = .118$, $p = 0.74$, $\eta_p^2 = 0.01$. Thus, NH listeners rated participant-chosen songs significantly higher than experimenter-chosen songs, for both binaural and monaural presentations.

With respect to the bimodal group, ratings improved steadily with the addition of more acoustic information to a level that was comparable to NH ratings for experimenter-chosen selections, and exceeded NH ratings for participant-chosen selections. For experimenter-chosen selections, the mean sound quality rating for CI-alone was 4.8, 95% CI [3.6, 6.0], mean for CI + 125 Hz was 5.3, 95% CI [3.6, 7.0], mean for CI + 250 Hz was 5.6, 95% CI [4.2, 6.9], mean for

CI + 500 Hz was 5.9, 95% CI [4.8, 6.9], mean for CI + 750 Hz was 6.2, 95% CI [5.1, 7.3], and mean for CI + WB was 6.9, 95% CI [6.1, 7.6]. For participant-chosen selections, the mean sound quality rating for CI-alone was 5.7, 95% CI [3.8, 7.7], mean for CI + 125 Hz was 6.2, 95% CI [4.0, 8.4], mean for CI + 250 Hz was 6.7, 95% CI [5.0, 8.4], mean for CI + 500 Hz was 7.3, 95% CI [5.6, 8.9], mean for CI + 750 Hz was 7.5, 95% CI [6.0, 9.0], and mean for CI + WB was 8.8, 95% CI [7.8, 9.8]. An independent samples *t*-test was used to compare ratings in the CI + WB condition to NH ratings in the binaural condition, and revealed no significant difference between groups for both the experimenter-chosen songs ($t_{22} = 0.194$, $p = 0.85$) and the participant-chosen songs ($t_{22} = 1.282$, $p = 0.21$). Thus, NH and bimodal listeners in the CI + WB condition did not differ in their sound quality ratings.

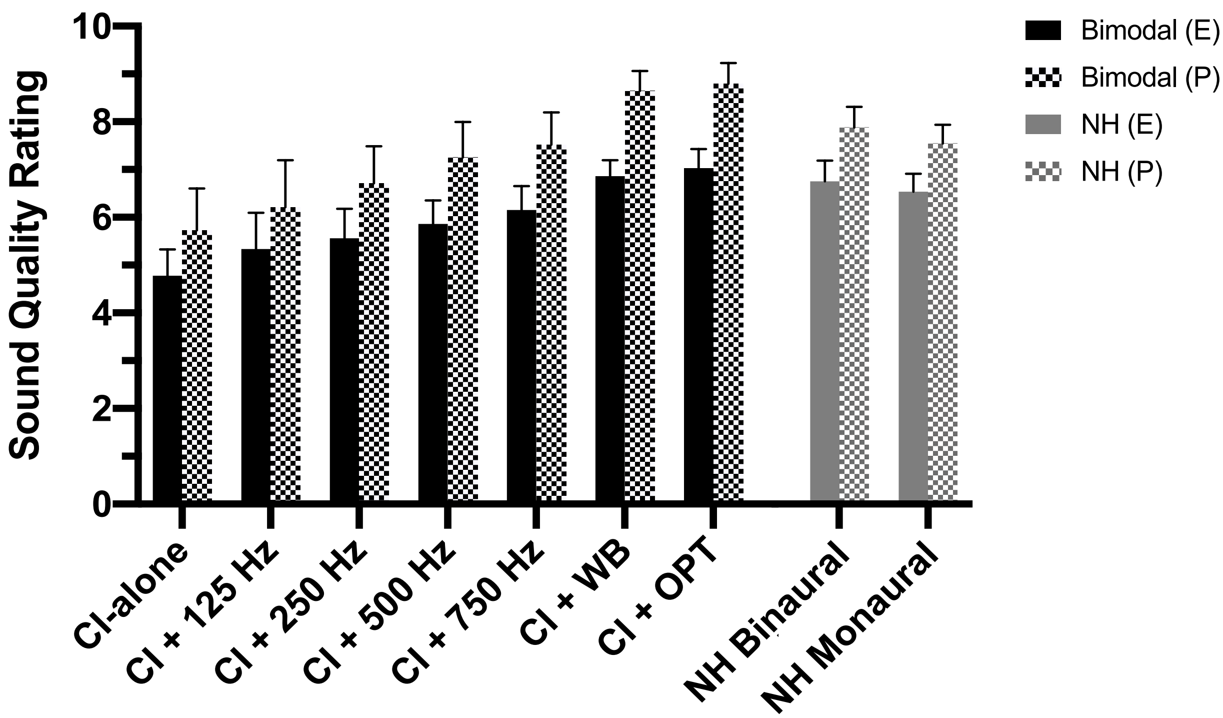


Figure 6. Mean sound quality ratings for experimenter-chosen songs (“E”, solid) and participant-chosen songs (“P”, patterned) for the bimodal (black) and NH (gray) groups. Error bars represent +1 SEM.

A closer examination of individual bimodal data shows that optimal performance was obtained in the CI + WB condition for 9 listeners, in the CI + 750 Hz condition for 2 listeners, and in the CI + 125 Hz condition for 1 listener. For experimenter-chosen selections, the mean sound quality rating for CI + OPT was 7.0, 95% CI [6.1, 7.9]. For participant-chosen selections, the mean sound quality rating for CI + OPT was 8.8, 95% CI [7.8, 9.8]. The bimodal benefit achieved for each individual's CI + OPT condition ranged from 0.13 to 5.08. A two-way repeated measures ANOVA was used to examine mean sound quality ratings in the bimodal group with the two factors being listening condition (CI-alone, CI + 125, CI + 250, CI + 500, CI + 750, CI + WB, and CI + OPT) and stimulus type (experimenter-chosen, participant-chosen). A Greenhouse–Geisser correction was used for sphericity. Analysis revealed a significant main effect of stimulus type, $F(1, 11) = 8.771$, $p < 0.01$, $\eta_p^2 = 0.44$, and listening condition, $F(2.489, 27.375) = 10.518$, $p < 0.01$, $\eta_p^2 = 0.49$. There was no significant interaction effect, $F(2.618, 28.802) = 1.530$, $p = 0.23$, $\eta_p^2 = 0.12$. Follow-up pairwise comparisons on the main effect of listening condition were completed with Bonferroni correction. Significant differences were found between CI-alone and both CI + WB ($p < 0.01$, $d = 1.358$) and CI + OPT ($p < 0.01$, $d = 1.451$). No other significant differences were observed. Thus, these results indicate that for musical sound quality, significant bimodal benefit can be achieved with WB amplification. When compared to CI + WB, the added improvement with CI + OPT amplification failed to reach statistical significance. Additionally, consistent with the NH results, significantly higher ratings were given to participant-chosen songs for all listening conditions.

4.1.3 Measure of speech recognition

Figure 7 shows results for CNC word recognition. Performance among bimodal listeners improved steadily with the addition of more acoustic information. Mean CNC word recognition for CI-alone was 63.3%, 95% CI [49.9, 76.7], mean for CI + 125 Hz was 69.2%, 95% CI [54.1, 84.2], mean for CI + 250 Hz was 71.8%, 95% CI [57.7, 86.0], mean for CI + 500 Hz was 73.7%, 95% CI [60.4, 87.0], mean for CI + 750 Hz was 78.7%, 95% CI [68.4, 89.0], and mean for CI + WB was 85.0%, 95% CI [75.2, 94.9].

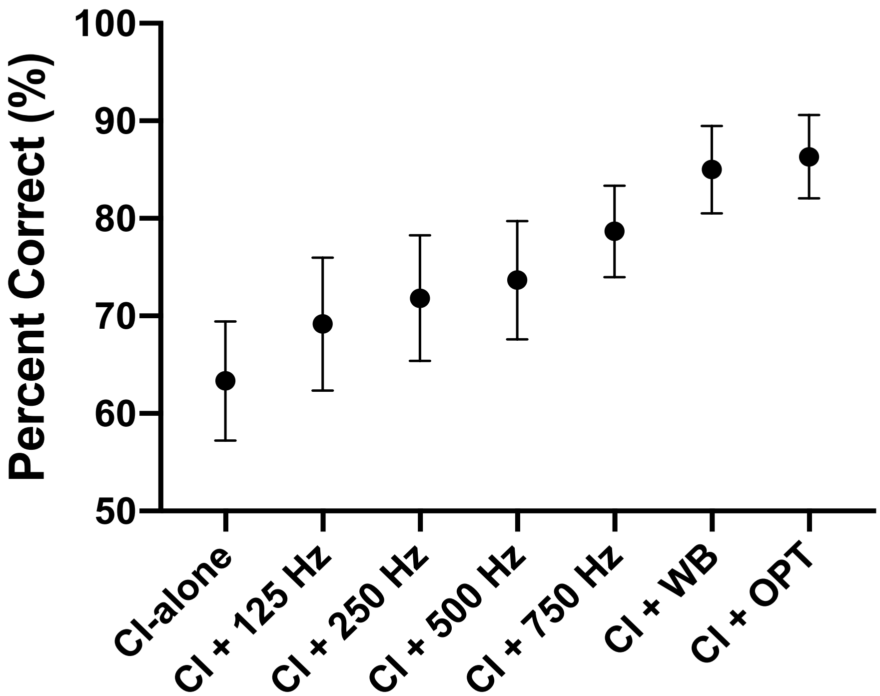


Figure 7. Mean CNC word scores in percent correct. Error bars represent ±1 SEM.

A closer examination of individual bimodal data shows that optimal performance was obtained in the CI + WB condition for 9 listeners, in the CI + 750 Hz condition for 2 listeners, and in the CI + 500 Hz condition for 1 listener. Mean CNC word recognition for CI + OPT was 86.3%, 95% CI [76.9, 95.8]. The bimodal benefit achieved for each individual's CI + OPT condition ranged from 8- to 58-percentage points. For those whose CI + OPT condition was *not* the CI + WB condition (n = 3), the 95% confidence interval table for a 50-item test of word recognition (Thornton & Raffin, 1978) was used to determine whether the difference between CI + WB and CI + OPT performance was significant as related to test-retest variability. Those differences were 8, 6, and 2-percentage points for Participants 4, 8, and 10, respectively – none of which were significant at the individual level.

A repeated measures ANOVA was used to examine mean CNC word scores in the bimodal group across the 7 conditions of interest (CI-alone, CI + 125 Hz, CI + 250 Hz, CI + 500 Hz, CI + 750 Hz, CI + WB, CI + OPT). Analysis revealed a significant effect of listening condition, $F(1.809, 19.899) = 11.224$, $p < 0.01$, $\eta_p^2 = 0.51$. Follow-up pairwise comparisons were completed with a Bonferroni correction and revealed a significant improvement between CI-alone and the following: CI + 250 Hz ($p < 0.05$, $d = 1.138$), CI + 500 Hz ($p < 0.04$, $d = 1.179$), CI + 750 Hz ($p < 0.01$, $d = 1.500$), CI + WB, ($p < 0.01$, $d = 1.537$), and CI + OPT, ($p < 0.01$, $d = 1.566$). Importantly, all other paired comparisons failed to reach significance. Thus, these results indicate that for speech recognition in quiet, < 250 Hz is minimally required for bimodal benefit. Performance continued to increase in the wider bandwidth conditions and CI + OPT resulting in significant improvement over the CI-alone condition, but not over CI + 250 Hz condition.

4.1.4 Additional observations

The extent to which each participant's optimal condition remained consistent across all 3 measures was examined. For example, if a participant performed best in the CI + WB condition for the timbre perception task, we examined whether this was also true for sound quality measures and CNC word scores. When all 3 measures were considered, participants' CI + OPT condition remained the same for only 6 participants, equivalent to 50% of the total sample. An additional analysis examined the extent to which participants' optimal conditions were consistent across the music tasks only. For timbre perception and sound quality measures, participants' CI + OPT conditions remained the same for 10 participants, equivalent to 83% of the total sample. Thus, it is possible that similar acoustic cues contribute to performance on tasks in the music domain, which may differ from those utilized for tasks of word recognition. This was addressed further in Experiment II.

