Research Article

Abnormal Binaural Spectral Integration in Cochlear Implant Users

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ABSTRACT

Bimodal stimulation, or stimulation of a cochlear implant (CI) together with a contralateral hearing aid (HA), can improve speech perception in noise. However, this benefit is variable, and some individuals even experience interference with bimodal stimulation. One contributing factor to this variability may be differences in binaural spectral integration (BSI) due to abnormal auditory experience. CI programming introduces interaural pitch mismatches, in which the frequencies allocated to the electrodes (and contralateral HA) differ from the electrically stimulated cochlear frequencies. Previous studies have shown that some, but not all, CI users adapt pitch perception to reduce this mismatch. The purpose of this study was to determine whether broadened BSI may also reduce the perception of mismatch. Interaural pitch mismatches and dichotic pitch fusion ranges were measured in 21 bimodal CI users. Seventeen subjects with wide fusion ranges also conducted a task to pitch match various fused electrode–tone pairs. All subjects showed abnormally wide dichotic fusion frequency ranges of 1–4 octaves. The fusion range size was weakly correlated with the interaural pitch mismatch, suggesting a link between broad binaural pitch fusion and large interaural pitch mismatch. Dichotic pitch averaging was also observed, in which a new binaural pitch resulted from the fusion of the original monaural pitches, even when the pitches differed by as much as 3–4 octaves. These findings suggest that abnormal BSI, indicated by broadened fusion ranges and spectral

averaging between ears, may account for speech perception interference and nonoptimal integration observed with bimodal compared with monaural hearing device use.

Keywords: cochlear implants, hearing aids, bimodal, pitch, fusion

INTRODUCTION

In recent years, much progress has been made in the treatment of sensorineural hearing loss with hearing devices such as hearing aids (HAs) and cochlear implants (CIs). In particular, the new concept of combining electric and acoustic hearing from a CI together with a HA in the same ear (Hybrid “electroacoustic” stimulation) or opposite ear (bimodal stimulation) has led to improved speech perception in noise as compared with a CI alone for many individuals, especially for those with less severe losses (Turner et al. 2004; Kong et al. 2005; Dorman and Gifford 2010). Improved speech perception can also be seen in spatially separated background noises with bilateral HA, bilateral CI, or bimodal CI and HA use compared with a single HA or CI worn monaurally (Ahlstrom et al. 2009; Litovsky et al. 2006a; Dunn et al. 2005). However, there remains significant variability in the benefit of combining hearing devices bilaterally, with some cases of little benefit or worse performance for speech recognition compared with either ear alone in adults (Carter et al. 2001; Ching et al. 2007) and children (Litovsky et al. 2006b).

Differences in hearing status and device programming can contribute to this variability in binaural benefit. Another potential factor, which has been

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relatively unexplored in relation to patient outcomes, are differences across patients in central auditory processing due to experience with hearing loss and hearing devices.

In normal-hearing (NH) listeners, the two ears provide essentially matched spectral information, allowing integration of “multiple looks” to reduce uncertainty about the signal and average out independent noise to the two ears; this is similar to the uncertainty reduction provided by two eyes or multi-sensory inputs (Hillis et al. 2002; Ernst and Banks 2002). This process of fusing and integrating spectral information between ears can be called binaural spectral integration (BSI).

By contrast, hearing-impaired listeners often have interaural pitch discrepancies due to hearing loss or as a result of hearing device programming, which may lead to integration of mismatched spectral information, rather than matched spectral information as in NH listeners. Hearing loss can result in diplacusis, the perception of different pitches between ears for the same frequency tone (Albers and Wilson 1968). Cochlear implant programming also introduces mismatches between frequency-to-electrode allocations and cochlear place of stimulation, and thus between electric and acoustic hearing. This mismatch arises because CI processors are programmed to analyze the range of sound frequencies needed for speech perception, and divide and allocate these frequencies to the electrodes in the CI *independent of the actual cochlear place frequencies actually stimulated electrically*. For a typical CI, the default range of frequencies analyzed can be as wide as 100–8,000 Hz. Due to its anatomical and design limitations, the electrode array is typically implanted to depths ranging from 8 to 21 mm (Lee et al. 2010), corresponding to cochlear place frequencies of no lower than 500–1,500 Hz (Greenwood 1990). This leads to a severe tonotopic mismatch between the sound frequencies analyzed versus those actually stimulated electrically in the cochlea.

Our previous studies have shown that Hybrid CI users who wear HAs in both ears or a second CI in the contralateral ear can adapt pitch perception over months of experience to reduce any perceived pitch mismatch between acoustic and electric inputs arising from this tonotopic mismatch (Reiss et al. 2007, 2011). However, not all patients adapt to reduce this mismatch. Bimodal CI users are more likely to experience no changes in pitch or even a drop in pitch for all electrodes, exacerbating the mismatch (Reiss et al. 2007, 2011, 2012a, b); consistent with this finding, several long-term studies also found electrode pitch to be mismatched to and lower than the frequency-to-electrode allocations (e.g., Blamey et al. 1996; Dorman et al. 2007). For bimodal CI users, it is

possible that instead of or in addition to adapting pitch, the brain adapts BSI to increase fusion of interaurally mismatched inputs to effectively reduce the perception of mismatch. Van den Brink et al. (1976) demonstrated that dichotic fusion ranges in normal-hearing listeners, or the frequency range of acoustic tones (pitches) in one ear that fused with a single tone (pitch) in the other ear, were consistently larger than the amount of pitch mismatch (diplacusis) between ears. He suggested that fusion ranges adjust to prevent the perception of any interaural pitch mismatch due to diplacusis. Hong and Turner (2009) showed a similar association of larger fusion ranges with larger amounts of diplacusis for listeners with unilateral hearing loss. Fusion ranges may also be larger in bimodal CI users with a large spectral mismatch created by CI programming.

