Internalized elevation perception of simple stimuli in cochlear-implant and normal-hearing listeners

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In normal-hearing (NH) listeners, elevation perception is produced by the spectral cues imposed by the pinna, head, and torso. Elevation perception in cochlear-implant (CI) listeners appears to be non-existent; this may be a result of poorly encoded spectral cues. In this study, an analog of elevation perception was investigated by having 15 CI and 8 NH listeners report the intracranial location of spectrally simple signals (single-electrode or bandlimited acoustic stimuli, respectively) in both horizontal and vertical dimensions. Thirteen CI listeners and all of the NH listeners showed an association between place of stimulation (i.e., stimulus frequency) and perceived elevation, generally responding with higher elevations for more basal stimulation. This association persisted in the presence of a randomized temporal pitch, suggesting that listeners were not associating pitch with elevation. These data provide evidence that CI listeners might perceive changes in elevation if they were presented stimuli with sufficiently salient elevation cues.

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I. INTRODUCTION

Sound interacts with the body to produce characteristic perceptual cues for a sound source that the auditory system can use to assign the source to a specific location in space (Middlebrooks *et al.*, 1989; Middlebrooks, 1992). These cues are created by the physical interaction of the sound wave and the structures of the head, pinna, and torso. The cues that are used for horizontal-plane localization are interaural cues (i.e., time and intensity differences between the ears). The cues that are used for vertical-plane localization are spectral cues (i.e., frequency-specific peaks and notches). Hearing impairment reduces the ability to utilize spectral cues for vertical-plane localization in part because of spectral smearing and broadened auditory filters. Individuals with cochlear implants (CIs), who have their hearing restored by direct electrical stimulation of the cochlea, suffer from severe smearing and, as a consequence, demonstrate minimal ability to localize in the vertical plane when using clinical processors (Majdak *et al.*, 2011). The goal of this study was to determine if CI listeners could perceive changes in auditory image elevation using spectrally simple stimuli that essentially only changed in place of stimulation. This was done using an approach that measured internalized elevation perception, which we have termed “verticalization” perception. The advantage of this technique is that it avoids the spectral limitations of a CI.

Vertical-plane localization cues are commonly referred to as spectral or pinna cues because they are introduced primarily by the frequency-dependent interference that is caused by the interactions of sounds traveling directly into

the ear canal and the same sounds reflecting off the pinna before entering the ear canal (Hebrank and Wright, 1974; Middlebrooks and Green, 1991, 1992; Butler and Humanski, 1992). This interference introduces frequency-specific peaks and notches in the spectrum primarily between 4 and 16 kHz for humans; this allows for the perception of elevation and the ability to discriminate front from back (Langendijk and Bronkhorst, 2002).

At present, CIs alter incoming acoustic signals in many ways that could adversely affect the spectral cues commonly used to perform vertical-plane localization. First, CIs use behind-the-ear (BTE) microphones that bypass the filtering introduced by the pinna. Majdak *et al.* (2011, Fig. 5) showed a uniform spectral profile for all elevations for sounds recorded with CI BTE microphones, therefore not providing a unique spectral profile to associate with different elevations. One solution to this specific problem might be the use of a microphone located at the opening of or partially placed in the ear canal, which would reintroduce the pinna-based spectral cues.

Second, a limited frequency range is available to CI listeners. Typically the frequencies allocated to the electrodes range from about 0.2 kHz for the lower frequency boundary to 5–10 kHz for the upper frequency boundary. Therefore CI processing strategies do not provide information for the entire 4–16 kHz frequency range associated with vertical-plane localization cues (Langendijk and Bronkhorst, 2002).

Third, the number of electrodes in a CI limits the resolution of the spectral profile due to the relatively large bandwidths (BW) allocated to each electrode compared to a typical auditory filter (Goupell and Litovsky, 2014). However, NH listeners can localize in the vertical plane when presented stimuli with a fairly large amount of spectral smoothing (Kulkarni and Colburn, 1998) or when presented spectrally degraded stimuli by using channel-vocoder simulations of CI processing (Goupell *et al.*, 2010). Therefore,

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the limited number of electrodes has the potential to transmit reduced but usable spectral cues for elevation perception.

Fourth, even if there was a sufficient number of electrodes to sufficiently encode spectral cues, many CIs use monopolar stimulation, which can excite nearly 1/8 of the cochlea per electrode (Nelson *et al.*, 2008). Spectral smearing from current spread reduces or removes the ability of CI listeners to detect spectral cues (Henry *et al.*, 2005; Anderson *et al.*, 2011; Won *et al.*, 2011; Azadpour and McKay, 2012). Goupell *et al.* (2008) investigated the ability of CI users to detect different spectral profiles, which is a prerequisite skill for vertical-plane localization. In three separate experiments, CI listeners discriminated the existence of spectral peaks and notches, the height of peaks and depth of notches, and the electrode location of peaks and notches. Just-noticeable differences (JNDs) for detecting different spectral profiles were smaller for peaks than for notches, and in many notch conditions, the CI listeners were unable to detect notches with the deepest possible depth (i.e., zero current). Furthermore inclusion of level-rolling greatly increased JNDs, suggesting that the CI listeners were unable to discriminate different spectral profiles and were utilizing the overall level to perform the tasks. Therefore, using a complex multi-electrode stimulus may be a non-optimal way of determining if the spectral profile is associated with percepts varying in elevation in CI listeners.

Given these problems with encoding spectral cues in CIs, it is not surprising that Majdak *et al.* (2011) measured poor vertical-plane localization performance in five bilateral CI listeners when presented virtual stimuli (individualized BTE processor head-related transfer functions presented through the direct input of the processor, which bypassed the microphones). They found some ability of the CI listeners to identify the correct front-back hemifield with a ± 2.5 -dB overall level rove. However, this ability was reduced after imposing a ± 5 -dB overall level rove, and the response patterns were correlated with overall level of the stimuli. Therefore, there was little evidence that the CI listeners were using spectral cues to localize in the vertical planes.