Lastly, DRs were present in 5 of the total 12 participants. For timbre perception, the condition yielding optimal performance was CI + WB for 4 of those 5 participants. For sound quality, the optimal condition was CI + WB for those same 4 participants. For word recognition, the optimal condition was CI + WB for only 2 of the 5 participants with DRs. Future research with a larger sample size is needed to determine whether cochlear DRs may have a greater impact on optimal acoustic bandwidth for speech recognition than for music.

4.2 Experiment II

4.2.1 Pitch discrimination

Figure 8 shows results from the pitch perception task. Of note, 1 bimodal participant (participant 1) was unable to complete the task for the 740-Hz stimulus due to thresholds in the profound hearing loss range; thus, this participant's data were omitted from analysis of the 740-Hz stimulus.

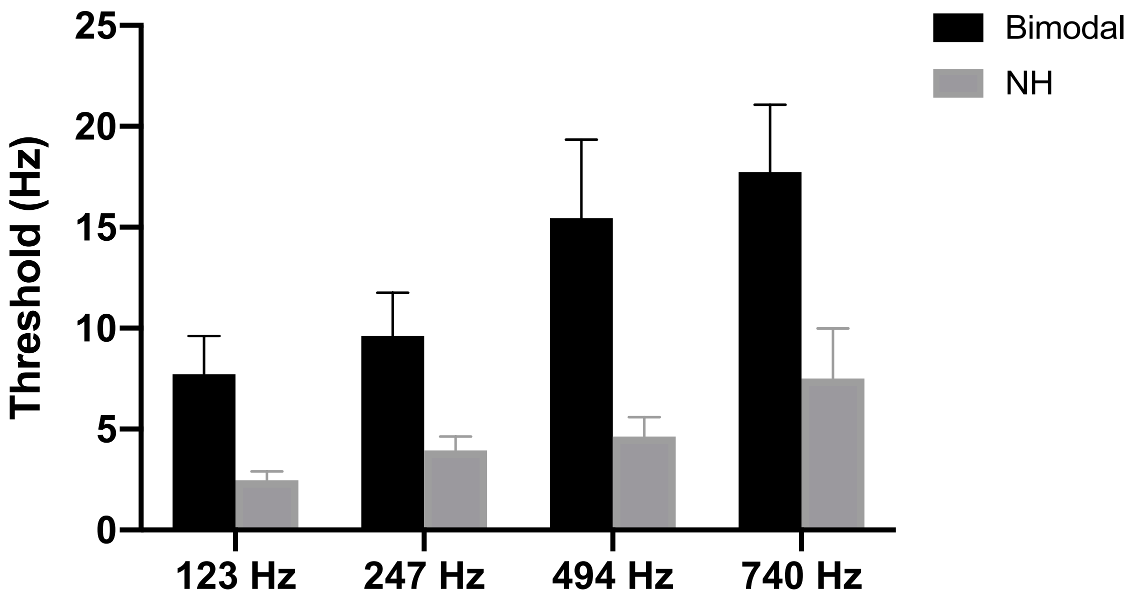


Figure 8. Mean pitch discrimination thresholds for the non-CI ear of bimodal (black) and test ear of NH (gray) listeners. Error bars represent +1 SEM.

In order to assess whether pitch discrimination thresholds were different between groups and across frequency, a mixed-model analysis of variance (ANOVA) was performed with the between groups factor of group (bimodal, NH) and the repeated-measures factor of frequency (123, 247, 494, 740 Hz). A Greenhouse–Geisser correction was used for sphericity. Analysis revealed a significant effect of group, $F(1, 22) = 12.145$, $p < 0.01$, $\eta_p^2 = 0.36$, and frequency, $F(2.080, 45.764) = 6.364$, $p < 0.01$, $\eta_p^2 = 0.22$. The interaction effect was not significant, $F(2.080, 45.764) = 1.193$, $p = 0.31$, $\eta_p^2 = 0.05$. Follow-up pairwise comparisons on the main effect of frequency were completed with a Bonferroni correction, and revealed a significant difference between 123 and 740 Hz, $p < 0.01$. These results indicate that NH listeners had better pitch discrimination compared with bimodal listeners, and pitch discrimination was significantly better for the lowest frequency when compared to the highest frequency tested.

4.2.1.1 Pitch discrimination and bimodal benefit (CI + 125, CI + 250, CI + 500, CI + 750, CI + WB)

With respect to pitch discrimination, the primary question of interest was whether pitch discrimination was related to bimodal benefit. Our data were analyzed in two ways. First, the relationship between pitch discrimination thresholds at 123, 247, 494, and 740 Hz and bimodal benefit for timbre and sound quality in the respective corresponding filter conditions was examined. Thus, the analyses were as follows: 123-Hz threshold vs. bimodal benefit for CI + 125 Hz, 247-Hz threshold vs. bimodal benefit for CI + 250 Hz, 494-Hz threshold vs. bimodal benefit for CI + 500 Hz, and 740-Hz threshold vs. bimodal benefit for CI + 750 Hz. An "average" low-frequency pitch discrimination threshold was also computed as the average of the 123-, 247-, 494-, and 740-Hz thresholds, and was used for analysis with the CI + WB condition. All analyses were completed using partial correlations while controlling for CI-alone (baseline) performance.

For timbre, all correlations were consistent with a small effect size and non-significant: 123-Hz threshold vs. bimodal benefit for CI + 125 Hz (r = -0.216, p = 0.52), 247-Hz threshold vs. bimodal benefit for CI + 250 Hz (r = 0.270, p = 0.42), 494-Hz threshold vs. bimodal benefit for CI + 500 Hz (r = 0.217, p = 0.52), 740-Hz threshold vs. bimodal benefit for CI + 750 Hz (r = 0.179, p = 0.62), and "average" low-frequency pitch discrimination vs. bimodal benefit for CI + WB (r = 0.067, p = 0.85).

For sound quality, all correlations were consistent with a small to medium effect size and non-significant: 123-Hz threshold vs. bimodal benefit for CI + 125 Hz (r = -0.168, p = 0.62), 247-Hz threshold vs. bimodal benefit for CI + 250 Hz (r = -0.033, p = 0.92), 494-Hz threshold vs. bimodal benefit for CI + 500 Hz (r = 0.355, p = 0.28), 740-Hz threshold vs. bimodal benefit for CI + 750 Hz (r = 0.309, p = 0.39), and "average" low-frequency pitch discrimination vs.

bimodal benefit for CI + WB (*r* = -0.056, *p* = 0.87).

4.2.1.2 Pitch discrimination and bimodal benefit (OPT bimodal benefit)

The second analysis focused solely on the relationship between pitch discrimination and bimodal benefit for the CI + OPT condition, for each stimulus. These correlations were examined in an effort to determine whether pitch discrimination was predictive of optimal acoustic bandwidth. Again, all analyses were completed using partial correlations while controlling for CI-alone (baseline) performance.

For timbre, all correlations were consistent with a small to medium effect size and non-significant: 123-Hz threshold vs. OPT bimodal benefit (*r* = -0.327, *p* = 0.33), 247-Hz threshold vs. OPT bimodal benefit (*r* = -0.113, *p* = 0.74), 494-Hz threshold vs. OPT bimodal benefit (*r* = 0.031, *p* = 0.93), 740-Hz threshold vs. OPT bimodal benefit (*r* = 0.006, *p* = 0.99), and “average” low-frequency pitch discrimination vs. OPT bimodal benefit (*r* = -0.080, *p* = 0.81).

For sound quality, all correlations were consistent with a small to medium effect size and non-significant: 123-Hz threshold vs. OPT bimodal benefit (*r* = -0.395, *p* = 0.23), 247-Hz threshold vs. OPT bimodal benefit (*r* = -0.386, *p* = 0.24), 494-Hz threshold vs. OPT bimodal benefit (*r* = 0.065, *p* = 0.85), 740-Hz threshold vs. OPT bimodal benefit (*r* = 0.051, *p* = 0.89), and “average” low-frequency pitch discrimination vs. OPT bimodal benefit (*r* = -0.182, *p* = 0.59).

All pitch discrimination correlation results are summarized in Table 6.

Table 6. Summary of all pitch discrimination correlation results. "ns" indicates a p-value that was greater than 0.05, and was not statistically significant.

Analysis	Task	Correlation	*r*	*p*
Pitch Discrimination and Bimodal Benefit (CI + 125, CI + 250, CI + 500, CI + 750, CI + WB)	Timbre	123-Hz threshold vs. bimodal benefit for CI + 125 Hz	-0.216	ns
		247-Hz threshold vs. bimodal benefit for CI + 250 Hz	0.270	ns
		494-Hz threshold vs. bimodal benefit for CI + 500 Hz	0.217	ns
		740-Hz threshold vs. bimodal benefit for CI + 750 Hz	0.179	ns
		"Average" LF pitch discrimination vs. bimodal benefit for CI + WB	0.067	ns
	Sound Quality	123-Hz threshold vs. bimodal benefit for CI + 125 Hz	-0.168	ns
		247-Hz threshold vs. bimodal benefit for CI + 250 Hz	-0.033	ns
		494-Hz threshold vs. bimodal benefit for CI + 500 Hz	0.355	ns
		740-Hz threshold vs. bimodal benefit for CI + 750 Hz	0.309	ns
		"Average" LF pitch discrimination vs. bimodal benefit for CI + WB	-0.056	ns
Pitch Discrimination and Bimodal Benefit (CI + OPT)	Timbre	123-Hz threshold vs. OPT bimodal benefit	-0.327	ns
		247-Hz threshold vs. OPT bimodal benefit	-0.113	ns
		494-Hz threshold vs. OPT bimodal benefit	0.031	ns
		740-Hz threshold vs. OPT bimodal benefit	0.006	ns
		"Average" LF pitch discrimination vs. OPT bimodal benefit	0.080	ns
	Sound Quality	123-Hz threshold vs. OPT bimodal benefit	-0.395	ns
		247-Hz threshold vs. OPT bimodal benefit	-0.386	ns
		494-Hz threshold vs. OPT bimodal benefit	0.065	ns
		740-Hz threshold vs. OPT bimodal benefit	0.051	ns
		"Average" LF pitch discrimination vs. OPT bimodal benefit	-0.182	ns

4.2.2 Frequency following response

First, to determine whether recorded F0 amplitudes were reflective of true neural activity and not merely noise floor artifact, we utilized methods outlined by Russo, Nicol, Musacchia, & Kraus (2004). In accordance with Russo et al. (2004), the noise floor was estimated at the stimulus F0 by calculating the FFT of the pre-stimulus interval (-20-0 ms). If the quotient was greater than or equal to one, the response was considered present. Using this criterion, all NH listeners exhibited responses at the stimulus F0 above the noise floor for both the /da/ and music stimuli. All bimodal listeners exhibited responses above the noise floor for the /da/ stimulus. For the music stimuli, there were 2 bimodal participants that exhibited responses below the noise floor for B2, 2 for B3, 1 for B4, and 1 for F#4. These participants were removed from analysis as they did not meet criterion.

4.2.2.1 Frequency following response – speech stimulus

For the /da/ stimulus, spectral analysis was conducted using an FFT applied over the epoch from 60-180 ms. This time window captures the steady state vowel portion of the stimulus. Since the FFR envelope is not affected by changes in polarity, the use of alternating stimulus polarities allowed the envelope to be effectively separated from the spectral components (e.g., F1, F2, etc.). Using this approach, our analysis of the /da/ stimulus focused on individual envelope spectra at the stimulus F0 (100 Hz).