In addition, if mismatched inputs are fused between ears, then what is the percept of the fused sound? Studies of multi-input integration in other sensory modalities show that information is often averaged between multiple inputs. In the visual system, incongruent inputs to the two eyes are averaged such that information about the individual cues is lost in the integration process (Hillis et al. 2002; Anstis and Roger 2012); similar effects are seen in auditory-visual integration for spatially incongruent auditory and visual stimuli (Binda et al. 2007). Are similar averaging and loss of information effects also seen with binaural integration?

In the current study, we developed a new technique to measure fusion of dichotic stimuli presented to the two ears, and measure the pitch of this fused percept in bimodal CI users. Here we show that bimodal CI users fuse tones that differ by as much as 3–4 octaves between ears, exhibiting much wider dichotic fusion ranges than the NH listeners in the Van den Brink study. In addition, we show that the fused percepts elicit a new binaural pitch that is an average of the monaural pitches, *even if the original pitches are separated by an octave or more*, suggesting integration of mismatched rather than matched spectral information between ears.

METHODS

Subjects

These studies were conducted according to the guidelines for the protection of human subjects as set forth by the Institutional Review Board (IRB) of Oregon Health and Sciences University (OHSU), and the methods employed were approved by that IRB. Twenty-one adult CI subjects (8 females and 13 males) with residual hearing in the contralateral, non-implanted ear participated in this study. All subjects

had at least 1 year of experience with their CI and were able to use a HA in the contralateral ear.

All subjects used a standard 22-electrode CI array and used the advanced combinational encoder strategy. The subjects' ages, gender, CI ear, duration of CI use, etiology, duration of severe/profound deafness, average contralateral low-frequency hearing loss, and HA use are shown in Table 1. All subjects used the Cochlear Nucleus Freedom except for CI56, who used the Cochlear Nucleus N24. The subject ages ranged from 53 to 82 years, and duration of CI use ranged from 1 to 12 years. Many of the subjects had a long duration of hearing loss, with the latest low-frequency thresholds ranging from 50 to 97 dB HL. Note that the majority of CI users in the study used a contralateral HA together with the CI on a regular basis, but three did not.

Procedures

All stimuli were presented via computer to control both electric and acoustic stimulus presentation. Electric stimuli were delivered to the CI using NIC2 CI research software (Cochlear) via the programming pod interface. Stimulation of each electrode consisted of a pulse train of 25 μ s biphasic pulses presented at 1,200 pps with a total duration of 500 ms. The pulse rate of 1,200 pps/electrode was selected to minimize the effects of any temporal cues on pitch. Most of the subjects used 900 or 1,200 pps in their everyday programs, with the exceptions of CI21 and CI40 who

used 500 pps. Temporal effects may lead to upward shifted pitch measurements with 1,200 pps compared with 500 pps pulse trains; however, such effects are likely to be small, as rate changes are generally indiscriminable above 300 pps for Cochlear Nucleus CI users (e.g., Kong et al. 2009). The electrode ground was set to monopolar stimulation with both the ball and plate electrodes active (MP1+2). The level of the electric stimulation for each electrode was set to a "medium loud and comfortable" current level corresponding to 6 or "most comfortable" on a visual loudness scale from 0 (no sound) to 10 (too loud).

Acoustic stimuli were delivered using an ESI Juli sound card, TDT PA5 digital attenuator and HB7 headphone buffer, and Sennheiser HD-25 headphones. Acoustic tones were presented to the contralateral ear and set to "medium loud and comfortable" levels again using the same loudness scale as for electric levels. Loudness was balanced sequentially across all tone frequencies. Tone frequencies that could not be presented loud enough to be considered a "medium loud and comfortable" level, because of the limited range of residual hearing in the contralateral ear, were excluded. Then, each CI electrode was loudness-balanced sequentially with the acoustic tones to reduce potential loudness effects on electric-to-acoustic pitch comparisons.

Under simultaneous presentation conditions, electric and acoustic stimuli were synchronized using the triggering feature of the L34 research CI processor (Cochlear).