Solutions to improve vertical-plane localization or more so, percepts varying in elevation, for multi-electrode stimuli necessitates improvements in spectral cue capture (in-the-ear microphones and larger spectral range) and spectral cue encoding (larger number of channels with more focused stimulation). It has yet to be shown, however, that CI users can actually perceive changes in elevation. One possible way to avoid the poor spectral resolution of a CI is to utilize spectrally simpler stimuli. Single sine tones and narrowband noises have been shown to be associated with different perceived elevations (Pratt, 1930; Trimble, 1934; Roffler and Butler, 1968a,b; Butler and Helwig, 1983; Middlebrooks, 1992; Blauert, 1997), and the perceived location of narrowband sound sources relate well to the expected perceived location predicted from the position of spectral peaks in a listener's head-related transfer function (Middlebrooks, 1992; Blauert, 1997). By controlling single-electrode place of stimulation in CI listeners, it may be possible to cause changes in auditory image elevation or verticalization with changes in place of excitation.

The purpose of this study was to determine if CI listeners associate changes in place of stimulation with changes in verticalization and to determine if the perception is similar to that experienced by NH listeners. To do this, we measured the perceived intracranial location of single-electrode stimulation in CI listeners and approximations of this stimulation in NH listeners [sine tones and bandlimited pulse trains (PTs)]. We hypothesized that CI listeners would demonstrate the verticalization of simple stimuli because the stimuli would be interpreted as a single peak in the spectral profile. If CI users can perceive changes in elevation with these simple stimuli, this would motivate further research on improved encoding of vertical-plane localization cues in CI users.

II. EXPERIMENT 1: VERTICALIZATION FOR COCHLEAR-IMPLANT LISTENERS

A. Listeners and equipment

Data were collected from 11 late onset-of-deafness (i.e., listeners who grew up with normal hearing, lost their hearing post-lingually, and were implanted later in life) and four early onset-of-deafness (i.e., listeners who lost their hearing pre-lingually and were implanted later in life) CI listeners. Listener codes will contain all capital letters for the late onset listeners (e.g., CAQ) and only an initial capital letter for early onset listeners (e.g., Cau). Six listeners were unilateral and nine listeners were bilateral CI users. Table I specifies the listeners' age, age of onset of deafness, and duration of CI use in each ear. All CI listeners used Cochlear devices with a 24-electrode array, which have approximately 0.75-mm center-to-center inter-electrode spacing. Electrodes are numbered such that 22 is the apical-most electrode and 1 is the basal-most electrode (two electrodes are extra-cochlear). All listeners traveled to the University of Maryland, College Park for testing. They performed the testing over 2–3 days.

TABLE I. Age, approximate age of onset of severe-to-profound hearing loss, and duration of CI use for the listeners in experiment 1.

Code	Age (yr)	Onset of deafness		CI use	
		Type	Age (yr)	Left (yr)	Right (yr)
CAI	69	Late	57	6	2
Caj	61	Early	0	–	14
CAL	53	Late	34	3	10
CAM	68	Late	40	–	5
CAN	72	Late	28	–	6
CAO	68	Late	3	–	1
CAP	45	Late	38	6	5
CAQ	54	Late	44	5	4
CAR	21	Late	4	–	4
CAS	49	Late	41	5	1
CAT	25	Late	10	3	7
Cau	52	Early	1	11	10
Cav	27	Early	0	8	4
Caw	51	Early	0	4	1
CAX	52	Late	42	2	–

Stimuli were delivered via direct stimulation using bilaterally synchronized L34 research processors run with the Nucleus Implant Communicator (NIC, Cochlear Ltd., Sydney, Australia). All testing was performed on a personal computer with custom-made software written in MATLAB (Mathworks, MA).

B. Stimuli

Stimuli were electrical PTs presented on single electrodes in monopolar configuration. The electrodes tested were the even-numbered electrodes plus electrodes 1 and 3. Some listeners were not presented stimulation at all 13 electrodes because some electrodes (often the basal-most) were deactivated in their clinical processors. Each biphasic pulse in the PT had a 25- μ s phase width and a 7- μ s phase gap. The PTs were 500 ms in duration, each pulse in the PT had the same amplitude, and the PT was presented at the most comfortable (*C*) sensation level. The nominal pulse rate was 300 or 1000 pulses per second (pps). The 1000-pps rate was used to approximate typical CI stimulation rates from clinical processors. The 300-pps pulse rate was tested because temporal pitch salience is better in CI listeners at and below this rate compared to 1000 pps (Zeng, 2002). Conditions in which the pulse rate was constant across trials were tested as well as conditions in which the pulse rate was randomly roved across trials. Rate roving was included in an attempt to confound the listeners' ability to perform the task using pitch. For the random-rate PTs, the rate was randomized by 50% of the nominal pulse rate from trial-to-trial using a uniform distribution (i.e., the rate ranged from 150 to 300 or 500 to 1000 pps).

C. Procedure

1. Mapping

Loudness maps were measured by adjusting CI current units (CUs) to achieve threshold (*T*) and *C* sensation levels. *T* and *C* levels were found at even-numbered electrodes and interpolated for the *T* and *C* levels on the odd-numbered electrodes. Then stimuli were presented at electrodes sequentially in groups of five (i.e., 22, 21, 20, 19, and 18) with a 500-ms inter-stimulus interval. Listeners compared *C* levels across the electrodes, and levels were adjusted until equal loudness was achieved across the array. Separate maps were made for each ear for 300 and 1000 pps.

2. Verticalization task

Real sound sources with complex spectra that are acoustically filtered by the head, pinna, and torso are often perceived as "externalized," meaning they are perceived extracranially from a single punctate location in space. Removing this filtering often creates an "internalized" or intracranial perception (Hartmann and Wittenberg, 1996). Likewise, simple tones are often perceived intracranially because they lack a broadband spectrum in which a spectral shape could be transmitted, although the degree of internalization vs externalization is difficult to quantify (Plenge, 1974). For the stimuli in this study, we assumed the

spectrally simple stimuli would be internalized and that we would evaluate the intracranial percept of elevation. The metric of intracranial left-right perception is called "lateralization" (e.g., Plenge, 1974). As an analogous term for intracranial elevation perception, we will use the term "verticalization."