Grand average envelope spectra for the bimodal (left) and NH (right) groups are shown in Figure 9. On average, NH listeners demonstrated a larger F0 amplitude compared to the bimodal group, though an independent samples *t*-test revealed that this difference was not statistically significant, $t_{22} = -1.054$, $p = 0.30$.

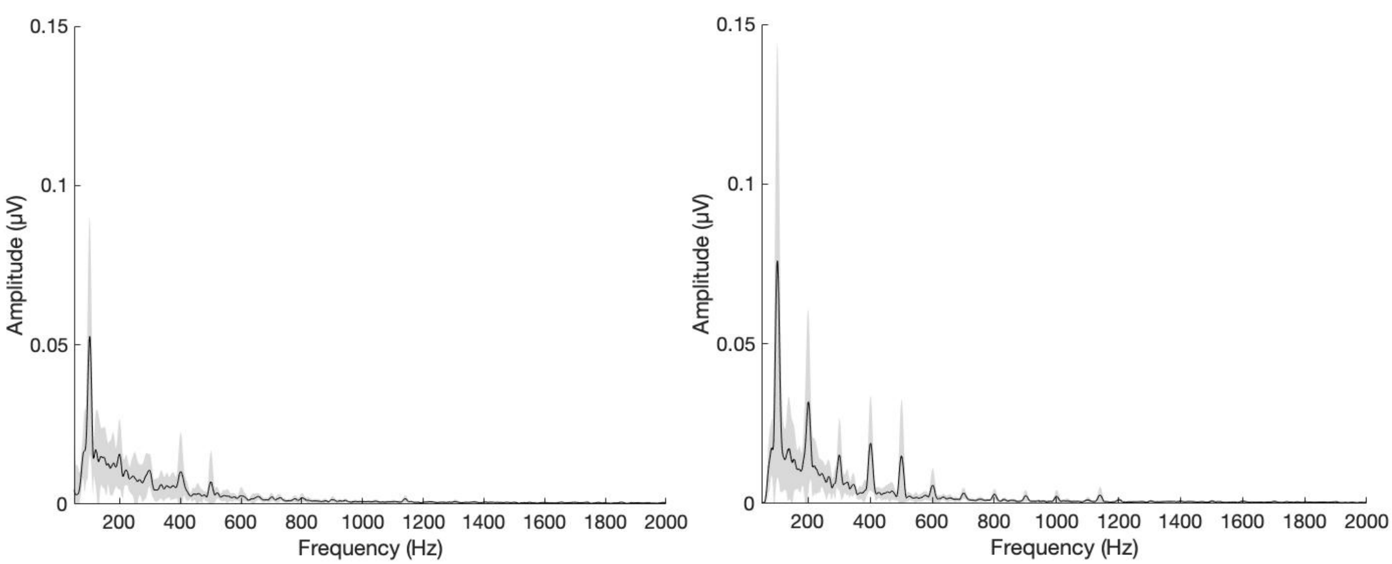


Figure 9. Grand average envelope spectra for the bimodal (left; n = 12) and NH (right; n = 12) groups; shading = SEM. Peak in the FFR at 100 Hz reflect neural phase-locking to the F0 of the /da/ stimulus.

4.2.2.2 Frequency following response – music stimuli

For the B2, B3, B4, and F#5 stimuli, the FFT was applied over the epoch from 20-180 ms. For analysis of the music stimuli, responses to alternating polarities were subtracted, thereby allowing the spectral components to be extracted. Using this approach, our analysis of the music stimuli focused on individual fine structure spectra at the stimulus F0. Of note, 1 bimodal participant (participant 1) did not complete the task for the 740-Hz stimulus due to thresholds in the profound hearing loss range; thus, this participant's data for the 740-Hz stimulus were omitted from analysis. As previously mentioned, six participants did not exhibit a response sufficiently above the noise floor for at least one test frequency, and thus, were also omitted from analysis. The omitted participants include participants 6 and 7 at B2, participants 4 and 11 at B3, participant 11 at B4, and participant 12 at F#5. Grand average fine structure spectra for the bimodal (left) and NH (right) groups for the B2, B3, B4, and F#5 stimuli are shown in Figures 10, 11, 12, and 13, respectively.

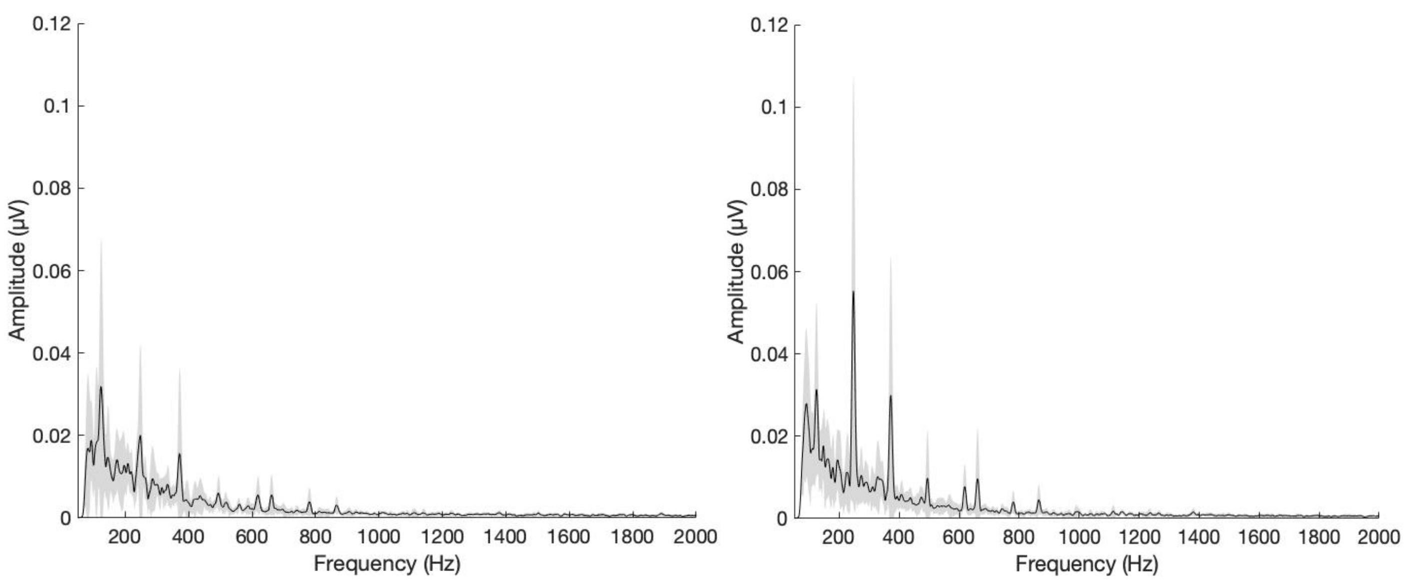


Figure 10. Grand average fine structure spectra for the bimodal (left; n = 10) and NH (right; n = 12) groups; shading = SEM for the B2 stimulus (123 Hz). Peaks in the FFR reflect neural phase-locking to the F0 of the B2 stimulus (123 Hz) and harmonics of 123 Hz.

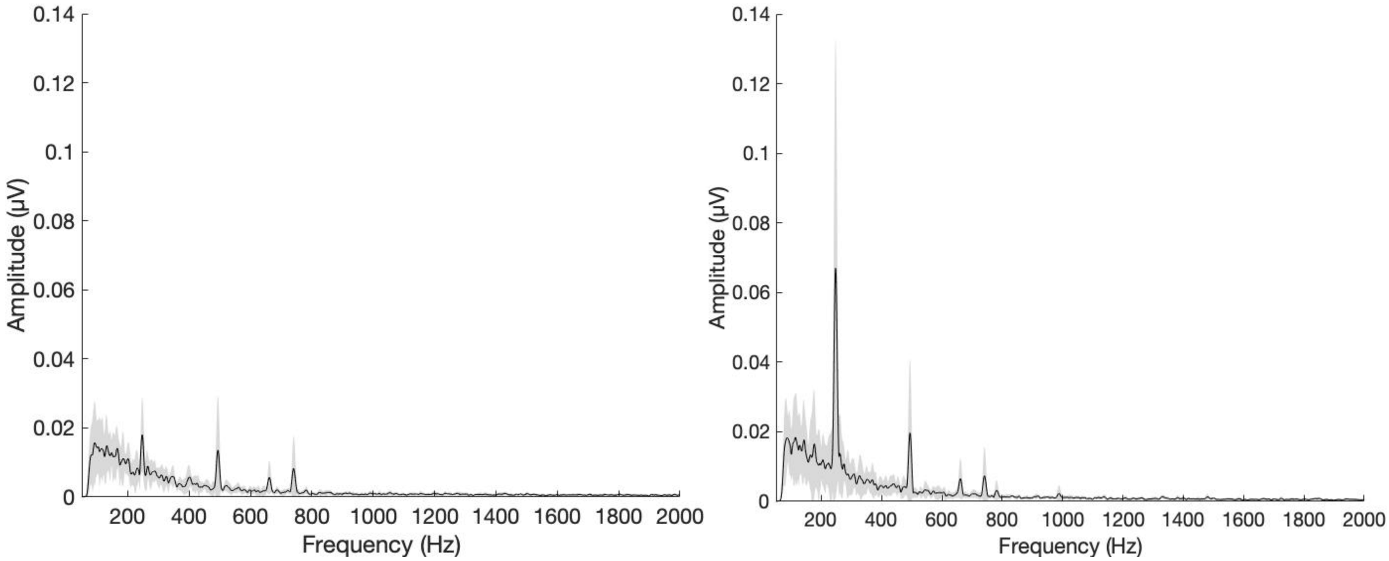


Figure 11. Grand average fine structure spectra for the bimodal (left; n = 10) and NH (right; n = 12); shading = SEM for the B3 stimulus (247 Hz). Peaks in the FFR reflect neural phase-locking to the F0 of the B3 stimulus (247 Hz) and harmonics of 247 Hz.

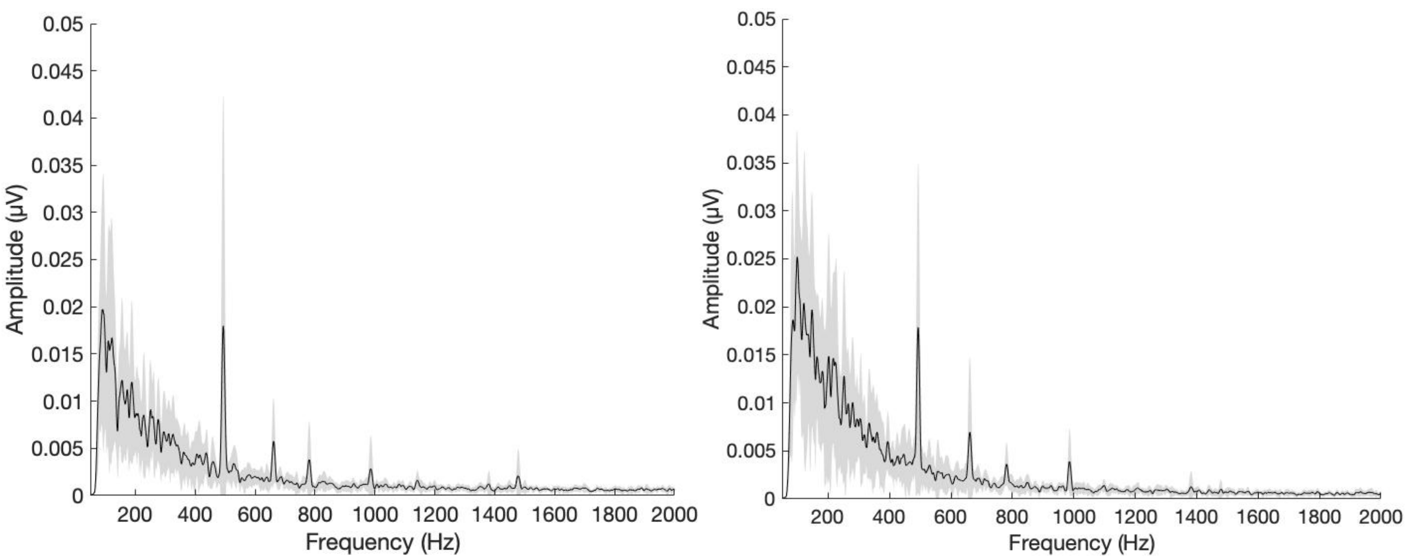


Figure 12. Grand average fine structure spectra for the bimodal (left; n = 11) and NH (right; n = 12); shading = SEM for the B4 stimulus (494 Hz). Peaks in the FFR reflect neural phase-locking to the F0 of the B4 stimulus (494 Hz) and harmonics of 494 Hz.