TABLE 1

Demographic information about subject age, gender, CI ear, duration of CI use, etiology of hearing loss, duration of severe/profound hearing loss, average low-frequency threshold shift (averaged over 125–750 Hz frequency range) in the nonimplanted ear, and regularity of HA use

Subject	Age (years)	Gender	CI ear	Duration CI use (years)	Etiology of HL	Duration S/P HL (years)	Average contralateral LF thresh shift (dB HL)	Regular contralateral HA user
CI2	79	F	L	3	Unknown	40+	92	No
CI6	76	M	R	2	Unknown	40+	85	Yes
CI14	69	M	L	1	Noise	40+	72	No
CI18	61	F	L	3	Unknown	35	50	Yes
CI19	60	F	R	5	Scarlet fever, noise, and Menieres	50	70	Yes
CI20	75	M	L	5	Noise	35	65	Yes
CI21	66	F	R	2	Family history and measles	57	82	Yes
CI24	54	M	R	1.5	Noise	9	80	Yes
CI25	53	F	R	2	Family history	10–15	75	Yes
CI28	70	M	R	8	Ototoxic	45	90	Yes
CI29	77	M	L	2	Noise	20	68	Yes
CI30	64	M	R	3	Noise and family history	30	58	No
CI32	82	M	R	7	Noise	20	48	Yes
CI34	65	M	R	1	Unknown	0–5	97	Yes
CI38	79	M	L	1	Noise	23	63	Yes
CI40	73	M	R	6	Noise	15–20	55	Yes
CI49	75	F	L	2	Unknown	10	70	Yes
CI54	78	M	L	4	Noise	40	83	Yes
CI56	61	M	R	12	Usher type 3 and allergies	25	78	Yes
CI63	69	F	L	2	Noise	20	57	Yes
CI71	71	F	R	5	Family history	50	73	Yes

Interaural Pitch Matching

A two-interval, two-alternative forced-choice constant-stimulus procedure was used to obtain pitch matches. One interval contained the reference stimulus, an electric pulse train delivered to a particular electrode in the implant ear, and the other interval contained a comparison acoustic tone delivered to the contralateral, nonimplanted ear. The electric and acoustic stimuli were each 500 ms in duration and separated by a 500-ms interstimulus interval, with interval order randomized. The reference electrode was held constant and the comparison tone frequency varied in $\frac{1}{4}$ octave steps within the residual hearing range, and presented in pseudorandom sequence across trials to reduce context effects (Reiss et al. 2007, 2012a). In each trial, the subject was asked to indicate which interval had the higher pitch.

Pitch matches were computed as the 50 % point on the psychometric function generated from the average of the responses at each acoustic tone frequency. The range of pitch-matched frequencies (or electrodes) were selected as the 25 and 75 % points in the function; whereas these points are arbitrary, such measurements still give an indication of the pitch-matched range that can be compared with the fusion range results. For a pitch match to be considered valid, the subject was required to “bracket” the pitch for that electrode. Specifically, if an electrode's pitch was too high pitched for the subject to rank any audible acoustic tone frequencies as higher in pitch 100 % of the time (because of the limited high-frequency residual hearing), that pitch match was conservatively recorded as “out of range”.

Dichotic Fusion Range Measurement

A five-alternative forced-choice task was used to measure the frequency ranges over which dichotic tones were fused. In each trial, the comparison stimulus was presented *simultaneously* with the reference stimulus for 1,500 ms. The electric pulse train was timed to start with the beginning of the 10-ms acoustic onset ramp and end with the end of the 10-ms offset ramp. Subjects were instructed to first determine whether they heard one or two sounds. If they heard only one and the same sound in both ears, they were instructed to choose “Same.” If the subject could hear sounds in both ears, then the subject was instructed to choose between three main alternatives: “Left ear higher,” “Right ear higher,” or “Same.” Generally, the subject was only able to determine which ear was higher in pitch if the stimuli to the two ears were not fused, and one ear could be identified as having the higher pitch and the other ear as having the lower pitch.

However, in occasional instances, the subject was only aware of the stimulus in one ear (lateralization of

the Stenger effect; Stenger 1907); this occurred even though stimuli were loudness balanced across ears. Two additional buttons provided the options of “Left only” or “Right only” for these instances. Lateralized responses were assigned to the fused category based on the observation (through subjects' informal reports and subsequent direct measurement in the fusion pitch matching task described below) that the lateralized pitch changed with the contralateral tone frequency, even when the stimulus to the lateralized side was held constant. Thus, binaural fusion is indicated by the influence of the stimulus in the ear opposite to the lateralized ear on the pitch heard in the lateralized ear. Note that lateralization was seen in only four of the subjects tested (CI6, CI18, CI56, and CI71), and not necessarily for all electrode–tone pairs.

A “Repeat” button was also provided to allow subjects to listen to the stimuli again if needed. All subjects were provided with a practice training run with feedback to help instruct and confirm appropriate usage of the buttons. A screenshot of the five alternatives is shown in Figure 1.

As in the pitch matching procedure, a reference electrode was held constant while comparison stimuli were varied across trials in pseudorandom sequence. For analysis, two methods were used to analyze the fusion ranges. In the first method, fusion values for each response were assigned as follows: “Left higher”=0, “Same”=0.5, “Right higher”=1, “Left only”=0.5, and “Right only”=0.5. Note that values of 0.5 corresponded to fusion, and lateralized responses were assigned to the fused category. Each point on the fusion-versus-contralateral stimulus function was calculated as the fusion values averaged over all trials for each contralateral reference stimulus. In this method, both “Same” values and inconsistent “Left higher” and “Right higher” responses will yield values in the fusion range. In other words, an inability to reliably distinguish which ear had the higher pitch is interpreted as an indicator of fusion. The fusion range was defined as a continuous frequency (or electrode) range where averaged fusion values fell between 0.25 and 0.75, as shown in example fusion functions of three subjects in Figure 2A. The fusion ranges (shaded regions) varied from very narrow (206 to 319 Hz, i.e., very little fusion) to very wide (274 to over 2,000 Hz and out of the range of measurement).