The listeners' task was a pointing task, which was to indicate the location of where a sound was heard inside of the head on an interface with the image of a circular face (see Fig. 1) (e.g., Hartmann and Wittenberg, 1996; Blauert, 1997; Whitmer *et al.*, 2012; Goupell *et al.*, 2013b). Listeners were explicitly told to attend to the location of the sound image and ignore any pitch or loudness differences in the stimuli. To begin a trial, listeners pressed a "play" button. They then responded with the perceived location of the sound. Listeners had the option of selecting the number of sound sources they perceived (one, two, or three). They marked the perceived location of each sound source with separate boxes on the picture of the face and had the option of selecting a position slightly outside of the image of the face, particularly in the corners of the interface that the circular head does not cover. If more than one source was perceived, listeners were instructed to mark the most dominant or loudest sound image as the first source. Listeners could repeat the stimulus as many times as they preferred by pressing a "repeat" button. They completed a trial by pressing a "done" button.

Listeners were presented stimuli in blocks in which the pulse rate, roving, and presentation ear(s) were fixed, but the electrode number was randomized. The maximum number of conditions for the bilateral CI listeners was 2 pulse rates (300 or 1000 pps) $\times$ 2 roving conditions (constant rate or random rate) $\times$ 3 presentation ear configurations (left, right, or both) = 12 conditions. The maximum number of trials for the bilateral CI listeners was 13 electrodes (fewer electrodes were tested if some electrodes were deactivated) $\times$ 12 conditions $\times$ 20 repetitions per condition = 3120 trials. For the unilateral CI listeners, there were only 4 conditions and 1040 trials. Some CI listeners did not perform all of the conditions because they demonstrated minimal change in verticalization

FIG. 1. (Color online) The graphical user interface used by the listeners. Listeners reported the number of sound images that they heard and marked on the face where they heard the sounds in the horizontal and vertical dimensions.

across the electrode array or because they lacked time to complete the testing.

D. Data analysis

Listener responses were converted to a numerical scale. In the horizontal dimension, the left-most edge of the response area (very near the left-most edge of the head) was -10 , the center of the head was 0 , and the right-most edge of the response area was $+10$. In the vertical dimension, the bottom-most edge of the response area was -10 , the center of the head was 0 , and the top-most edge of the response area was $+10$. For this study, we focused on the responses in the vertical dimension. The data in the horizontal dimension were also analyzed and can be summarized briefly. Horizontal dimension responses were near the ear for unilateral presentation (either left or right) and were generally more centered for bilateral presentation; however, they were not always exactly centered, consistent with previous results (Goupell *et al.*, 2013a; Kan *et al.*, 2013).

Only the first (i.e., strongest) source response was analyzed and reported. Perceiving multiple source responses would be expected more often in bilateral presentation in the case where there was incomplete binaural fusion. Because a CI listener often needs a substantial amount of interaural place of stimulation mismatch (>3 mm) for incomplete binaural fusion (Goupell *et al.*, 2013b; Kan *et al.*, 2013), we expected very few multiple source responses. Indeed only 2.5% of the trials consisted of multiple responses; this justifies disregarding the secondary and tertiary source responses.

Analyses of variance (ANOVAs) were performed on the data set. First, one-way ANOVAs with factor electrode were performed for each individual listener. Second, a four-way omnibus ANOVA with factors electrode, pulse rate, roving, and presentation ear was performed over all 15 listeners.

E. Results

The individual data for the CI listeners are presented in Figs. 2 and 3. The results of the experiment show that the CI listeners demonstrated a significant change (generally, an increase) in verticalization as the electrode number decreased (i.e., the stimulation moved basally along the cochlea) in the individual one-way ANOVAs. For 12 of 15 listeners, the effect of electrode was highly significant with $p < 0.0001$. Listener CAS had a marginally significant effect of electrode [$F(12,3126) = 1.9$, $p = 0.026$, $\eta^2_p = 0.007$]. Listeners CAL and CAP did not have a significant effect of electrode ($p > 0.05$ for both).

In general, verticalization was higher for the lower numbered (i.e., more basal) electrodes; however, there was great variability across the listeners. Some listeners demonstrated a large verticalization range (e.g., listeners CAM, CAN, and Cau) while some had smaller ranges (e.g., listeners CAR and CAX). Some listeners demonstrated an abrupt increase in verticalization for high-numbered (i.e., more apical) electrodes (e.g., listeners CAN and CAX) while some demonstrated an increase in verticalization closer to the middle of the array (e.g., listeners Caj and CAM). Some listeners demonstrated non-monotonic verticalization functions (listeners CAN, CAQ, and Cau).

FIG. 2. (Color online) Verticalization for the CI listeners for the 300-pps conditions as a function of electrode number. Each point shows the average verticalization. Error bars show ± 1 standard error. Right-ear conditions are shown by squares. Left-ear conditions are shown by circles. Both-ear conditions are shown by triangles. Open symbols show constant-rate conditions. Closed symbols show random-rate conditions.

For the bilateral CI listeners, the effect of presentation ear could be evaluated within a single listener. There appeared to be no effect of presentation ear for listener CAT. The other three listeners showed different verticalization responses for the left and right ears (e.g., listener CAI at 1000 pps and Cau at 1000 pps). In the cases when there were differences between the left and right ear verticalization responses, presenting stimuli to both ears may have had the listeners respond to a preferential ear (e.g., listener CAI at 1000 pps), may have had the listeners average their responses between the left and right ears (e.g., listener Cau), or may have produced a higher verticalization compared to the single-ear conditions (e.g., listener CAT).

We performed a four-way ANOVA with factors electrode, pulse rate, roving, and presentation ear over all 15 listeners. Because there were only four early onset listeners, age of onset of deafness was not included as a factor in the analysis.

The results of the four-way ANOVA revealed a significant main effect of electrode [$F(12,1128) = 19.8$, $p < 0.0001$,

FIG. 3. (Color online) Verticalization for CI listeners for the 1000-pps conditions as a function of electrode number. Conventions are the same as in Fig. 2.

$\eta^2_p = 0.17$], which can be seen in Fig. 4 where the mean verticalization was calculated over all listeners, rates, roving, and presentation ear. A Helmert contrast showed that verticalization for all electrodes higher than electrode 8 was

FIG. 4. Average verticalization calculated across the CI listeners and all conditions. Error bars show ± 1 standard deviation across listener average verticalization.

FIG. 5. Average verticalization for the CI listeners calculated across roving and presentation ear conditions. Therefore data are shown separately for each rate. Error bars show ± 1 standard deviation across listener average verticalization.

significantly lower than the verticalization averaged over electrodes 8 and lower ($p < 0.05$). In other words, the observed increase in verticalization as electrode number decreased saturated at electrode 8. None of the interactions involving the factor electrode were significant ($p > 0.05$ for all).