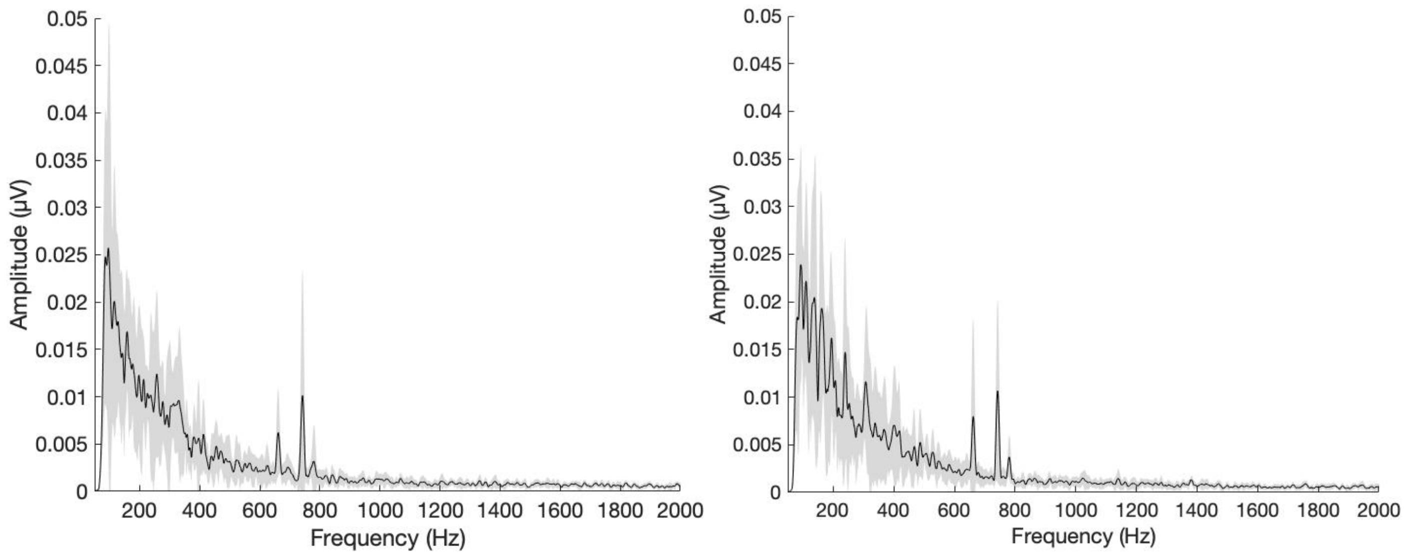


Figure 13. Grand average fine structure spectra for the bimodal (left; n = 10) and NH (right; n = 12) groups; shading = SEM for the F#4 stimulus (740 Hz). Peaks in the FFR reflect neural phase-locking to the F0 of the F#4 stimulus (740 Hz). *Note: Peaks at the harmonics of this stimulus are essentially absent.

Because between 1 and 2 participants failed to exhibit a present response at each frequency tested, statistical analysis involving repeated measures was not completed for the music stimuli; results will instead be discussed descriptively. Bimodal participants demonstrated a general trend toward decreasing amplitude with increasing frequency. Mean F0 amplitude was nearly identical between groups for all music stimuli, except for the B3 (247 Hz) stimulus, where NH listeners exhibited a substantial spike in response magnitude. At B3, F0 amplitude was approximately .05 μV larger for NH listeners compared with bimodal participants. Mean F0 amplitude for all FFR stimuli, including /da/, is shown for the bimodal and NH groups in Figure 14.

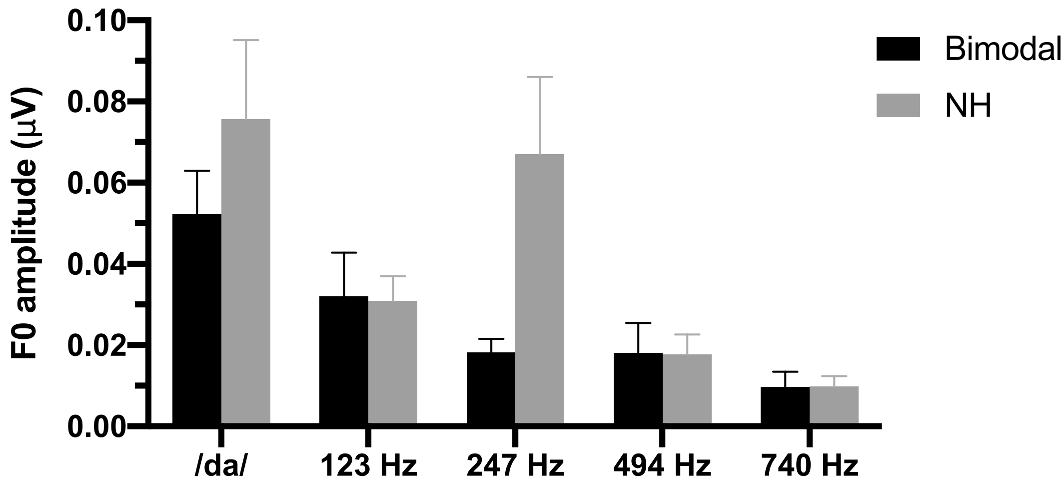


Figure 14. Mean F0 amplitude for each FFR stimulus for the non-CI ear of bimodal (black) and test ear of NH (gray) listeners. Error bars represent +1 SEM. *Note: F0 amplitude for /da/ represents the envelope spectra; F0 amplitude for the music stimuli represents the fine structure spectra.

The substantial group difference in F0 amplitude for the B3 stimulus sparked further analysis. Because the individual harmonic components of a complex tone can contribute significantly to the representation of F0 periodicity, the envelope spectra of our music stimuli were also examined. In a healthy cochlea, low "resolved" harmonics will produce distinct peaks on the basilar membrane, and the neurons at the point of maximum displacement will phase-lock to the frequency of the harmonic (a sinusoid, if the harmonic is resolved). The auditory system interprets the responses across these resolved harmonics, and via a pattern recognition mechanism, F0 can be determined. Higher "unresolved" harmonics produce a complex waveform that repeats at a rate equal to F0. Thus, unresolved harmonics likewise contribute to subcortical F0 representation, though data from NH listeners suggests pitch percepts via unresolved harmonics are typically less salient (Moore, 2007). The stimuli utilized in the present study each had different spectral envelope shapes, differing in the relative energy at F0 and various harmonics. For the B2 (123 Hz) stimulus, harmonics 2 through 5 may contribute to representation of F0 (see Figure 3A for the original stimulus spectrum). For B3 (247 Hz), contribution may come from harmonics 2 and 3 (see Figure 3B). Since the harmonic energy above F0 in both the B4 (494 Hz) and F#5 (740 Hz) stimuli was negligible, FFR envelope analysis focused solely on B2 and B3. Using the methods previously described by Russo et al. (2004), all NH and bimodal participants exhibited envelope responses above the noise floor at the stimulus F0 of both B2 and B3. Mean F0 amplitudes for the B2 and B3 stimuli are shown for the bimodal and NH groups in Figure 15.

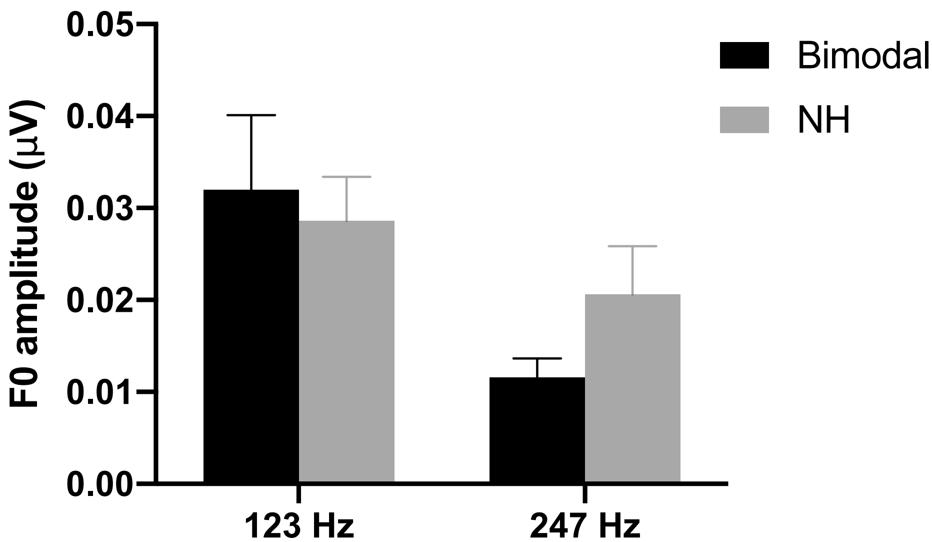


Figure 15. Mean F0 amplitude for the B2 (123 Hz) and B3 (247 Hz) FFR stimuli for the non-CI ear of bimodal (black) and test ear of NH (gray) listeners. Error bars represent +1 SEM. *Note: F0 amplitude represents the envelope spectra.

In order to examine differences across group and stimulus frequency, a mixed-model analysis of variance (ANOVA) with the between-groups factor of group (bimodal, NH) and the repeated-measures factor of frequency (123, 247 Hz) was completed. Analysis revealed no significant effect of group, $F(1, 22) = 0.301$, $p = 0.59$, $\eta_p^2 = 0.01$, but there was a significant effect of frequency, $F(1, 22) = 6.010$, $p < 0.02$, $\eta_p^2 = 0.22$. The interaction effect was not significant, $F(1, 22) = 1.143$, $p < 0.30$, $\eta_p^2 = 0.05$. Thus, the main effect of frequency suggests the contribution of harmonic information may be less for B3 as compared to B2.

With regard to our fine structure FFR analysis, NH listeners demonstrated a substantially higher F0 amplitude in comparison to bimodal listeners for the B3 stimulus. Further, they demonstrated a substantial increase in response amplitude for the B3 stimulus in comparison to B2 (this was also true when compared to B4 and F#5). We did not observe this same trend in our envelope FFR analysis. In fact, F0 amplitude decreased from B2 to B3 among NH listeners. Previous work has demonstrated that fine structure FFR for stimuli between 100 and 500 Hz is most robust in the range of 250-300 Hz (Batra et al., 1986; Hoormann et al., 1992). Other reports examining multiple frequencies between 126-832 Hz found response amplitudes to be largest at 192 Hz (Tichko & Skoe, 2017) or 320 Hz (Hoormann et al., 1992). Thus, an increase in response amplitude at B2 (247 Hz) among NH listeners may simply reflect a frequency-dependent accentuation in amplitude that is congruent with previous literature (Batra et al., 1986; Hoormann et al., 1992; Tichko & Skoe, 2017). This frequency-dependent spike in F0 amplitude was not observed in bimodal listeners, which may be a mere product of phase-locking deficits to TFS secondary to SNHL.