However, one potential pitfall of this method is that an inability to reliably choose one ear as higher in pitch may not be the same as choosing “Same,” i.e., may not reflect true fusion. For example, two sounds may be heard, but these sounds may have very similar pitch and difficult for the subject to reliably indicate which had the higher pitch. To address this potential pitfall, a second method was developed to quantify fusion based on a high percentage of “Same”

FIG. 1. Touch screen buttons showing the response options for the fusion range measurement task.

responses alone, i.e., without also including inconsistent responses. In this method, fusion values were assigned values as follows: “Left higher”=0, “Same”=1, and “Right higher”=0. Values were averaged over all trials and the fusion range was defined as the range where averaged fusion values were above 0.5. The 0.5 criterion value corresponds exactly to the 0.25 and 0.75 criterion values in Method 1 when the non-“Same” responses are either consistently higher (equal numbers of “Same”=0.5 and “Lower”=0 responses average to 0.25 for the function in Method 1) or consistently lower (equal numbers of “Same”=0.5, and “Higher”=0 responses average to 0.75). As shown in Figure 2B for individual subjects and 4A for the population, the fusion range values obtained using the two methods were identical or similar for larger fusion ranges of 2–5 octaves, but could differ significantly in either direction for smaller fusion ranges. One possible interpretation of the differences in results between methods for smaller fusion ranges is that such subjects have more “normal” binaural integration and are thus more likely to hear distinct sounds that are close in pitch, or pitch-matched but differing slightly in source location or timbre. If this is the case, then the results from Method 2 will correctly reflect the true fusion ranges because it is based on the “Same” responses only and not inconsistent responses arising from two sounds with similar pitch.

Fusion Pitch Matching

Subjects with wide fusion ranges ($N=17$) also conducted a task to pitch match various fused electrode–tone pairs. This procedure was similar to that for interaural pitch matches, except that the reference stimulus was presented simultaneously with a tone in the contralateral ear (“paired dichotic stimulus”). The subject was asked to compare the pitch of this paired dichotic stimulus with a comparison acoustic tone presented to the contralateral ear. Specifically, each trial consisted

of a two-interval, two-alternative forced-choice task that consisted of a 500 msec paired dichotic stimulus in one interval and a 500-ms comparison stimulus in the contralateral ear in the other interval, with a 500-ms interstimulus interval. Subjects were asked to indicate whether the paired dichotic stimulus or the comparison stimulus was higher in pitch. The comparison stimuli were varied in a pseudorandom sequence and the fusion pitch match was calculated as in the pitch matching procedure.

RESULTS

Figure 3 shows example pitch and fusion results for six subjects as a function of electrode. Pitch match results are shown as blue circles to indicate the 50 % points along with vertical lines to indicate the 25–75 % points of the pitch match range. Fusion range results are shown as vertical red lines (solid for Method 1 and dashed/offset to the right for Method 2). A range of pitch match patterns was seen across subjects. The subjects in Figure 3A, D had electrode pitch matches (blue circles) that closely followed the CI processor frequency-to-electrode allocations (gray-shaded regions), and thus had minimal interaural pitch mismatch in everyday listening through the CI processor and contralateral ear. The subject in Figure 3B had a mix of matched and mismatched pitches, with electrode 20 showing minimal mismatch, and electrode 16 showing a large mismatch. The subjects in Figure 3C–F, on the other hand, had larger pitch mismatches often accompanied by “flat” pitch patterns across electrodes, with discrepancies between perceived electrode pitch and the frequency-to-electrode allocation ranging up to 3 octaves.

Many of the subjects shown had fusion ranges of an octave or more, much larger than the fusion ranges seen in normal-hearing listeners. For example, the

FIG. 2. Fusion functions in three CI subjects. Each curve shows a CI electrode's averaged fusion values as a function of the paired contralateral tone frequency. **A** Results obtained using Method 1. Values near 0.5 indicate fusion of the electrode with the tone, whereas values of 0 or 1 indicate the tone could be discriminated as lower or higher in pitch, respectively. *Green-, purple-, and blue-shaded* areas indicate the fusion ranges for the three corresponding color curves for fusion values between 0.25 and 0.75. **B** Results

obtained using Method 2, in which only "Same" responses were counted as fused. Values at or above 0.5 indicate fusion of the electrode with the tone, i.e., at least 50 % of responses were "Same". As in (**A**), the different shaded areas indicate the fusion ranges for the three different subjects as defined by values above 0.5. Note that the fusion range calculations differed only for CI29, who had narrower fusion ranges with Method 2 than Method 1.

subject in Figure 3A had fusion ranges on the order of about 1 octave, while the subject in Figure 3D had fusion ranges of up to nearly 3 octaves. The subjects with the greatest degree of pitch mismatch in Figure 3E, F had the largest fusion ranges, as wide as 4 octaves for electrode 18 in Figure 3E and for electrodes 22 and 18 in Figure 3F.

Generally, the fusion ranges tended to encompass the pitch mismatch between mapped and electrode pitches (difference between gray shaded regions and blue circles). This trend is particularly apparent in Figure 3C–F where the range of mismatch connects the blue circles with the gray regions, even for electrodes that could not be pitch matched within

the audible frequency range, as in Figure 3C (blue $\times$ -symbols). Thus, even if an interaural pitch mismatch is present, the mismatch may not be perceived because the mismatched stimuli are perceptually fused and heard as one sound. The exception is for electrode 16 of CI29 shown in Figure 3B, where the fusion range did not encompass the mismatch; very little and no fusion were observed with methods 1 and 2, respectively. Interestingly, this subject also had the shortest duration of experience with the CI, suggesting that experience may also be a factor in determining fusion patterns.