There was a significant effect of presentation ear [$F(1,1128) = 34.4$, $p < 0.0001$, $\eta^2_p = 0.06$]. Tukey *post hoc* tests showed that verticalization was higher for the diotic conditions compared to the right ear ($p < 0.0001$) and left ear ($p < 0.0001$). Verticalization was also higher for the right ear compared to the left ear ($p = 0.024$).

There was a significant main effect of pulse rate [$F(1,1128) = 5.2$, $p = 0.023$, $\eta^2_p = 0.01$] in which the 300-pps stimuli yielded significantly higher verticalization responses than 1000-pps stimuli, which can be best seen in Fig. 5 where the mean verticalization was calculated over all different roving and presentation ear conditions. There was also a significant interaction of pulse rate $\times$ presentation ear [$F(2,1128) = 15.9$, $p < 0.0001$, $\eta^2_p = 0.03$].

The main effect of rate roving was not significant [$F(1,1128) = 2.0$, $p = 0.16$, $\eta^2_p = 0.002$]. However, interactions

FIG. 6. (Color online) Verticalization responses for CI Listener CAN plotted as a function of rate for the random-rate conditions. The 300-pps condition (a) and the 1000-pps condition (b) are shown. Data for electrode 22 are shown by squares, electrode 18 by circles, and electrode 3 by triangles. Dashed lines represent linear regressions performed for each electrode.

roving $\times$ presentation ear [$F(2,1128)=3.5$, $p=0.030$, $\eta_p^2=0.006$] and pulse rate $\times$ roving $\times$ presentation ear [$F(2,1128)=3.1$, $p=0.046$, $\eta_p^2=0.005$] were significant. A one-way ANOVA for each pulse rate showed no effect of presentation ear at 300 pps [$F(2,576)=0.826$, $p=0.44$, $\eta_p^2=0.003$] and a significant effect at 1000 pps [$F(2,634)=0.826$, $p<0.001$, $\eta_p^2=0.16$]. The rate roving was introduced to evaluate the possibility that listeners were evaluating a pitch perception rather than the verticalization perception. To further explore this possibility, we performed correlations between rate and verticalization for each electrode. Figures 6(a) and 6(b) show the individual verticalization responses as a function of the rate of stimulation, when the rate was randomized, for three example electrodes (3, 18, and 22) for listener CAN, who was representative of all of other CI listeners. Listener CAN did not show a significant correlation between rate and electrode. In fact over a total of 416 correlations calculated over all listeners who exhibited significant verticalization, there were no significant correlations between rate and verticalization using Bonferroni-correction ($p<0.5/416=0.00012$) and only 35 significant correlations between rate and verticalization using uncorrected comparisons ($p<0.05$). Of these significant correlations, only 14 were positive, which would be the expected direction if higher verticalization was chosen for higher rates. This analysis shows that listeners were indeed ignoring the pitch perception, and likely using verticalization perception to perform the task.

In summary, listeners responded with higher verticalization for more basal electrodes and the verticalization increased until electrode 8. The highest verticalization responses occurred for presentation to both ears. PTs presented at 300 pps produced higher verticalization than 1000 pps. There was not a main effect of rate roving, but there were some significant interactions involving rate roving. Further investigation did not show evidence that verticalization and pulse rate were significantly correlated within a rate condition (i.e., rates randomized from 150 to 300 pps were not correlated with verticalization).

F. Discussion

The purpose of this experiment was to determine if CI listeners perceived changes in verticalization (auditory image elevation) using single-electrode stimulation, which

would produce a simple spectral profile with a single peak. We found that most listeners responded with higher verticalization for more basal stimulation (lower-number electrodes) (see Figs. 2–5). The position at which there was an increase in verticalization occurred at different electrodes. For example, the position of increasing verticalization as a function of electrode could start at more apical electrodes (listener CAN, Fig. 2), or it could occur closer to the middle of the array (listener Caj, Fig. 2), suggesting variability in the associations of verticalization across listeners. Verticalization for some listeners was non-monotonic, where the verticalization perception increased with decreasing electrode number until it peaked, then the verticalization started to decrease again (listener Cau, Figs. 2, 3, and 5), which could be representative of a sound source moving from the front to above to behind the head. The lack of homogeneity in the verticalization responses across CI listeners was expected as it is assumed that they have uneven neural degeneration across the cochlea and different amounts of overall neural degeneration that is likely related to overall duration of deafness (compare the different durations of deafness in Table I) (Blamey et al., 2013). Furthermore, exact placement of the electrode is quite variable with respect to insertion depth and distance to the modiolus (Kawano et al., 1998), which would affect the exact neural populations that were excited. Different insertion depths would explain how the increase in verticalization would be so variable across CI listeners. Listeners that have deeper insertions would be expected to show increases in verticalization more toward the middle of the array compared to listeners that have shallower insertions. Last, even NH listeners show a great variability in localizing narrowband stimuli in the vertical plane, which is a result of the variability in the spectral peak and notch locations in listeners' head-related transfer functions. In five NH listeners, Middlebrooks (1992) showed trends similar to ours in which more basal stimulation is perceived as higher or even behind the head, but the localization of individual frequencies was inconsistent across listeners.

The magnitude of verticalization is also inconsistent across listeners. The largest verticalization ranges are nearly half of our scale (10 units on a 20 unit scale), whereas some listeners showed little to no change in verticalization perception across the electrode array. There could be many explanations for this result. First, many CI listeners do not localize sound sources well compared to NH listeners, even bilateral CI users (Majdak et al., 2011; Litovsky et al., 2012). In the horizontal plane, the poor sound source localization for CI users is thought to be a result of poorly encoded interaural cues and lack of acoustic binaural hearing experience (Litovsky et al., 2010). These reasons may also apply to vertical-plane localization. Spectral information is poorly encoded in CIs (Goupell et al., 2008; Majdak et al., 2011) and our experiment with highly controlled direct stimulation of single electrodes aimed to bypass these spectral limitations. However, single-electrode stimulation is very unnatural, analogous to how a sine tone presented acoustically is unnatural. Most people who have never performed psychoacoustical experiments over headphones have never experienced internalization of sound images. It may be that some

of the CI listeners found the single-electrode stimulation so unnatural that no verticalization was perceived. Alternatively, it could be that the CI listeners who did not demonstrate large verticalization ranges do not often attempt to localize sound sources because they are so poor at it. It would be interesting to compare horizontal sound source localization acuity with verticalization range to determine if listeners who are better at localization in the horizontal plane demonstrate a larger verticalization range.