4.2.2.3 Frequency following response and bimodal benefit (CI + 125, CI + 250, CI + 500, CI + 750, CI + WB)

Similar to pitch discrimination, the primary question of interest with respect to FFR testing was whether neural representation of F0 was related to bimodal benefit. Our data were analyzed in the same manner as for pitch discrimination. First, the relationship between F0 amplitude at 123, 247, 494, and 740 Hz and bimodal benefit for timbre and sound quality in the respective corresponding filter conditions was examined. Additionally, F0 amplitude for the 170-ms /da/ stimulus was examined in relation to the CI + WB condition. Thus, the comparisons were as follows: F0 amplitude at 123 Hz vs. bimodal benefit for CI + 125 Hz, F0 amplitude at 247 Hz vs. bimodal benefit for CI + 250 Hz, F0 amplitude at 494 Hz vs. bimodal benefit for CI + 500 Hz, and F0 amplitude at 740 Hz vs. bimodal benefit for CI + 750 Hz. An “average” low-frequency F0 amplitude was also computed as the average of the F0 amplitudes at 123, 247, 494, and 740 Hz, and was used for comparison with the CI + WB condition. F0 amplitude for /da/ was examined in relation to the CI + WB condition for the speech stimulus. Note that F0 amplitude as determined via fine structure analysis was used for all correlations involving the music stimuli.

For timbre, all correlations were consistent with a small to medium effect size and non-significant: F0 amplitude at 123 Hz vs. bimodal benefit for CI + 125 Hz (r = 0.097, p = 0.80), F0 amplitude at 247 Hz vs. bimodal benefit for CI + 250 Hz (r = 0.317, p = 0.41), F0 amplitude at 494 Hz vs. bimodal benefit for CI + 500 Hz (r = 0.095, p = 0.79), F0 amplitude at 740 Hz vs. bimodal benefit for CI + 750 Hz (r = 0.082, p = 0.83), “average” low-frequency F0 amplitude vs. bimodal benefit for CI + WB (r = 0.231, p = 0.50), and F0 amplitude for /da/ vs. bimodal benefit for CI + WB (r = 0.287, p = 0.39).

For sound quality, all correlations were small and non-significant: F0 amplitude at 123 Hz vs. bimodal benefit for CI + 125 Hz (r = -0.243, p = 0.53), F0 amplitude at 247 Hz vs. bimodal benefit for CI + 250 Hz (r = -0.126, p = 0.75), F0 amplitude at 494 Hz vs. bimodal benefit for CI + 500 Hz (r = -0.055, p = 0.88), F0 amplitude at 740 Hz vs. bimodal benefit for CI + 750 Hz (r = 0.069, p = 0.86), “average” low-frequency F0 amplitude vs. bimodal benefit for CI + WB (r = -0.158, p = 0.64), and F0 amplitude for /da/ vs. bimodal benefit for CI + WB (r = -

0.037, $p = 0.92$).

For word recognition, the correlation between F0 amplitude for /da/ vs. bimodal benefit for CI + WB was small and non-significant ($r = 0.128$, $p = 0.71$).

4.2.2.4 Frequency following response and bimodal benefit (CI + OPT)

The second analysis focused solely on the relationship between F0 amplitude and bimodal benefit for the CI + OPT condition. Again, note that F0 amplitude as determined via fine structure analysis was used for all correlations involving the music stimuli, and all analyses were completed using partial correlations while controlling for CI-alone (baseline) performance.

For timbre, all correlations were consistent with a small to medium effect size and non-significant: F0 amplitude at 123 Hz vs. OPT bimodal benefit ($r = 0.327$, $p = 0.39$), F0 amplitude at 247 Hz vs. OPT bimodal benefit ($r = -0.081$, $p = 0.84$), F0 amplitude at 494 Hz vs. OPT bimodal benefit ($r = -0.120$, $p = 0.74$), F0 amplitude at 740 Hz vs. OPT bimodal benefit ($r = -0.281$, $p = 0.46$), "average" low-frequency F0 amplitude vs. OPT bimodal benefit ($r = 0.042$, $p = 0.90$), and F0 amplitude for /da/ vs. OPT bimodal benefit ($r = 0.385$, $p = 0.24$).

For sound quality, the following correlations were small and non-significant: F0 amplitude at 123 Hz vs. OPT bimodal benefit ($r = 0.199$, $p = 0.61$), F0 amplitude at 740 Hz vs. OPT bimodal benefit ($r = -0.064$, $p = 0.87$), "average" low-frequency F0 amplitude vs. OPT bimodal benefit ($r = -0.290$, $p = 0.39$), and F0 amplitude for /da/ vs. OPT bimodal benefit ($r = -0.093$, $p = 0.79$). However, the correlation between F0 amplitude at 247 Hz vs. OPT bimodal benefit was strong and significant ($r = -0.788$, $p < 0.01$) and the correlation between F0 amplitude at 494 Hz vs. OPT bimodal benefit was moderate and trending toward significance ($r = -0.569$, $p = 0.09$). Figure 16A-B demonstrates the partial correlations between OPT bimodal benefit and F0 amplitude at 247 Hz and 494 Hz, respectively. Note that this figure is a plot of the residuals, as all variables have been regressed onto the control variable (CI-alone performance for sound quality) for the purposes of displaying this partial correlation.

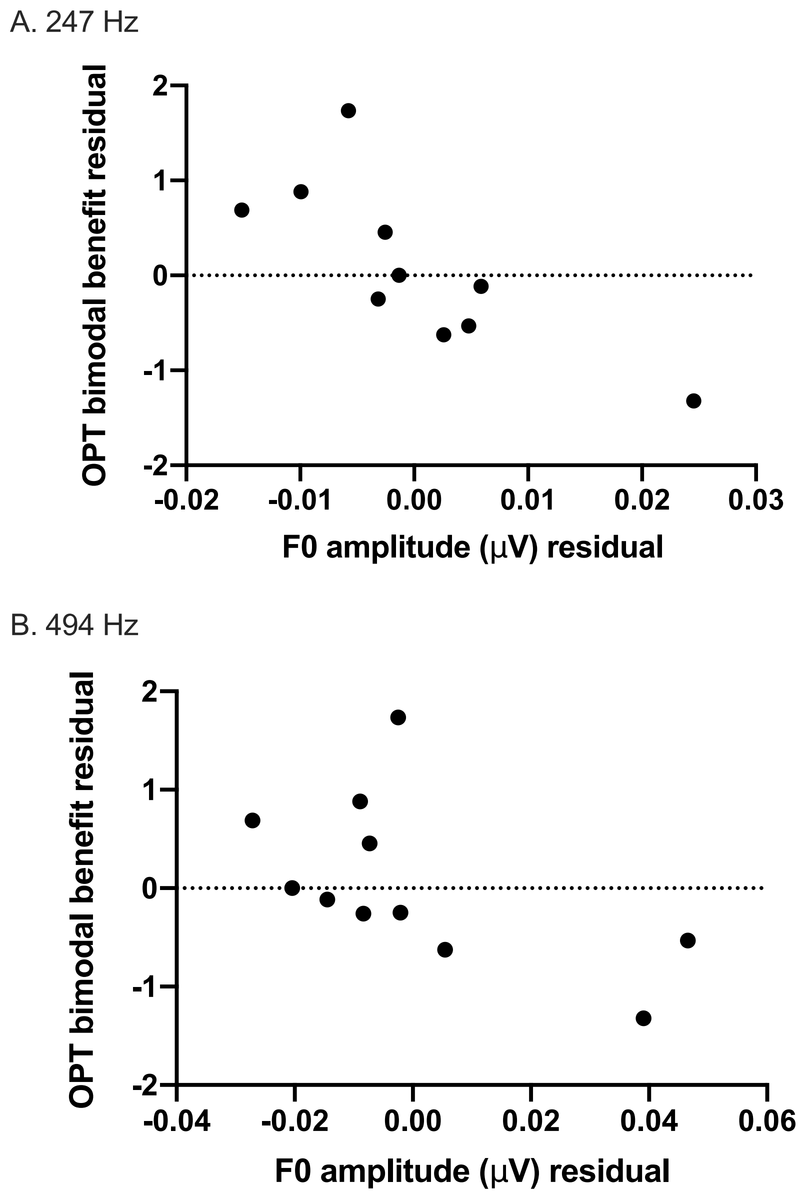


Figure 16A-B. Partial correlations between OPT bimodal benefit and F0 amplitude at 247 Hz (A) and 494 Hz (B).

For word recognition, the correlation between F0 amplitude for /da/ vs. OPT bimodal benefit was small and non-significant ($r = 0.128$, $p = 0.71$).

All FFR correlation results are summarized in Table 7.

Table 7. Summary of all FFR correlation results. "ns" indicates a p-value that was greater than 0.05, and was not statistically significant.

Analysis	Task	Correlation	*r*	*p*
FFR and Bimodal Benefit (CI + 125, CI + 250, CI + 500, CI + 750, CI + WB)	Timbre	F0 amplitude at 123 Hz vs. bimodal benefit for CI + 125 Hz	0.097	ns
		F0 amplitude at 247 Hz vs. bimodal benefit for CI + 250 Hz	0.317	ns
		F0 amplitude at 494 Hz vs. bimodal benefit for CI + 500 Hz	0.095	ns
		F0 amplitude at 740 Hz vs. bimodal benefit for CI + 750 Hz	0.082	ns
		"Average" LF F0 amplitude vs. bimodal benefit for CI + WB	0.231	ns
		F0 amplitude for /da/ vs. bimodal benefit for CI + WB	0.287	ns
	Sound Quality	F0 amplitude at 123 Hz vs. bimodal benefit for CI + 125 Hz	-0.243	ns
		F0 amplitude at 247 Hz vs. bimodal benefit for CI + 250 Hz	-0.126	ns
		F0 amplitude at 494 Hz vs. bimodal benefit for CI + 500 Hz	-0.055	ns
		F0 amplitude at 740 Hz vs. bimodal benefit for CI + 750 Hz	0.069	ns
		"Average" LF F0 amplitude vs. bimodal benefit for CI + WB	-0.158	ns
		F0 amplitude for /da/ vs. bimodal benefit for CI + WB	-0.037	ns
	Word Recognition	F0 amplitude for /da/ vs. bimodal benefit for CI + WB	0.128	ns
FFR and Bimodal Benefit (CI + OPT)	Timbre	F0 amplitude at 123 Hz vs. OPT bimodal benefit	0.327	ns
		F0 amplitude at 247 Hz vs. OPT bimodal benefit	-0.081	ns
		F0 amplitude at 494 Hz vs. OPT bimodal benefit	-0.120	ns
		F0 amplitude at 740 Hz vs. OPT bimodal benefit	-0.281	ns
		"Average" LF F0 amplitude vs. OPT bimodal benefit	0.042	ns
		F0 amplitude for /da/ vs. OPT bimodal benefit	0.385	ns
	Sound Quality	F0 amplitude at 123 Hz vs. OPT bimodal benefit	0.199	ns
		F0 amplitude at 247 Hz vs. OPT bimodal benefit	-0.788	< 0.01
		F0 amplitude at 494 Hz vs. OPT bimodal benefit	-0.569	ns
		F0 amplitude at 740 Hz vs. OPT bimodal benefit	-0.064	ns
		"Average" LF F0 amplitude vs. OPT bimodal benefit	-0.290	ns
		F0 amplitude for /da/ vs. OPT bimodal benefit	-0.093	ns
	Word Recognition	F0 amplitude for /da/ vs. OPT bimodal benefit	0.128	ns

4.2.3 Additional analyses

Further analyses were completed to examine additional relationships between bimodal benefit, pure-tone thresholds, musical background, pitch discrimination, and F0 amplitude. Note that F0 amplitude as determined via fine structure analysis was used for all correlations involving the music stimuli. Unless indicated otherwise, all analyses involving bimodal benefit were completed with each participant's bimodal benefit score for the CI + OPT condition. In all cases, partial correlations were completed while controlling for CI-alone (baseline) performance.