It should also be noted that while generally the fusion ranges measured with Methods 1 and 2 were

FIG. 3. Example interaural pitch match and fusion range results for six CI subjects, with narrow fusion ranges <1 octave (**A–C**) and broad fusion ranges >2–3 octaves (**D–F**). The fusion ranges (red vertical lines; solid for Method 1 and dotted offset for Method 2) encompass the interaural frequency mismatch between the electrode frequency allocation (gray shaded areas) and the electrode pitch match (blue circles, with vertical blue lines indicating 25–75 % range of pitch match). The horizontal black dashed line indicates the upper limit of the loudness-balanced residual frequency range; accordingly, blue x-symbols on this line indicate that the pitch match is out of range of the residual hearing and red asterisks on this line indicate that the upper limit of the fusion range is not bracketed because of the residual hearing limit. **A** Subject with minimal interaural mismatch

and correspondingly small fusion ranges for three different electrodes. **B** Subject with variable interaural mismatch and small fusion ranges independent of mismatch; note that this subject had a relatively short duration of 14 months of experience with the CI, compared with the other subjects. **C** Subject with several electrodes “out of range” and fusion ranges encompassing the distance between the upper hearing limit and frequency-to-electrode allocation. **D** Subject with minimal interaural mismatch but large fusion ranges. **E** Subject with a “flat” and low pitch match profile across electrodes, and fusion ranges that grow with interaural mismatch. **F** Subject with a “flat” and high pitch match profile across electrodes and fusion ranges that again encompass mismatch range.

similar, there were some differences, especially for subjects with smaller fusion ranges as in Figure 3A, B. One interesting example is shown in Figure 3F where the fusion ranges measured with Method 1 were broad and continuous, but the fusion ranges measured with Method 2 were discontinuous with multiple, disconnected fusion ranges. This suggests the possibility of multiple fusion ranges in some individuals. Alternatively, this may reveal a weakness of Method 2 which discards information about inconsistency of higher versus lower pitch responses as additional indicators of fusion.

Consistent with the observed relationship between fusion ranges and pitch mismatch in individual examples, the summary plot of all of the subject population data in Figure 4B (blue circles) shows a significant correlation of fusion range with interaural pitch mismatch ($p=0.038$, Pearson correlation test); however, this correlation was weak and only observed for fusion ranges measured using Method 1. If the analysis was limited to fusion ranges that could be measured within the residual hearing range, the correlation remained significant (orange plus signs in Figure 4B; $p=0.015$). No significant correlations of fusion range were seen with acoustic

FIG. 4. Population summary of long-term fusion range widths. **A** Comparison of results obtained using the two different methods, where Method 1 counted both “Same” and averaged “Left higher” and “Right higher” responses, and Method 2 only counted “Same” responses. **B** Fusion range widths obtained using Method 1 plotted versus interaural pitch mismatch from 21 CI subjects (open blue circles, two to three electrodes per subject). The correlation between interaural mismatch

and fusion range width was significant ($R=0.266$, $p=0.038$, Pearson correlation test). Even when the analysis was limited to fusion range widths that were not truncated by residual hearing range limits in 14 CI subjects, the correlation remained significant (orange plus symbols, $R=0.481$, $p=0.015$). No significant correlation was observed for fusion range widths measured using Method 2.

threshold shift, duration of CI use, or duration of deafness (although it should be noted that the duration of CI use did not sample many short durations).

Data from one subject tested at multiple time points also suggests that fusion ranges adapt over time to minimize the perception of interaural pitch mismatch. Figure 5 shows fusion ranges measured at 15 and 27 months after implant activation. The fusion range for electrode 22 was initially nearly 2 octaves at 15 months, but narrowed over time to less than 1 octave at 27 months, consistent with the small pitch mismatch. The fusion range for electrode 12 was initially centered on the electrode pitch at 15 months, but shifted upward while the electrode pitch remained unchanged. Thus, a large initial pitch mismatch was eventually minimized perceptually by an upward shift of the fusion range. Three other subjects tested at multiple time points after at least 2 years of CI experience did not show any changes.

Subjects with wide fusion ranges also performed a fusion pitch matching task to measure the pitch of the fused tone. Figure 6 shows examples of fusion pitch matches, i.e., pitch matches between a CI electrode paired with a fused contralateral acoustic tone relative to acoustic-only contralateral tone references. Four subjects are shown, with multiple electrode–tone pair results shown for each subject. Generally, the examples in Figure 6A–C show that the fusion pitch (green circles) is often a weighted average of the electrode pitches (blue circles) and tone frequencies (black crosses). In other words, the fusion pitch of the electrode–tone pair falls some-

where between the original pitches of the two stimuli presented individually.