A major concern with the verticalization results was that the CI listeners used pitch to perform the task rather than the perception of height, even though we explicitly told the listeners to ignore pitch at the beginning of the experiment and to attend only to location. Indeed, more basal stimulation produces a *higher* place pitch and our verticalization task asked listeners to determine the *higher* location in the head. Therefore a control condition was performed to clarify if this was a confusion between two completely different percepts rather than an evaluation of only the verticalization percept. The 50% randomization of the rate should have made the place pitch unusable for the task by confounding it with the relatively stronger temporal pitch cue. In other words, randomly roving the temporal pitch would make the place pitch less salient or non-existent. Since temporal pitch is more salient at low rates (150–300 pps) compared to place pitch (Zeng, 2002), the verticalization of the 300-pps rate conditions should have been most affected by the rate roving if listeners were using pitch to perform the verticalization task.

There was no main effect of randomly roving the stimulation rate from trial to trial compared to keeping the stimulation rate constant. However, there were some interactions with rate randomization that were significant. We further investigated the relationship between verticalization and rate for the random-rate conditions and an example is shown in Fig. 6. If listeners assigned pitch to verticalization, verticalization should have increased as the rate increased for a fixed electrode. Given that this correlation was not seen, our interpretation of the data is that listeners performed the task as instructed and did not utilize pitch. There is also additional evidence that listeners were not using pitch to perform the task. First, the non-monotonic verticalization functions from some of the listeners are evidence of verticalization because utilizing pitch would have predicted solely monotonically increasing functions. Second, the 300-pps conditions producing a higher verticalization than the 1000-pps conditions are evidence of verticalization because utilizing pitch would have predicted 1000 pps to be higher than 300 pps. Last, comparison of the error bars for the 300-pps conditions with and without roving show little change; utilizing pitch would have predicted larger error bars for the roving conditions. However, it is possible that the listeners were utilizing a combination of height and pitch cues, which may explain some of the significant interactions with the roving factor. It is also possible that listeners were able to separately attend to just the place pitch and ignore the randomly varying temporal pitch and verticalization.

There were some other significant effects in this experiment where interpretations were less obvious. For example, PTs presented at 300 pps produced higher verticalization than PTs presented at 1000 pps. Because there was no clear effect of rate

from the rate randomization analysis in Fig. 6, this difference might be a result of small spectral or level differences in the electrical stimulation. Given the covarying nature of so many different factors in a naturally inhomogeneous population, we parametrically investigated these stimulus factors in NH listeners by presenting acoustic PTs as CI simulations in the hope to better interpret the CI verticalization response patterns.

III. EXPERIMENT 2: VERTICALIZATION OF MONOTIC AND DIOTIC SINE TONES IN NH LISTENERS

To better understand the CI data, NH listeners were tested in the same paradigm using simple stimuli that are typically not used in experiments that test elevation perception.

A. Listeners

Eight NH listeners between the ages of 18 and 25 yr participated in this experiment. They had hearing thresholds of less than or equal to 15 dB hearing level (HL) measured between 250 and 8000 Hz at octave intervals.

B. Equipment

Listeners were seated in a double-walled sound attenuating booth (IAC; New York). MATLAB was used to generate and present sound stimuli to all listeners. Stimuli were presented via MATLAB to a Tucker-Davis Technologies System 3 (RP2.1, PA5, and HB7; Florida). Listeners heard the sounds through ear-insert headphones (Etymotic ER2; Illinois). The rationale to use ear-insert headphones was to eliminate any small effects of the pinna that may occur with circumaural headphones. In addition, the ear-insert headphones have a relatively flat frequency response up to 16 kHz, making them desirable for performing CI simulations because they bypass the outer ear transfer function.

C. Stimuli

The stimuli were 500-ms sine tones generated with a 100-kHz sampling rate, which were resampled to 97.65625 kHz for presentation on the Tucker-Davis Technologies System 3. The stimuli were temporally shaped by a Tukey window with a 10-ms rise-fall time. The sine tones had a frequency of 0.125, 0.25, 0.5, and 1 to 15 kHz in 1-kHz steps (18 frequencies total).

The stimuli were presented at comfortable levels that were equal loudness. The motivation for this was to mimic the equally loud *C* levels that were presented to the CI listeners in experiment 1. Equal loudness was determined by having five NH listeners match the loudness of each test frequency to a 1-kHz sine tone that was presented at 50 dB-A. Each listener adjusted each frequency once, and the final equal-loudness levels used for the verticalization experiment were the average responses over the five listeners.

D. Procedure

NH listeners used the same testing interface as the CI listeners in experiment 1. The order of testing was randomized, identical to the testing format of the CI Listeners. NH

FIG. 7. (Color online) The results of experiments 2–5 with the NH listeners. (a) The average verticalization is shown for sine tones as a function of frequency for presentation to the left ear (triangles), right ear (squares), and both ears (circles). (b) The average verticalization response is shown as a function of frequency comparing tones and acoustic PTs. The CI listeners' 300-pps average verticalization responses are superimposed on the NH data in this panel for comparison. (c) Verticalization is shown for varied PT BW. (d) Verticalization is shown for varied overall level. Symbols represent the average response. Error bars show ± 1 standard deviation across listeners.

listeners completed 20 repetitions of each condition for a total of 360 trials per block (20 repetitions $\times$ 18 frequencies). A block in which the tones were presented diotically was performed first, followed by a block in just the left ear, followed by a block in just the right ear, resulting in $360 \times 3 = 1080$ total trials in the experiment.

Prior to the test, listeners were asked to listen to a 10-s tone rising logarithmically in frequency from 0.125 to 16 kHz. The purpose of this was to acclimate the listeners in perceiving internalized elevation or verticalization.

E. Results and discussion

The average results of the experiment are shown in Fig. 7(a) as a function of frequency. The average verticalization data were analyzed with a two-way repeated-measures ANOVA with factors of presentation ear (left, right, and both) and frequency (18 levels).