4.2.3.1 Pure-tone thresholds and bimodal benefit

LFPTA was defined as the average of thresholds at 125, 250, and 500 Hz, and ranged from 15 dB HL to 70 dB HL. The partial correlation between LFPTA and OPT bimodal benefit was moderate and significant for timbre perception ($r = -0.601$, $p < 0.05$), but was small and non-significant for sound quality ($r = 0.129$, $p = 0.71$) and word recognition ($r = -0.213$, $p = 0.53$).

Because several participants had useable hearing above 500 Hz, traditional PTA and a HFPTA were also examined. The partial correlation between PTA and OPT bimodal benefit was small and non-significant for timbre perception ($r = -0.202$, $p = 0.55$) and for sound quality ($r = -0.242$, $p = 0.47$). However, the relationship between PTA and OPT bimodal benefit for word recognition was strong and significant ($r = -0.755$, $p < 0.01$). In examining the relationship with HFPTA, note that the CI + WB condition was used instead of CI + OPT. This was to ensure that the listening condition of comparison included the maximum HF bandwidth. The partial correlation between HFPTA and bimodal benefit for CI + WB was small and non-significant for timbre perception ($r = -0.288$, $p = 0.39$) and moderate but non-significant for word recognition ($r = -0.489$, $p = 0.13$). However, the relationship between HFPTA and bimodal benefit for CI + WB was moderate and significant for sound quality ($r = -0.650$, $p < 0.03$).

Thus, low-frequency audiometric thresholds in the non-implanted ear were related to timbre perception, but were not related to sound quality ratings or word recognition. Mid-frequency audiometric thresholds were related to word recognition, but were not related to timbre perception or sound quality ratings. High-frequency audiometric thresholds were related to sound quality ratings, but were not related to timbre perception or word recognition.

4.2.3.2 Pure-tone thresholds and pitch discrimination

Spearman correlations were completed between LFPTA and pitch discrimination thresholds. These were moderate-to-strong and significant for 247 Hz ($\rho = 0.710$, $p < 0.01$) and 494 Hz ($\rho = 0.657$, $p < 0.02$), and were small and non-significant for 123 Hz ($\rho = 0.211$, $p = 0.51$) and 740 Hz ($\rho = 0.062$, $p = 0.86$). The correlations for 247 and 494 Hz are shown in Figure 17A-B.

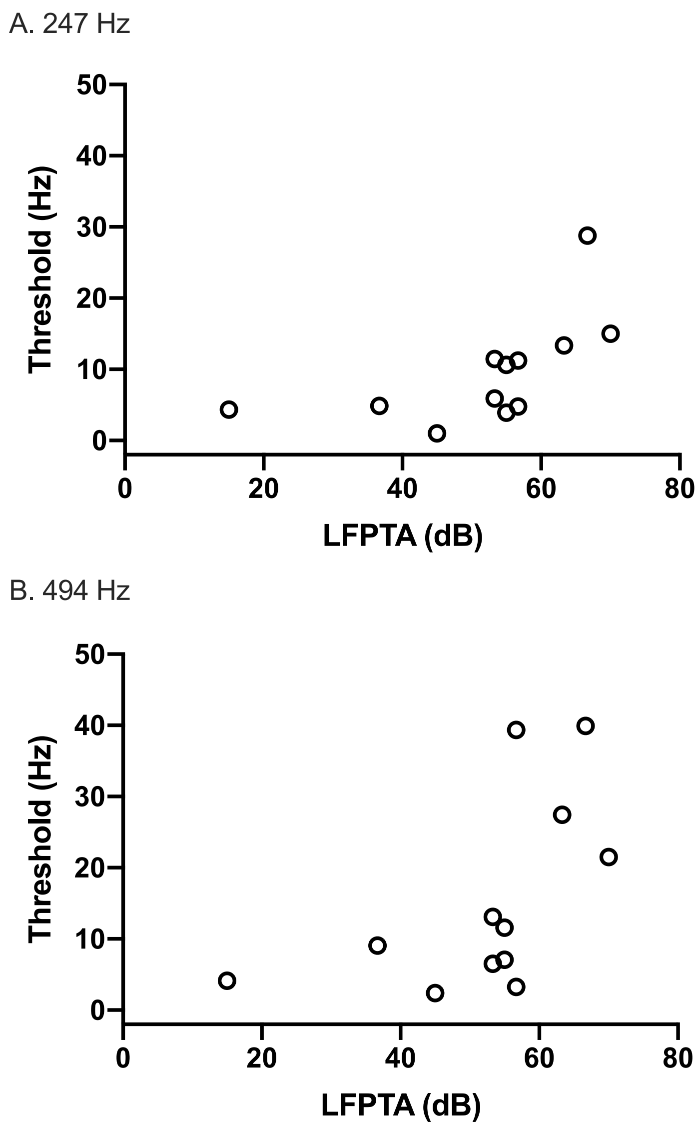


Figure 17A-B. Relationship between individual LFPTA and pitch discrimination thresholds for 247 Hz (A) and 494 Hz (B).

4.2.3.3 Pure-tone thresholds and frequency following response F0 amplitude

Spearman correlations were completed between LFPTA and FFR F0 amplitude, and were moderate and significant for 494 Hz ($\rho = 0.650$, $p < 0.03$) and 740 Hz ($\rho = 0.640$, $p < 0.05$), and were small and non-significant for 123 Hz ($\rho = 0.348$, $p = 0.33$) and 247 Hz ($\rho = 0.311$, $p = 0.38$). The correlations for 494 and 740 Hz are shown in Figure 18A-B.

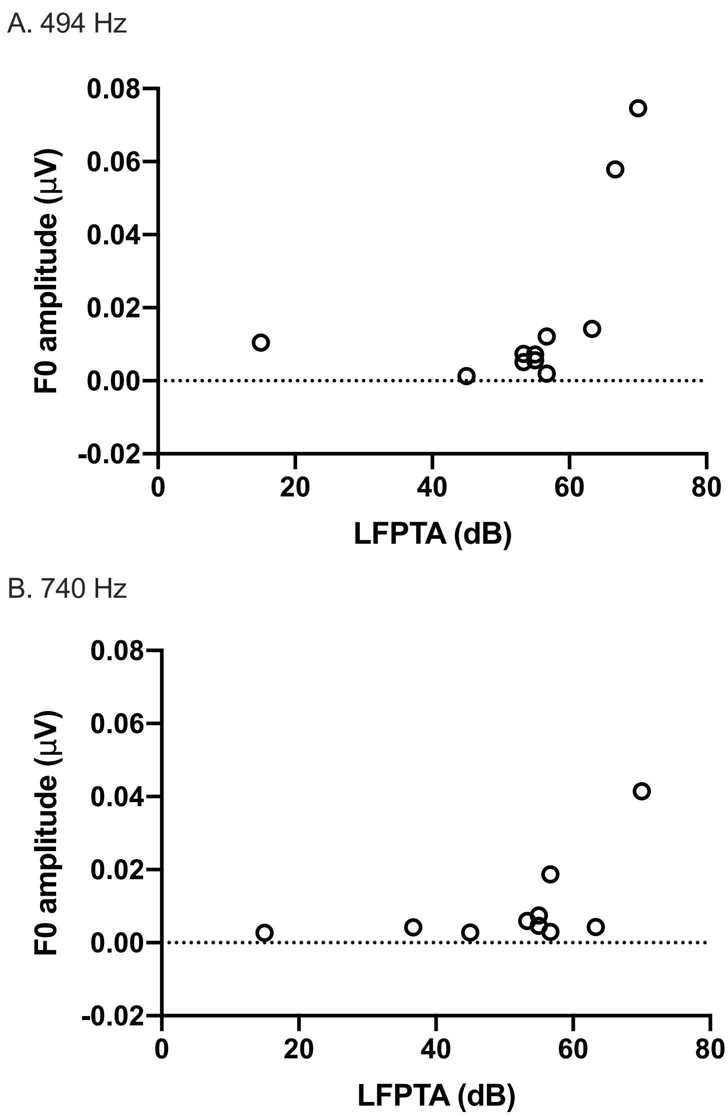


Figure 18A-B. Relationship between individual LFPTA and F0 amplitude at 494 Hz (A) and 740 Hz (B). Note: Participant 11 was excluded in panel A. Participant 12 was excluded in panel B.

4.2.3.4 Pitch discrimination and frequency following response F0 amplitude

Spearman correlations between pitch discrimination and FFR F0 amplitude were completed for each respective stimulus. For NH listeners, the correlations were small and non-significant for 123 Hz (ρ = -0.028, p = 0.93), 247 Hz (ρ = -0.007, p = 0.99), 494 Hz (ρ = -0.427, p = 0.17), and 740 Hz (ρ = -0.105, p = 0.75). For bimodal listeners, the correlations were small and non-significant for 123 ($\rho = -0.018$, $p = 0.96$) and 740 Hz ($\rho = 0.261$, $p = 0.47$), but were moderate-to-strong and significant for 247 Hz ($\rho = 0.636$, $p < 0.05$) and 494 Hz ($\rho = 0.845$, $p < 0.01$).

4.2.3.5 OMSI and bimodal benefit

The relationship between OMSI in the non-implanted ear and OPT bimodal benefit for timbre and sound quality was also examined. The partial correlations between OMSI and OPT bimodal benefit were weak and non-significant for timbre perception ($r = 0.226$, $p = 0.50$) and sound quality ($r = -0.126$, $p = 0.71$). Thus, musical background was not related to bimodal benefit for timbre perception or sound quality ratings.

4.2.3.6 OMSI and overall performance

OMSI scores were also compared to overall performance for both groups. For the NH listeners, the Spearman correlation was moderate and non-significant between OMSI and timbre perception ($\rho = 0.47$, $p = 0.13$) and small and non-significant between OMSI and sound quality ($\rho = -0.10$, $p = 0.77$). For the bimodal group, the CI + OPT condition was utilized for analysis, and the Spearman correlation was small and non-significant between OMSI and timbre perception ($\rho = -0.254$, $p = 0.42$) and was strong and statistically significant between OMSI and sound quality ratings ($\rho = -0.636$, $p < 0.03$). The latter is shown in Figure 19. Thus, musical background was not related to overall timbre perception for either group, but was related to sound quality ratings for bimodal listeners. The fact that this correlation was negative is of particular note – those with more musical experience tended to rate sound quality more poorly, and those with less musical experience tended to rate sound quality more positively.

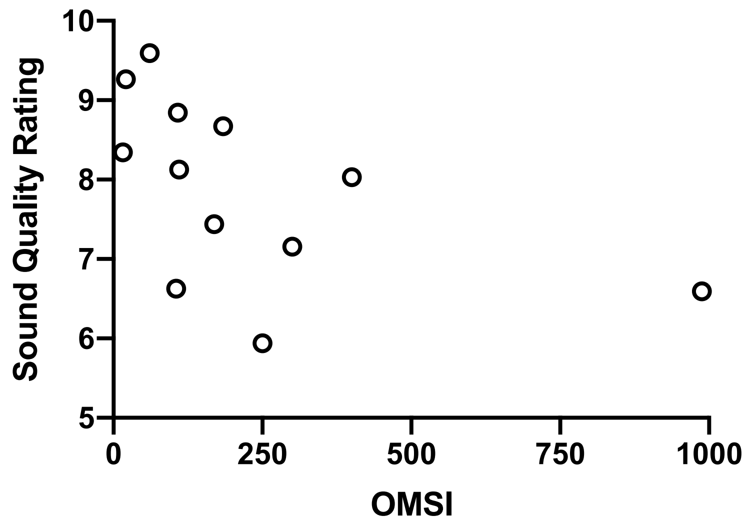


Figure 19. Relationship between individual OMSI and sound quality ratings in bimodal listeners.