Note that the relative influences of the electrode pitch and tone frequency on the fusion pitch varied with the pair. In Figure 6A, equal weighting of each was observed for electrode 22 paired with a 250-Hz tone, whereas stronger weighting of the electrode was observed for the same electrode paired with a 420-Hz or electrode 20 paired with a 707-Hz tone. Another example is shown in Figure 6B, in which the electrode pitch is high and the tone is low in frequency, but still shows the same averaging effects as in Figure 6A where the relative frequencies are reversed. In Figure 6C, as in Figure 6A, equal weighting of each was observed for electrode 22 paired with a 353-Hz tone, whereas stronger weighting of the electrode was observed for the same electrode paired with a 707-Hz tone; the net effect for both Figure 6A, C is to maintain the fused pitch within the frequency allocation range for that electrode (gray area). By contrast, for electrode 18, equal weighting was observed for all electrode–tone pairs, leading to systematic increases in fusion pitch with pair tone frequency. This example also shows that weighting can vary for the same tone frequency paired with different electrodes. Note that CI56 shown in this example also showed lateralization for electrode 18, and the data here show the variation of pitch with electrode–tone pair even though the sound was perceived as being in only one ear (the acoustic side). Figure 6D shows an example of the occasional instance in which very little averaging was seen, with the fusion pitch dominated by the tone

FIG. 5. Example of changes in fusion ranges over time for a bimodal CI user. The fusion range narrowed for electrode 22 and shifted upward for electrode 12, consistent with the observed correlation of long-term fusion range with interaural pitch mismatch.

frequency in this case for all tone frequencies paired with electrode 18 in this subject.

A fusion pitch index (FPI) was developed to describe the relative influences of the monaural

electric and acoustic pitches on the binaural fused pitch. The FPI is defined as the absolute value of the $\log_2$ difference between the fusion pitch and electrode pitch, in octaves, normalized by the $\log_2$

FIG. 6. Example pitch shifts seen for fused electric-acoustic tone pairs in three CI users. **A** Fusion pitch shifts in one subject for electrodes 22 and 20 paired with various pair tones spanning the fusion range, with pitch shifts in an upward direction from the electrode pitch. Different electrodes are separated by vertical black line for this subject. Fusion electrode-tone pitches (green circles) are weighted averages of the electrode pitches (blue circles) and tone frequencies (crosses). **B** Fusion pitch shifts in another subject for one electrode paired with three different pair tones, with pitch shifts in a downward direction from the electrode pitch. Pair tone frequency is

increasing from left to right. **C** Fusion pitch shifts in one subject for two different electrodes paired with three different pair tones spanning the fusion range, with pitch shifts in an upward direction from the electrode pitch. This subject showed lateralization to the acoustic side for electrode 18. **D** Fusion pitch shifts were not observed in a third subject for one electrode paired with four different pair tones. Instead, all fusion pitches were dominated by the acoustic tone frequency.

difference between the electrode pitch and pair tone frequency, in octaves:

$$\text{FPI} = \left| \frac{\log_2(\text{FusionPitch}/\text{ElectrodePitch})}{\log_2(\text{AcousticPitch}/\text{ElectrodePitch})} \right|$$

A small FPI near 0 indicates that the fusion pitch is close to the electrode pitch, i.e., is dominated by the electrode pitch. A FPI near 1 indicates that the fusion pitch is close to the acoustic tone frequency, i.e., is dominated by the acoustic tone pitch.

The population summary of FPI values of all subjects and electrodes plotted versus tone frequency in Figure 7A shows that no significant correlation was observed between tone frequency and FPI. Figure 7B shows that the distributions of FPI were mostly between 0 (dominance by CI electrode pitch) and 1 (dominance by acoustic tone frequency, as exemplified in Figure 7D). The minority of FPI values below 0 and above 1 reflect the occasional occurrence of fusion pitches outside the range between the two original pitches when the difference is very small, as for electrode 19 paired with 707 Hz in Figure 7B.

DISCUSSION

Dichotic Fusion Ranges

Both bimodal CI and Hybrid CI users have an interaural pitch mismatch between the frequencies stimulated electrically and acoustically, but may resolve the mismatch in different ways. For Hybrid CI

users, electrode pitch perception changes relative to contralateral acoustic pitch over time, and the changes tend to occur in the direction of reducing perceived interaural pitch mismatch (Reiss et al. 2007, 2011). Analogous adaptations in auditory or visual receptive fields have been reported in response to auditory-visual mismatch, such as after months of experience with displacing prisms in the barn owl (Knudsen 2002) or on the time scale of seconds with the ventriloquism aftereffect (Recanzone 1998). By contrast, bimodal CI users show more variability in how they adapt to pitch mismatch, with some even showing pitch adaptation that increases mismatch (Reiss et al. 2012a, b). These new findings suggest that increased binaural fusion frequency ranges may be an alternative compensatory mechanism to reduce perceived interaural mismatch in bimodal CI users with pitch mismatch introduced by CI programming.

These findings indicate that bimodal CI users fuse dichotic stimuli that differ by as much as 1–4 octaves in pitch. This phenomenon may be a general effect seen with hearing loss; HA users also exhibit wide binaural frequency fusion ranges on the order of an octave (Hong and Turner 2009)—not as large as seen in bimodal CI users but larger than for NH individuals, who fuse dichotic tones differing by no more than 0.2 octaves (Odenthal 1963; Van den Brink et al. 1976).