Greenhouse–Geisser correction was used for the frequency factor and the ear $\times$ frequency interaction because the assumption of sphericity was violated. Verticalization increased with increasing frequency [$F(1.31, 9.18) = 22.7$, $p = 0.001$, $\eta^2_p = 0.76$]. Helmert contrasts showed significant differences ($p < 0.05$) between 0.125–8 kHz and all higher frequencies (i.e., there was no significant change in verticalization for 9–15 kHz). There was an effect of condition [$F(2, 14) = 4.99$, $p = 0.023$, $\eta^2_p = 0.42$]. Specifically, using two-sample Bonferroni-corrected t -tests, the responses for the right ear were higher than the left ear ($p = 0.003$) and the responses for both ears was higher than the left ear and the right ear ($p < 0.0001$ for both).

Higher frequencies were perceived with higher verticalization, which saturates around 8 kHz; this is a result that is broadly consistent with the responses of the CI listeners in experiment 1 and with the results of previous reports using sine tones or narrowband noises (Roffler and Butler, 1968a,b; Middlebrooks, 1992). Middlebrooks (1992) described narrowband sounds as “unnatural,” yet still a useful tool to investigate the cues related to vertical-plane localization and elevation of the auditory image. Furthermore the systematic relationship of increasing elevation with increase in frequency is similar to the results of Blauert (1997, pp. 107–113), at least for 4–8 kHz. However, the results of the present experiment are not consistent with the results of Blauert (1997, pp. 107–113), who showed that frequencies above 8 kHz were heard from behind. Perhaps a reason for the discrepancy is that our interface did not allow for front and behind responses, and future work could include such response possibilities.

IV. EXPERIMENT 3: VERTICALIZATION AS A FUNCTION OF STIMULUS TYPE IN NH LISTENERS

Because the general trends of the CI listeners' responses were replicated using sine tones in NH listeners, this experiment was designed to improve upon the acoustic simulations for a better comparison between the CI and NH listeners. Monopolar electrical stimulation of the cochlea has a large BW as a result from the current spread (Nelson *et al.*, 2008). Therefore we compared the verticalization of sine tones and acoustic PTs with a relatively large BW in NH listeners.

A. Stimuli

Sine tones and PTs were generated for this experiment. They were all generated with a 100-kHz sampling rate before resampling to 97.65625 kHz. The stimuli had a

500-ms duration and the tones had 10-ms rise-fall times, similar to the stimuli in experiment 2. They had center frequencies of 0.125, 0.5, 3, 6, 9, 12, and 15 kHz.

The acoustic PTs used to simulate electrical PTs were tonal carriers modulated by a train of Gaussian envelopes (Goupell *et al.*, 2010; Goupell *et al.*, 2013b). The spatial BWs for the GET PTs were determined by using Greenwood's cochlear place-to-frequency mapping function (Greenwood, 1990); spatial BWs were calculated 0.75-mm above and below the CF resulting in a 1.5-mm BW.

Our criterion for a fully modulated PT was greater than 99%. In these stimuli, the BW is inversely proportional to the equivalent rectangular duration (ERD) of the pulses and envelope modulation depth decreases with the increased overlap of successive pulses caused by increased pulse rate and increased ERD. The pulse rate in these simulations was either a constant 300 pps or randomly roved across trials from 150 to 300 pps in increments of 10 pps. Only the lower pulse rate of 300 pps was used in the NH simulation because 1000-pps PTs in general could not provide a sufficient modulation depth. Thus to prevent overlapping pulses at 300 pps and maintain a 99% modulation depth, the largest ERD of an individual pulse that could be used for these stimuli was estimated to be 3.75 ms. However, a compromise was necessary in our CI simulation because we could not keep the spatial BW constant at all CFs if we required a sufficient modulation depth. For frequencies of 0.125 and 0.5 kHz, the PTs had BWs of 260 Hz (chosen to be slightly smaller than $1/\text{ERD} = 1/3.75 \text{ ms} = 266 \text{ Hz}$). Frequencies from 3 to 15 kHz had a 1.5-mm spatial BW according to the Greenwood equation in an effort to simulate monopolar current spread (Goupell *et al.*, 2013b; Kan *et al.*, 2013). In summary, the PTs were designed to guarantee 99% modulation depth, which was achieved by using 1.5-mm BW PTs for CFs at and above 3 kHz, and by using 260-Hz BW PTs for CFs below 3 kHz.

Sine tones were presented with the same equal-loudness levels as in experiment 2. The PTs had the same peak spectral amplitude as a 1-kHz PT presented at 50 dB-A. Given that the BW increased with increasing CF, the use of peak spectral amplitude normalization generally created a comfortable loudness at all frequencies, but there was no formal loudness balancing between frequencies as was used for the sine tones. Also there was no loudness compensation for the PTs presented at a rate lower than 300 pps in the random-rate conditions, similar to the stimulus presentation in experiment 1 for the CI listeners.

B. Method

The NH listeners were the same as in experiment 2. All stimuli were presented diotically. The three stimulus types (sine tones, constant-rate PTs, random-rate PTs) were presented in a randomized order in a method of constant stimuli. There were 20 repetitions for each condition, yielding 420 total trials for this experiment (3 stimulus types $\times$ 7 frequencies $\times$ 20 repetitions = 420 trials).

C. Results and discussion

The results of experiment 3 are shown in Fig. 7(b). Using a two-way repeated-measures ANOVA (Greenhouse–Geisser

correction was used for the frequency factor and the frequency $\times$ type interaction because the assumption of sphericity was violated), there was an effect of frequency [$F(1.47, 10.3) = 18.3$, $p = 0.001$, $\eta_p^2 = 0.72$] and stimulus type [$F(2, 14) = 9.78$, $p = 0.002$, $\eta_p^2 = 0.58$]. The sine tones had higher verticalization responses compared to the constant-rate and random-rate PTs (two-sample Bonferroni-corrected t-tests: $p = 0.0003$ and $p < 0.0001$, respectively). The constant-rate PTs had higher verticalization responses than the random-rate PTs ($p = 0.003$). The interaction frequency $\times$ stimulus type was also significant [$F(2.31, 16.2) = 9.75$, $p = 0.009$, $\eta_p^2 = 0.46$].