All additional correlation results are summarized in Table 8.

Table 8. Summary of all additional correlation results. “ns” indicates a p-value that greater than 0.05, and was not statistically significant.

Analysis	Task	Correlation	*r* or ρ	*p*
Pure-Tone Thresholds and Bimodal Benefit	Timbre	LFPTA vs. OPT bimodal benefit	-0.601	< 0.05
	Sound Quality	LFPTA vs. OPT bimodal benefit	0.129	ns
	Word Recognition	LFPTA vs. OPT bimodal benefit	-0.213	ns
	Timbre	PTA vs. OPT bimodal benefit	-0.202	ns
	Sound Quality	PTA vs. OPT bimodal benefit	-0.242	ns
	Word Recognition	PTA vs. OPT bimodal benefit	-0.755	< 0.01
	Timbre	HFPTA vs. bimodal benefit for CI + WB	-0.288	ns
	Sound Quality	HFPTA vs. bimodal benefit for CI + WB	-0.650	< 0.03
	Word Recognition	HFPTA vs. bimodal benefit for CI + WB	-0.489	ns
Pure-Tone Thresholds and Pitch Discrimination		LFPTA vs. 123-Hz threshold	0.211	ns
		LFPTA vs. 247-Hz threshold	0.710	< 0.01
		LFPTA vs. 494-Hz threshold	0.657	< 0.02
		LFPTA vs. 740-Hz threshold	0.062	ns
Pure-Tone Thresholds and FFR F0 Amplitude		LFPTA vs. FFR F0 amplitude at 123-Hz threshold	0.348	ns
		LFPTA vs. FFR F0 amplitude at 247-Hz threshold	0.311	ns
		LFPTA vs. FFR F0 amplitude at 494-Hz threshold	0.650	< 0.03
		LFPTA vs. FFR F0 amplitude at 740-Hz threshold	0.640	< 0.05
Pitch discrimination and FFR F0 amplitude		Pitch discrimination vs. FFR F0 amplitude at 123-Hz threshold	-0.018	ns
		Pitch discrimination vs. FFR F0 amplitude at 247-Hz threshold	0.636	< 0.05
		Pitch discrimination vs. FFR F0 amplitude at 494-Hz threshold	0.845	< 0.01
		Pitch discrimination vs. FFR F0 amplitude at 740-Hz threshold	0.261	ns
OMSI and Bimodal Benefit	Timbre	OMSI vs. OPT bimodal benefit	0.226	ns
	Sound Quality	OMSI vs. OPT bimodal benefit	-0.126	ns
OMSI and Overall Performance	Timbre	OMSI vs. Overall performance for CI + OPT	-0.254	ns
	Sound Quality	OMSI vs. Overall performance for CI + OPT	-0.636	< 0.03

Chapter 5

DISCUSSION

There were two primary aims of this study: (1) to determine the minimum and optimum acoustic bandwidth necessary to obtain bimodal benefit for music perception, music appreciation, and speech perception, (2) to determine whether optimal acoustic bandwidth is correlated with resolution of acoustic, low-frequency stimuli via behavioral (pitch discrimination) and objective (FFR) measures.

5.1 Experiment I

5.1.1 Timbre perception

For NH listeners, no differences were noted between monaural and binaural listening. For bimodal listeners, mean timbre perception performance generally increased with increasing acoustic information; however, performance remained poorer than the NH group for all conditions tested.

The timbre perception task utilized in the present study has previously been validated in NH and CI listeners, and our results were comparable to prior studies. Here, NH listeners scored 87% and 89% in the monaural and binaural conditions, respectively, as compared to 88% reported previously by Kang et al. (2009). For CI-alone testing, listeners scored 45.5%, as compared to 45.0% and 43.2% reported by Kang et al. (2009) and Drennan et al. (2015), respectively. Importantly, scores for CI-alone listening were well above chance performance (12.5%) – a result likely due to the salience of temporal envelope cues via CI processing. Indeed, timbre perception via CI-mediated listening tends to be comparatively better than other measures of music perception (i.e., melody perception) (Jung et al., 2012; Kang et al., 2009), which has largely been attributed to the contribution of temporal envelope cues associated with timbre.

With the addition of acoustic hearing, listeners have greater access to fundamental frequency (F0) and low-frequency temporal fine structure (TFS) (Limb & Roy, 2014; Moore et al., 2006); thus, it was expected that timbre perception performance would improve via bimodal listening. Indeed, an overall trend toward improved performance with a systematic increase in acoustic bandwidth was demonstrated, though the improvement failed to reach statistical significance. These results are consistent with previous work utilizing the same measure of timbre perception. Yüksel et al. (2019) demonstrated about a 14-percentage point improvement among children with low-frequency contralateral acoustic hearing when compared to previous reports in children with CI-only listening (48% vs. 34%, from Jung et al., 2012). Other measures have been used with bimodal listeners in an effort to examine the contribution of specific timbral properties. Kong et al. (2012) hypothesized that with the addition of acoustic hearing, bimodal listeners would incorporate greater use of spectral cues. Although their hypothesis was not statistically supported, results were trending toward increased incorporation of the spectral envelope cue. Our results were similar, albeit with a different test measure.

Despite the trend toward improved performance with greater acoustic information, the lack of statistically significant benefit with increasing bandwidth was somewhat surprising. It was hypothesized that with more acoustic information, listeners would benefit from greater access to important timbral cues not otherwise available via the CI (e.g., TFS). The fact that our hypothesis was not supported suggests that individual perceptual weighting of timbral cues (i.e., relative sensitivity to TFS versus temporal envelope) may be an important consideration – not merely *access* to those cues (Looi et al., 2008). Since both TFS and temporal envelope cues contribute to timbre perception, it is possible that CI users learn to weight temporal envelope cues more heavily due to their salience via CI processing – even in the presence of TFS via the non-CI ear. To that end, Kong et al. (2012) provided evidence that bimodal listeners demonstrate strong reliance on the temporal envelope, even in the presence of spectral cues (via the addition of acoustic hearing). Future research is warranted to further examine the relative sensitivity to temporal envelope cues versus TFS in CI users with residual acoustic hearing and whether differential weighting of these cues may be contributing to the current results.

There is also a methodological consideration worthy of discussion as it relates to our bimodal results. The timbre stimuli are comprised of a 5-note sequence between C4 (262 Hz) and C5 (523 Hz). Given the frequency range of the stimuli, the CI + 125 and CI + 250 Hz conditions would have included minimal acoustic information as both the F0s and harmonics of each passage were largely limited; therefore, these conditions may have been perceptually indistinguishable from one another, and from the CI-alone condition. Perhaps then it is not surprising that there was no marked improvement between CI-alone and CI + 125 or CI + 250 Hz. For the CI + 500 Hz condition, 4 of the 5 stimulus notes are encompassed within the 500 Hz low-pass filter. Thus, it *is* somewhat surprising that listeners did not experience greater bimodal benefit in the CI + 500 Hz condition; however, significant benefit likewise was not achieved in the wider bandwidth conditions, for which all 5 stimulus notes were encompassed (e.g., CI + 750, CI + WB). To that end, significant timbre perception benefit does not appear to result from mere access to this acoustic information. It is worth mentioning that a notable trend toward improved performance with increasing bandwidth beyond CI + 500 Hz was observed, and thus, it is possible that listeners received some benefit from the increased representation of harmonics, particularly in the CI + 750 Hz and CI + WB conditions.

Despite the lack of significant improvement with increasing acoustic bandwidth at the group level, improved performance did reach significance for the CI + OPT condition. In other words, when considering each individual's best-performing condition, significant benefit over the CI-alone condition was observed. Taken together, these data indicate that a "one size fits all" bandwidth approach may not be appropriate for timbre perception; rather, individualized acoustic bandwidth may yield optimal timbre perception benefit. Importantly, we predicted that the presence of DRs may influence this result, such that optimal benefit would be achieved with a reduced bandwidth for individuals with DRs. Our data (albeit a limited sample) do not support this premise, as 4 of the 5 participants with DRs performed optimally with WB amplification.

5.1.2 Sound quality

Sound quality was measured using two stimulus types – experimenter-chosen and participant-chosen. The use of two stimulus types was implemented in an effort to control for any inherent bias in ratings due to stimulus familiarity or stimulus dislike. Results indicate that both NH and bimodal listeners rated their own song selections significantly higher than the experimenter-chosen selections, thereby demonstrating a response bias toward better sound quality ratings when songs were familiar and liked. This is consistent with literature in the music psychology domain, which has demonstrated that music sound quality ratings can be influenced by demographics, personality traits, musical training, and familiarity with certain musical styles (Ginocchio, 2009; LeBlanc et al., 1999, 1991; Nater et al., 2006; Robinson et al., 1996). This is an important consideration for future investigations as both NH and bimodal participants were unable to disentangle the ratings of sound quality from song familiarity and enjoyment, despite explicit instructions to the contrary. Interestingly, our results are in contrast to Roy et al. (2012)

who did *not* find a difference in sound quality ratings for familiar vs. unfamiliar songs. Listeners in their study were CI-only participants and did not have residual hearing. It is possible that residual acoustic hearing is an important factor which warrants further study.

Similar to the results for timbre perception, no differences were noted between monaural and binaural listening in the NH group. For bimodal listeners, a systematic improvement in sound quality ratings was observed with increasing acoustic bandwidth; however, the improvement only reached significance for the CI + WB condition. Importantly, while there was also a significant difference between CI-alone and CI + OPT ratings, the difference between the CI + OPT and CI + WB condition was not statistically significant. Thus, CI + WB was minimally required for a significant improvement in sound quality and also appears to be sufficient for optimal sound quality ratings. Consistent with the results for timbre perception, the presence of DRs does not appear to inform these findings, as 4 of the 5 participants with DRs performed optimally in the WB condition.

5.1.3 Speech recognition

In an effort to replicate a portion of Sheffield & Gifford (2014)'s study, speech recognition in quiet was examined using CNC words. Additionally, this measure allowed across-stimulus analysis in the present study and provided a within-subject comparison of the cues contributing to bimodal benefit for speech recognition and music perception. In the present study, CI + 250 Hz was minimally required for significant bimodal benefit, which was largely in agreement with Sheffield & Gifford (2014) who found that the minimum acoustic bandwidth required for significant benefit was CI + 250 Hz when using the same stimuli. The CNC words used for testing are spoken by a male talker with a mean F0 around 123 Hz and standard deviation of 17 Hz. Thus, the F0 of the talker is encompassed within a < 250 Hz low-pass filter, though may have not been fully encompassed within the passband of the < 125 Hz low-pass filter. Traunmüller and Eriksson (1995) summarize several original reports on average voice F0 and the average F0 variation standard deviation. For a male talker with F0 around 125 Hz, one standard deviation can be as much as 30-40 Hz; thus, it is likely that the < 125 Hz condition was too restrictive, as it would not have encompassed the natural F0 perturbations present in everyday speech (i.e., dynamic pitch). While mean word recognition in our study improved steadily with increasing bandwidth, the improvement failed to reach statistical significance. This is in partial contrast with Sheffield & Gifford (2014), who found CI + WB performance to be significantly better than performance in the CI + 125, CI + 250, and CI + 500 Hz conditions. There are a couple possible reasons for this discrepancy. First, performance in the CI + 125, CI + 250, and CI + 500 Hz conditions was lower in the Sheffield & Gifford (2014) study, although CI + WB performance was similar across studies. Thus, the absolute magnitude of improvement between these three filter conditions and CI + WB was greater in Sheffield & Gifford (2014). Secondly, while the hearing configuration of the participants in both studies was similar, the participants in Sheffield & Gifford (2014) had poorer higher frequency thresholds (2000 Hz and above). It is possible that differences in hearing loss severity contributed to the slight discrepancy in findings. Importantly however, overall magnitude of improvement between the CI-alone and CI + WB conditions in the present study and Sheffield & Gifford (2014) was equivalent at approximately 22-percentage points for both.