This is the first study to systematically look at pitch fusion in a large group of CI listeners. Previous studies in CI listeners have examined fusion in the context of sound localization rather than pitch perception, especially with bilateral CIs. In these studies, fusion

FIG. 7. Population summary of fusion pitch shifts for all subjects and electrodes expressed as a fraction of the pitch shift re: electrode pitch normalized by the frequency difference between the electrode pitch and pair tone frequency. **A** Fusion pitch shifts plotted versus

tone pair frequency show no relationship between tone frequency and fusion pitch fractions. **B** Distribution of FPI values show values mainly between 0 and 1.

of sounds across ears is an important prerequisite for being able to lateralize sounds, and lateralization is only measured for electrode pairs that are fused as a single auditory image. Thus, while not directly reported, it can be inferred from the electrode pairs studied that the fusion ranges are similarly abnormally wide in bilateral CI users, with a single electrode in one ear fusing with 6–15 electrodes in the other ear in a few case studies (van Hoesel et al. 1993; van Hoesel and Clark 1997; Long et al. 2003); this corresponds to fusion over 4–20 mm differences in cochlear locations of stimulation between ears, on a scale of octaves. Thus, the wide fusion ranges seen in bimodal CI users in this study are consistent with the wide fusion ranges seen in case studies of bilateral CI users.

The wide dichotic pitch fusion ranges are not explained by poor peripheral discrimination, as sequential frequency discrimination is typically better than a quarter octave for acoustic hearing or every other electrode for electric hearing. In other words, dichotic fusion ranges, which can be thought of as simultaneous binaural discrimination limits, are much wider than sequential monaural discrimination limits in hearing-impaired listeners, and cannot be explained by peripheral deficits. Likewise, wide dichotic fusion ranges cannot be explained by simultaneous within-ear channel interactions, because the interaction is across ears. Another possible peripheral explanation for fusion of stimuli with binaurally disparate pitches is broad activation of a large population of neurons, spanning octaves, due to current spread in the implanted ear, which increases the likelihood of overlap of some electrically stimulated neurons with acoustically stimulated neurons in the other ear with the same characteristic frequency. However, normal-hearing listeners do not fuse complex sounds if they differ in the evoked pitch by more than the diplacusis amount (Van den Brink et al. 1976). Thus, even if current spread leads to broad activation, fusion in bimodal CI users still differs from that in NH listeners.

The correlation between interaural pitch mismatches and fusion ranges in bimodal CI subjects is consistent with the correlation between diplacusis and fusion ranges seen previously for NH listeners on a much smaller scale (Van den Brink et al. 1976). The data shown in Figure 5, in which fusion ranges change over time to coincide with pitch mismatch boundaries, is also consistent with the hypothesis that fusion ranges adapt to minimize the perception of mismatch; the lack of changes observed in other subjects with 2 years or more of CI experience suggests that fusion range adaptations may stabilize within 2 years. However, the correlation in Figure 4 is weak, and longitudinal data from more subjects is needed over time to demonstrate a causal relationship between pitch mismatch and increases in fusion range.

Other factors may also influence fusion range size. For instance, as large fusion ranges are also seen in hearing-impaired individuals without CIs, fusion ranges may be inherited from previous experience with hearing impairment and diplacusis, and may merely prevent pitch adaptation. Another potential factor that may influence fusion range size is the use of 1,200 pps pulse trains in subjects accustomed to other pulse rates in their clinical programs. While the use of 1,200 pps minimizes the effects of temporal cues on pitch, and is unlikely to change interaural acoustic–electric interactions because of the typical loss of acoustic phase locking with severe/profound hearing loss, further research is needed to rule out any effects of pulse rate on fusion of electrical and acoustic stimuli.

Why do bimodal CI users show less apparent pitch adaptation (and possibly more binaural fusion) than Hybrid CI users? One possible explanation is that Hybrid CI users differ in the fact that they also have access to residual hearing in the implanted ear. In the case of Hybrid CI users, pitch adaptation may be forced when the discrepancy is present within as well as across ears, especially for the most apical electrodes for which acoustic and electric frequency ranges overlap. For bimodal CI users, on the other hand, it may be simpler for the brain to adapt BSI instead of adapting tonotopic mapping. However, it should be noted that one study in Hybrid CI users who had lost residual hearing in the implanted ear still showed pitch adaptation to mismatch (Reiss et al. 2012a). Hybrid CI users also have more residual hearing and better pure tone thresholds, requiring much less amplification with their HAs than bimodal CI users. Another possible explanation is that the reduced frequency specificity of stimulation with greater degrees of hearing loss and/or amplification, especially at suprathreshold levels, leads to abnormally wide temporal envelope correlations across frequency and between ears and promotes increased fusion after long-term experience with such stimulation.

Fusion Pitch Averaging

Seventeen subjects exhibited broad fusion ranges and were further tested on the fusion pitch matching task. As predicted, several subjects exhibited averaging of the dichotic pitches within the fusion range, in which a new pitch arose from the fusion of two stimuli with different pitches when presented alone, even when the pitches differed by as much as 3–4 octaves. Dichotic pitch averaging has been seen previously in NH listeners but for smaller pitch differences of less than 0.1–0.2 octaves (Van den Brink et al. 1976). These pitch shifts are also consistent with informal reports by CI users that voice pitches shift with a second CI or a HA in the contralateral

ear. The pitch averaging seen for binaural inputs in the auditory system should not be surprising given the ubiquitous averaging or integration of multiple inputs seen across sensory systems, such as the binocular averaging of color differences in the visual system (Hecht 1928) or the averaging of visual and auditory speech stimuli in the McGurk effect (McGurk and MacDonald 1976); these averaging phenomena have a likely role in averaging out random noise in the environment (Hillis et al. 2002).