The CI data from experiment 1 for the 300-pps conditions (both constant and random rate) are replotted on Fig. 7(b). The frequencies for the CI data assume that the most apical electrode is at a 1-kHz place (Gstoettner *et al.*, 1999) with 0.75-mm spacing between electrodes as found in the CI arrays that were used in experiment 1 (Greenwood, 1990). In Fig. 7(b), there is some correspondence in the shapes of the NH listener PT verticalization responses and the CI responses, particularly the slight decrease in verticalization at higher frequencies. Several of the CI data points correspond to the random-rate PT data for the NH listeners. Note that there was a significant difference between the verticalization produced for the constant- and random-rate conditions for the NH listeners in this experiment although the effect size was small. There was no difference for the CI listeners in experiment 1. The random-rate stimuli that produced the slightly smaller verticalization in the NH listeners could be an effect of the level of the stimuli in which the lower pulse rates had less energy and thus produced less verticalization (Vliegen and Van Opstal, 2004). This idea was further investigated in experiment 5.

In summary, the acoustic PTs produced lower verticalization responses in NH listeners than the sine tones. Furthermore, the PTs showed a relatively good correspondence between the CI and NH listeners, suggesting they provided a better simulation of CI responses as compared to the sine tones.

V. EXPERIMENT 4: VERTICALIZATION AS A FUNCTION OF BW IN NH LISTENERS

Experiment 3 found lower verticalization responses of the acoustic PTs (i.e., large BW) compared to sine tones (i.e., narrow BW). Therefore the stimulus BW of the PTs may also affect verticalization. In this experiment, the BW of PT stimuli was varied to evaluate the effect of BW on the verticalization responses.

A. Method

The method of this experiment was similar to experiment 3. All PTs were peak spectral amplitude normalized. These were the same PTs as before except that the BW was varied from 0.75, 1.5, and 3 mm for all CFs > 0.5 kHz. At the 0.75-mm BW, 0.125- and 0.5-kHz CFs were assigned nominal BWs of 28 and 66.9 Hz, respectively. At the 1.5-mm BW, the 0.125- and 0.5-kHz CFs were assigned 260 Hz to be consistent with experiment 3. At the 3-mm BW, the 0.125- and 0.5-kHz CFs were assigned nominal BWs of 112.9 and 269.5 Hz, respectively.¹ All BWs were calculated using Greenwood's equation (1990). Rate roving was

omitted from this experiment. Listeners completed the task in an identical manner to previous experiments.

B. Results

The results of this experiment are shown in Fig. 7(c). Using a two-way repeated-measures ANOVA (Greenhouse-Geisser correction was used for the frequency factor and the frequency $\times$ BW interaction because the assumption of sphericity was violated), there was an effect of frequency [$F(1.73,12.1) = 10.9$, $p = 0.003$, $\eta^2_p = 0.50$] but no effect of BW [$F(2,14) = 0.28$, $p = 0.76$, $\eta^2_p = 0.04$]. Because there was no effect of BW for the PTs, we presume that the relatively small changes in BW that would occur between the 300- and 1000-pps rates for the CI listeners would not affect verticalization. More drastic changes in BW (e.g., the difference between a sine tone and a PT with a BW on the order of mm) would be necessary to observe a difference in verticalization.

VI. EXPERIMENT 5: VERTICALIZATION AS A FUNCTION OF STIMULUS LEVEL IN NH LISTENERS

Overall level can affect elevation perception in NH listeners (Vliegen and Van Opstal, 2004). This may have had some effect on verticalization responses in the random-rate conditions. This is because PTs presented at a rate lower than 300 pps would have less overall energy.

A. Method

The method was the same as experiment 4. The stimuli were 1.5-mm BW constant-rate PTs and level was varied between 35, 45, and 50 dB-A.

B. Results and discussion

The results of the experiment are shown in Fig. 7(d). Using a two-way repeated-measures ANOVA (Greenhouse-Geisser correction was used for factors and interaction because the assumption of sphericity was violated), there was a significant effect of frequency [$F(1.48,10.4) = 4.46$, $p = 0.049$, $\eta^2_p = 0.39$] and a significant effect of level [$F(1.22,8.54) = 10.8$, $p = 0.008$, $\eta^2_p = 0.61$] in which higher levels produced higher verticalization responses. Therefore the effect of level in NH listeners could possibly explain the higher verticalization responses observed in the CI listeners at 300 compared to 1000 pps, as well as the effect of roving for the CI listeners. The significant effect of level is consistent with Vliegen and Van Opstal (2004) in which increasing elevation gain (i.e., a measure of the stimulus-response elevation relationship) for an increasing sound level up to about 58 dB-A. However, they used wideband stimuli and explained the change in elevation gain in terms of the encoding of the spectral profile. Because the spectral profile that we used was very simple, it is difficult to imagine substantive changes as a function of level.

VII. GENERAL DISCUSSION

A. Summary

CI listeners using clinical processors and processing strategies (i.e., multi-electrode stimulation) cannot localize

in the vertical dimension (Majdak *et al.*, 2011). The purpose of this study was to determine if CI listeners can perceive changes in elevation of an auditory image using simple bandlimited stimuli that were absent of typical vertical-plane spectral cues induced by the pinna, head, and torso because it is possible that the auditory system interprets bandlimited stimuli as a single peak surrounded by notches; this then provides the sensation of elevation (Middlebrooks, 1992). The results of the experiments showed that the auditory image was perceived as higher in elevation for more basal stimulation. This was done in CI and NH listeners using direct stimulation or ear-insert headphones, respectively. The perceived location of these stimuli were within the head, therefore we will not discuss the extracranial elevation perception but the intracranial “verticalization” perception of the stimuli, similar to the distinction between extracranial localization and intracranial lateralization of sound sources in the horizontal plane.

The results of the experiment 2 showed that 13 of 15 CI listeners demonstrated significantly higher verticalization for more basal stimulation (see Figs. 2–5). This result is in contrast to Majdak *et al.* (2011), who showed CI listeners using BTE clinical processors were unable to localize in the vertical plane, which was likely a result of the CIs sufficiently transmitting detailed spectral information to the auditory nerve. This suggests that CI listeners might be able to perceive changes in elevation or verticalization, so long as they are not required to utilize degraded multi-electrode spectral profiles to perform the task.