Lastly, similar to our results for sound quality, there was no significant difference in performance between CI + OPT and any of the filter conditions. Thus, despite trends toward further improvement with increasing acoustic bandwidth and CI + OPT, our data suggest that CI

+ 250 Hz is both minimally required and sufficient for optimal speech recognition performance with a male talker in quiet. With respect to DRs, only 2 of the 5 participants with DRs performed optimally with the WB condition. For the 3 who performed best with a reduced bandwidth, the amplification cutoff frequency was always lower than the DR cutoff frequency (Participant 4: DR at 1500 Hz, optimal condition was CI + 750 Hz; Participant 8: DR at 750 Hz, optimal condition was CI + 500 Hz; Participant 10: DR at 1500 Hz, optimal condition was CI + 750 Hz). It is possible that DRs have a greater impact on speech stimuli; however, future study with a larger sample size is warranted.

5.1.4 Clinical implications

The benefit of amplification for individuals with aidable residual hearing in the non-CI ear can be substantial for both speech and music stimuli; however, the acoustic bandwidth that is both minimally and optimally beneficial appears dependent upon stimulus type. On average, significant benefit for speech recognition was obtained with a narrow, low-frequency acoustic bandwidth of < 250 Hz, whereas significant benefit for sound quality was achieved with WB amplification. Still, it is important to note that despite failing to reach statistical significance, average speech recognition also continued to improve out to the WB condition. Thus, our findings do not suggest that amplification should be limited to 250 Hz and below; rather, this simply illustrates that relatively little acoustic information may be required for certain stimuli in comparison to others.

On all test measures, the CI + OPT condition always resulted in significant improvement over the CI-alone condition. In fact, for timbre perception, CI + OPT was the *only* condition to produce significant bimodal benefit, thereby suggesting that a more personalized fitting approach may be necessary for some aspects of music perception.

To that point, the question becomes whether or not a “CI + OPT” setting is clinically practical. In the present study, the CI + OPT setting remained the same across all three test measures for only 6 participants (50% of the sample). Thus, for half of the subjects, different CI + OPT settings would be required depending upon the stimulus – a finding that is not realistically feasible. When considering the music stimuli alone, participants’ CI + OPT conditions remained the same for 10 participants (83% of the sample), suggesting it may be beneficial to utilize a CI + OPT setting that is specific to speech and one that is specific to music. Additionally, with respect to the influence of DRs, it is possible that their presence has a greater impact for speech than for music; however, this is based on a limited sample and further research is needed. Future research is also warranted to examine optimal acoustic bandwidth for other stimuli (e.g., speech recognition in noise, speech recognition using female talkers); however, a shift toward a more individualized fitting approach for the hearing aid ear appears to be an important clinical direction.

5.1.5 Limitations

As previously mentioned, the timbre identification task utilized poses a potential methodological issue, in that it is predicated upon participants having audibility minimally through 523 Hz (C4). While all of our participants have useable thresholds in that range, higher harmonic information may not have been audible. Future tasks which intend to isolate timbre *only*, in the absence of a potential audibility confound, may aim to utilize stimuli in a lower register or stimuli with a similar starting frequency but that varies over a more restricted spectral range.

Further, there is an important limitation with respect to the constructed CI + OPT condition for the music stimuli. While there may have been increases in performance compared to CI + WB, we cannot determine whether the increases observed were "clinically significant." For the speech stimuli, the 95% confidence interval table for a 50-item test of word recognition (Thornton & Raffin, 1978) was used to determine whether the difference between CI + WB and CI + OPT performance was significant; however, this provides us with an estimate of test-retest variability and not "clinical significance." Furthermore, no such binomial distribution statistic determining 95% confidence intervals even exists for our music stimuli. Thus, it is possible that the magnitude of improvement observed re: CI + WB (which in some cases was marginal) may have merely been due to test-retest variability and/or attentional factors. Further investigation is needed to parse out these effects.

5.2 Experiment II

5.2.1 Pitch discrimination

Pitch discrimination was measured at 123, 247, 494, and 740 Hz. NH listeners demonstrated superior pitch discrimination at all frequencies tested, and performance tended to be superior for the lowest frequency compared with the highest frequency tested. These findings are consistent with expectation (Bernstein & Oxenham, 2006; Moore, Glasberg, & Hopkins, 2006).

The primary point of interest was whether pitch discrimination ability related to bimodal benefit. Our results did not indicate a relationship between pitch discrimination at 123, 247, 494, and 740 Hz and bimodal benefit; in other words, better pitch discrimination did not yield better timbre perception or sound quality ratings. One interpretation of this finding is that the discrete frequencies used for pitch discrimination testing were simply not relevant to the music stimuli utilized in this study. While the 4 frequencies utilized are meaningful as it relates to the low-pass filter cutoffs, they account for only a small portion of the frequencies encompassed by the actual test stimuli. Alternatively, it is possible that spectral resolution over a wider frequency range would hold greater relevance for use as a predictor of bimodal benefit. Future studies may consider using spectral modulation detection (SMD) or spectral ripple discrimination tasks, as a means of measuring spectral resolution over a broader spectrum. To that point, 6 participants from our sample had previously completed SMD testing in our lab. Preliminary correlation analyses between SMD scores and timbre, sound quality, and word recognition scores were small and non-significant for these 6 participants; however, further assessment with a larger sample size is required before any conclusions can be made.

5.2.2 Frequency following response

FFR was measured for a /da/ stimulus and four musical stimuli with F0s corresponding to 123, 247, 494, and 740 Hz. No group differences in F0 amplitude were observed for /da/. Our fine structure analysis of the music stimuli showed a general trend toward decreasing amplitude with increasing frequency in the bimodal group. In contrast, NH listeners demonstrated a large spike in amplitude for the B3 (247 Hz) stimulus. Further, the magnitude of response for the B3 stimulus was substantially higher for the NH group compared with bimodal listeners. Additional envelope analysis was completed with the B2 and B3 stimuli. A significant decrease in F0 amplitude was observed across frequency and the difference between groups for the B3 stimulus was not significant. Previous work has shown that fine structure FFR may be most robust in the range encompassing the B3 (247 Hz) stimulus (Batra et al., 1986; Hoormann et al., 1992; Tichko

& Skoe, 2017), which may explain the spike in amplitude observed in our fine structure analysis. This same trend was not observed among bimodal listeners, which may be due to TFS phase-locking deficits secondary to SNHL. Due to a paucity of literature on this topic in listeners with hearing loss, future research is warranted to examine this effect further.

With respect to the relationship between F0 amplitude and bimodal benefit, a strong and significant correlation was observed between F0 amplitude for 247 Hz and OPT bimodal benefit for sound quality. The correlation between F0 amplitude for 494 Hz and OPT bimodal benefit for sound quality was moderate and trending toward significance. Interestingly, in both cases, the relationships were negative, such that poorer neural representation of F0 yielded better sound quality. This finding must be interpreted with caution due to the reduced sample size (n = 10) after omitting FFR recordings that did not meet response criterion; however, the counterintuitive nature of this inverse relationship was surprising and deserves attention. One possible explanation is that those with better subcortical representation of the acoustic stimulus perceive a larger discrepancy between an acoustic input to one ear and an electric input to the other. Under this hypothesis, these participants may experience greater interference between hearing aid and CI, which could contribute to reduced bimodal benefit. Future research examining this intriguing relationship with a larger sample size is warranted.

All other correlations, including those with the /da/ stimulus, were small and non-significant. This was particularly surprising for the /da/ stimulus, as our lab had previously found a relationship between F0 amplitude and bimodal benefit for CNC words (Kessler et al., 2020), as well as musical emotion perception (D'Onofrio et al., 2020). Kessler et al. (2020) and D'Onofrio et al. (2020) both used a fixed presentation level for delivery of the FFR stimulus (90 dB SPL), whereas the current study presented at the participant's "loud, but comfortable" level.

Thus, it is possible that the different outcomes are attributed to use of different stimulus levels, and more specifically, potential differences in audibility. Further, in both Kessler et al. (2020) and D'Onofrio et al. (2020), the hearing loss configurations consisted mostly of sloping losses; however, in the present study, there was a mix of sloping losses, flat losses, and reverse cookie-bite configurations. Participants in Kessler et al. (2020) also had better mid-frequency thresholds. It is possible that the greater audiometric heterogeneity and poorer mid-frequency thresholds in the present subject sample contributed to the discrepancy with our previous work.

5.2.3 Additional analyses

Some other relationships are worth noting. Better low-frequency (125, 250, and 500 Hz) audiometric thresholds in the non-implanted ear were correlated with better timbre perception, better pitch discrimination thresholds at 247 and 494 Hz, and greater FFR F0 amplitude at 494 and 740 Hz. Better mid-frequency audiometric thresholds (i.e., 500, 1000, 2000 Hz) were related to better word recognition. Better pitch discrimination thresholds were correlated with greater F0 amplitude for 247 and 494 Hz. Finally, greater musical background was correlated with poorer ratings of musical sound quality. The latter finding is perhaps of greatest intrigue, as it is somewhat counterintuitive. A possible explanation is that those with more musical experience may simply be less tolerant of the poorer music fidelity afforded via CI-mediated listening. In other words, a well-trained ear is likely to be more critical of sound quality, as compared to someone with little-to-no musical background or formal training.

5.2.4 Limitations

It is important to note that an independent samples *t*-test revealed a significant difference in mean age between the NH and bimodal groups ($t_{22} = -3.118$, $p < 0.01$). This presents a potential confound related to Experiment II, as previous literature has demonstrated a reduction in F0 amplitude as measured via FFR with increasing age (Bones & Plack, 2015; Clinard, Tremblay, & Krishnan, 2010; Marmel et al., 2013). Because the bimodal group consisted of more older individuals, any group differences in amplitude may have been driven by age. Importantly however, mean F0 amplitudes were nearly identical between groups at all frequencies tested (with the exception of 247 Hz). The likelihood that age would differentially impact one singular stimulus frequency that lies in between both a lower (123 Hz) and two higher (494, 740 Hz) stimulus frequencies is slim. Additionally, correlation analyses examining F0 amplitude and age were small and non-significant for both groups, thus providing further indication that age was not a contributing factor in our results.

Chapter 6

CONCLUSION

Substantial bimodal benefit for individuals with residual hearing in the non-CI ear can be obtained for both speech and music stimuli. In the present study, we observed a trend toward improved performance for all stimuli with increasing acoustic bandwidth; however, the acoustic bandwidth that is both minimally and optimally beneficial appears dependent upon stimulus type. On average, speech recognition with a male talker in quiet required a smaller acoustic bandwidth (< 250 Hz) for significant benefit, whereas music sound quality required WB amplification. When considering the condition for which individual optimal performance was obtained, significant bimodal benefit was observed for all stimuli tested. In fact, for timbre perception, CI + OPT was the *only* condition to produce significant bimodal benefit, thereby suggesting that a more personalized fitting approach may be necessary for some aspects of music perception. Importantly, we predicted that the presence of DRs may inform these results, such that optimal benefit would be achieved with a reduced bandwidth for individuals with DRs. Our results suggest it is possible DRs have a greater impact for speech than for music stimuli, though future research with a larger sample size is warranted. Finally, further research is also warranted to examine optimal acoustic bandwidth for additional stimulus types; however, a shift toward a more individualized fitting approach for the hearing aid ear appears to be an important clinical consideration.

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