However, the finding of abnormally broadened dichotic pitch fusion and integration on this scale is unique to individuals with CIs, and has not been reported in other systems. Thus, these findings are also relevant for other neural prostheses; for example, for blind individuals implanted with visual prostheses, large visuospatial mismatch introduced between the two eyes may similarly induce perceptual adaptation to increase binocular fusion, reduce perceived mismatch, and average the visuospatial relationships of objects and features across eyes. Such averaging could lead to blurring or distortion of visuospatial relationships with two eyes compared with one.

An important implication of fusion pitch averaging is that the resulting systematic shifting of fusion pitch with pair tone frequency in the fusion range provides additional support for the percept reflecting pitch fusion, rather than the perception of two separate, unfused sounds that are identical or indistinguishable in pitch. In fact, during the dichotic fusion range measurement task, several subjects with wide fusion ranges remarked that they could hear the pitch of the fused tone shifting with the pair tone (though they were not aware that the stimulus was only changing in one ear). This pitch averaging only occurred when subjects perceived the same sound in both ears, and not when two distinct sounds were perceived. This observation, consistent with the finding of pitch averaging for fused stimuli also observed with normal-hearing listeners for much smaller dichotic frequency differences (Van den Brink et al. 1976) is another, indirect verification of true fusion rather than a perception of two distinct, unfused sounds that are identical in pitch. Therefore, wide fusion ranges with pitch averaging are not likely to reflect peripheral limitations in discrimination due to a diffuse stimulation of each CI electrode, for example, but rather abnormal central integration that leads to pitch averaging and loss of information about the individual inputs somewhere along the auditory pathway.

Binaural Spectral Integration

The abnormally broad fusion and binaural pitch averaging observed in this study suggests binaural integration of mismatched rather than matched

spectral information. In NH listeners, BSI of small spectral differences is likely to serve a beneficial function in reducing noise. In bimodal CI users with large fusion ranges, however, BSI is likely to lead to averaging over a broad frequency range across ears, and may instead lead to additional smearing and compression of spectral information beyond that already present monaurally. Thus, it is possible that the resulting abnormally broad BSI may account for speech perception interference effects observed with binaural compared with monaural hearing device use, where some individuals show little benefit or even worse performance with binaural stimulation compared with monaural stimulation with either ear alone (Carter et al. 2001; Ching et al. 2007). Certainly, in some cases, bimodal CI users experience improved speech perception in noise when the overlap between acoustic and electric analysis frequency ranges is reduced (Reiss et al. 2012a, b), which minimizes the potential for such averaging of highly mismatched speech information between ears.

The finding of abnormally broad BSI in bimodal CI users also suggests a potential limitation of using vocoder simulations in NH listeners to model bimodal CI perception. A recent study showed that simulations in NH listeners tend to overpredict efficiency of integration of electric and acoustic information between ears compared with real bimodal CI users (Yang and Zeng 2013). This suggests that the lack of abnormally broad BSI in NH listeners may explain the inability of simulations to predict results in real bimodal CI subjects. However, another study by Kong and Braida (2011) suggests that NH and bimodal CI listeners both average vowel response centers between acoustic and electric inputs (simulations for NH listeners). One possible interpretation of this result is that NH listeners also demonstrate broad BSI for broadband stimuli like speech, even though they do not show broad BSI for simple stimuli like tones, and that narrow rather than broad BSI may explain some of the difficulties in some bimodal CI users. Another, interesting interpretation is that NH and bimodal CI listeners may integrate speech differently between ears. Bimodal CI users (and other hearing-impaired listeners) with abnormally broad BSI may have obligatory fusion and thus loss of independent spectral information between the two ears at a low level of spectral processing, e.g., vowel formant peak location may be averaged between ears before vowel identity is processed. In contrast, NH listeners may instead be hearing two unfused, separate streams in the two ears, processing information such as vowel identity independently for the two ears, and integrating or averaging these phoneme identities at a higher cognitive stage of processing.

Abnormally broad BSI may also explain the limitations in localization-related benefits seen in hearing-impaired listeners (Ching et al. 2007), such as for speech

perception in spatially separated noise. Localization based on two ears requires fusion, i.e. requires the binaural cues such as interaural level and timing differences to be incorporated into a single auditory image with a single location. In the simple case of a single sound source, abnormally broad fusion will still allow successful localization with stimuli that are mismatched in cochlear place or frequency between ears (e.g., van Hoesel et al., 1993). However, in the presence of multiple sound sources (such as in a cocktail party), abnormally broad fusion is more likely to lead to interference in localization as well as speech perception. If fusion is broad, level and timing cues will be processed across mismatched frequencies between ears instead of separated by frequency, and could potentially interfere with the ability to use grouping cues such as fundamental frequency for segregation of voices into separate auditory streams (Bregman 1990). Such interference could explain the limitations of binaural benefits to head shadow or louder-ear effects rather than true localization-related benefits in CI users (e.g., Gantz et al. 2002; Litovsky et al. 2006a). Further research is needed to fully understand the impact of abnormal BSI on localization, speech perception, and localization-related benefits for speech perception in background noise.

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