NH listeners performed the same verticalization task as the CI listeners and were presented sine tones and acoustic PTs, the latter designed to be simulations of electrical stimulation. All eight NH listeners showed a distinct systematic change in verticalization with increasing frequency. In both CI and NH listeners, small changes in stimuli [e.g., compare data for CI listeners presented 300- and 1000-pps PTs in Fig. 5 or NH listeners in Figs. 7(b) and 7(d)] affected verticalization a small but significant amount, which may ultimately be rooted in spectral and level changes, but the covarying nature of the cues restrict any strong conclusions. The largest difference in the verticalization responses occurred by substantially changing the spectrum from a sine tone to a 1.5-mm BW pulse train in the NH listeners [Fig. 7(b)] and by presenting stimuli to both ears instead of just one of the ears [Figs. 2 and 3, and 7(a)]. The latter effect has at least two possible explanations. First, the head was visualized as a circle on the response interface. In the diotic condition, the listener has a larger possible response range than on the side of the head. Alternatively, a monaural stimulus is perceived as at or near the stimulated ear and therefore cannot be perceived as verticalized above or below the ear; individual head-related-transfer-function-filtered stimuli presented monaurally are not perceived as elevated (Wightman and Kistler, 1997).

Both the NH and CI listeners’ responses showed right ear responses were significantly higher than left ear responses. It is unclear if this difference between left and right ear verticalization would remain significant in larger groups of NH and CI listeners.

B. Role of development of an auditory spatial map

CI listeners are an inherently inhomogeneous population, which is a result of factors such as hearing history, surgery, type of device, etc. (Lazard *et al.*, 2012; Blamey *et al.*, 2013). Therefore inhomogeneous psychophysical responses were expected and seen in these data. In addition, monaural spectral cues are highly individualized in NH listeners because of the differences in the pinna size and shape across listeners, which affect psychophysical responses (Middlebrooks, 1992; Otte *et al.*, 2013). Middlebrooks (1992, see Figs. 8–10) showed that NH listeners localized 1/6th-octave narrowband noises in the vertical direction with a peak in the individual's directional transfer function at the CF of the narrowband noise. Therefore some of the variability in the data from the late onset-of-deafness CI listeners might be explained by the fact that the listeners were comparing the single-electrode stimulation to a previously developed “library of directional transfer functions” (Middlebrooks, 1992). However, it is much more difficult to reconcile this explanation with the data of the early onset-of-deafness CI listeners, who likely had little to no experience processing broadband sounds and localizing in the vertical plane with frequencies above 4 kHz.

The elevation percept is thought to be developed over time as the brain learns to encode characteristic spectral cues neurally. For example over the lifespan, a listener must adapt to the spectral filtering changes that are related to the age of the subject, the change in size and shape of the pinna, and onset of hearing loss (Otte *et al.*, 2013). Furthermore, the finding that listeners can learn new localization maps and spectral cues argues that the library of directional transfer functions is learned through experience (Hofman *et al.*, 1998). Animal studies show that spectral cues are extremely important in the development of auditory spatial representation in mammals. Some studies show that small changes in spectral cues in a relatively normal auditory spatial map can be compensated for, and this is consistent with changes in a visual spatial map (Knudsen *et al.*, 1994). However, this is not necessarily the case for severe changes (Knudsen, 1985; Schnupp *et al.*, 1998). In the present study, all four of the early onset CI listeners demonstrated significant verticalization. It is unclear how the topographic representation of space would form with minimal to no acoustic experience as was experienced by our early onset CI listeners. In other words, how did the early onset CI listeners acquire their library of directional transfer functions? It could be that the brain has *a priori* knowledge of the pinna size and shape, making the library of directional transfer functions intact at birth. A variation of this idea is that a person could be born with an inherent association between frequency and elevation (an approximation for the pinna cues that will develop), and that the brain uses this simple inherent framework to bootstrap and develop a more sophisticated and refined library of directional transfer functions that is associated with a person's spatial map.

Alternatively, the early onset CI listeners may have developed an association between the impoverished spectral profile from electrical stimulation and elevation. Majdak

et al. (2011) tested five late onset bilateral CI users but no early onset CI users. It could be that while the late onset CI listeners could not adapt to the severe degradation of the spectral cues in multi-electrode stimulation, the early onset CI listeners may have become sensitive to them over time. Parise *et al.* (2014) has suggested the statistics of natural auditory scenes produce the association between higher pitches and higher elevations. If this is the case, then this would suggest that our early onset CI listeners learned this association in the presence of severe spectral degradation.

Another alternative is that the early onset CI listeners had some acoustic experience that helped them develop the association between place and elevation before more profound deafness had occurred. At the time that many of our early onset CI listeners were born, hearing screenings were not yet mandated, and therefore audiometric evaluations at birth were not available for our listeners. What is clear is that future experiments are necessary to conclusively demonstrate whether the association between elevation and place of stimulation is innate or developed. Of primary focus should be increasing the number of early onset-of-deafness CI listeners with well-known hearing histories and hearing thresholds and testing them in controlled single-electrode direct-stimulation experiments, as demonstrated in this study, and in free-field localization studies. Certainly, early onset adult CI users are relatively rare, and a better population to target may be children with CIs who were born deaf. Today there are universal hearing screenings and hearing thresholds would be available for children with CIs. Furthermore there are many children who now receive CIs very early in life; this would almost guarantee minimal typical acoustic exposure.

VIII. CONCLUSIONS

We tested percepts varying in elevation, based on stimulus frequency, in CI and NH listeners using bandlimited stimuli. Because the stimuli were perceived intracranially, we have called this verticalization, analogous to lateralization. Our data show that CI and NH listeners can perceive increased verticalization for more basal stimulation. Therefore the inability to localize broadband stimuli in the vertical plane using CIs is a result of the poor spectral cue encoding. Future advances in providing elevation perception to CI listeners should focus on the representation of the spectral profile presented to the auditory nerve.

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¹Note that many of the PTs $\leq$ 500-Hz CF did not achieve 99% modulation depth. Therefore they had a smaller BW than the intended BW. Given this confound, we included the PTs $\leq$ 500-Hz CF in the analysis but have regarded them with caution. Because there was no effect of BW in this experiment, these confounds seemed of relatively small importance.

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