Sound Frequency Discrimination in Normal-Hearing Listeners and Cochlear Implantees

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Abstract

The aims of this study were to compare the ability of normal listeners and cochlear implant users to discriminate between sounds of different frequencies and to investigate how sound frequency discrimination changes in relation to the frequency of the reference tone in both groups. Ten volunteers with normal hearing and six cochlear implantees using the Nucleus 22 (spectral peak) SPEAK encoding strategy were studied using a three-interval forced-choice paradigm. Three pure tones, 560 Hz, 2041 Hz and 5754 Hz, served as the reference stimuli. These corresponded to frequency bands allocated to electrodes 18, 11 and 4, respectively, in the cochlear implantees. All stimuli were presented in the sound field. Although cochlear implant users did not discriminate frequency as well as normally hearing individuals, they performed significantly better than expected by frequency-to-electrode allocation tables for the low frequency reference tone. The mean frequency difference limens (DL) increased significantly with increasing frequency of the reference tone in normal listeners ($p<0.0005$). Although this trend was also evident in cochlear implant users, it was not significant. Analysis of implanted electrode response patterns demonstrated that pure tones delivered in the sound field elicited responses from more than one electrode. Thus, implant users likely receive spectral cues along the electrode array regarding differences between pure tones even when both tones are allocated to one electrode.

Introduction

For people with severe to profound sensorineural hearing loss, at least some sound frequencies are inaudible with high gain amplification hearing aids. In some cases, a cochlear implant enables perception of a wider range of frequencies by delivering electrical pulses that directly stimulate the auditory nerve.

The ability to discriminate sound frequency information is essential for communication and music appreciation. The ability to discriminate sound frequency is necessary for perceiving prosody (intonation) in languages such as English[1] and is a cue to distinct lexical items in tone languages such as Chinese.[2] Thus, if a person is not able to encode sound frequency information, he or she will be a less effective communicator. Sound frequency discrimination is also the basis for understanding the relationship between pitches in musical patterns.[3,4] Despite its importance to speech and music perception, sound frequency discrimination has received little empirical attention in the cochlear implantee population.

Studies on speech perception in cochlear implant users have demonstrated a relationship between speech perception outcome measures and the ability to discriminate sound frequency.[5,6] Perception of a vocal effect has also been described, whereby cochlear implant users were able to discriminate numbers and sentences spoken by the same person in different tones of voice.[7] The ability of cochlear implant users to discriminate contrastive tones, vowels, and consonants in tone languages has also been shown to be related to speech perception.[8] While these studies provide information about the gross ability of cochlear implant users to discriminate sound frequency, they do not provide information regarding the resolving power of the auditory system.

At present, the ability of cochlear implant users to perceive and understand music has not been well characterized. Pijl proposed that temporal information is sufficient for the perception of musical pitch, and suggested that current cochlear implant encoding strategies for speech which tend to emphasize cochleotopic place cues, such as the SPEAK encoding program, do not necessarily provide information regarding melodic pitch interval size.[9] However, McDermott and McKay investigated music perception in one implanted adult, and reported that while rate could convey musical pitch information over a limited range, when both place and rate varied together, the place-related pitch was generally dominant.[10] Fujita and Ito presented tones played on a keyboard in the free field and found that some adult cochlear implant users can distinguish tones that are four semitones apart.[11] However, other adults could not differentiate tones that were 12 semitones (an octave) apart.

A psychophysical approach to sound frequency discrimination has been used by Busby and Clark, who delivered biphasic current pulses to early-deafened adult subjects directly through a Cochlear Limited prosthesis to three positions on the electrode array.[12] Average difference limens were less than two electrodes for 75% of subjects, with average limens between 2 and 6.5 electrodes for the remaining 25% of subjects. Subjects implanted at a later age and with longer durations of deafness prior to implantation had larger limens. However, stimuli were not presented free field, thus limiting the generalizability of results to everyday listening conditions.

Even though sound in the normal ear produces a temporo-spatial pattern of action potentials on the order of 30 000 auditory neurons,[13] the Nucleus 22 Cochlear Implant System presently consists of only 20 active stimulating electrodes implanted in the cochlea. This represents an extremely limited number of available frequency channels compared with normally hearing individuals. Sound frequencies, typically between 100 and 10000 Hz, are divided into bandwidths. Each bandwidth is allocated to specific electrodes in an organized manner based on cochleotopic principles (i.e. low frequencies at the apical end of the array and high frequencies at the basal end). Frequency-to-electrode allocation parameters are shown in Table 1.

Table 1
Default Frequency-To-Electrode Allocation Table

Electrode	Frequency (Hz)	
	Lower	Upper
20	150	350
19	350	550
18	550	750
17	750	950
16	950	1150
15	1150	1350
14	1350	1550
13	1550	1768
12	1768	2031
11	2031	2333
10	2333	2680
9	2680	3079
8	3079	3571
7	3571	4184
6	4184	4903
5	4903	5744
4	5744	6730
3	6730	7885
2	7885	9238
1	9238	10823

In theory, a pure tone should only stimulate the electrode to which it is assigned, and cochlear implant users should not be able to discriminate between two sound frequencies that are allocated to the same electrode. If true, this may have negative implications for how well a cochlear implant user can hear subtle pitch changes.

The first objective of this study was to quantify and compare the ability of normal listeners and cochlear implant users to discriminate sound frequency. Our second objective was to investigate how sound frequency discrimination changes in relation to the frequency of the reference tone. We hypothesized that sound frequency discrimination would be impaired in cochlear implant users as compared with normally hearing individuals as a result of a more limited number of frequency channels, nerve degeneration, and absence of phase locking and selective inhibition. We also hypothesized that discrimination based on this type of frequency allocation table is likely to be poorer in the high frequencies due to wider bandwidth allocations in the high versus low frequencies. Sound frequency discrimination was quantified as a frequency difference limen (DL), i.e., the minimum perceptible change in frequency, and was measured using a psychophysical three-interval forced choice paradigm at three different frequencies. Free-field presentation was used to closely approximate everyday listening conditions.

Methods

1. Subjects

Normally Hearing Participants
Subjects were 10 adults (4 male, 6 female) 21-33 years of age (mean = 25.0 years). All reported normal hearing and were free of colds at the time of testing.

Cochlear Implant Recipients
Subjects were 4 children (1 male, 3 female) with congenital severe to profound hearing loss 12-13 years of age (mean = 12.5 years), and 2 adults (1 male, 1 female) with postlinguistic onset of severe to profound sensorineural hearing loss at 42 and 58 years of age. Duration of total severe to profound deafness for the children (which equals age at implantation) ranged from 3.22-11.02 (mean=6.50) years. They had 2.83-9.00 (mean=6.48) years of experience with their cochlear implant at the time of the experiment. Duration of severe to profound deafness for the adults ranged from 2-26 (mean=14.00) years and subjects had 5.58-7.33 (mean=6.46) years of experience with their cochlear implant. All 6 implantees used a Nucleus 22 cochlear implant, with the SPECTRA-22 sound processor programmed with the SPEAK coding strategy MAPped in BP+1. All 20 electrodes were active with the exception of one child (Implant child 4), who had 18 active electrodes. Subjects used their own cochlear implants with speech processor settings that they used normally.

Details about the subjects are provided in Table 2. All but one child (Implant child 1) achieved a score of 65% or better on the Phonetically Balanced Kindergarten (PBK) word test, which requires an open-set response.[14] Thus, at least 3 of the 4 children were considered to be very good implant users and the other child a fairly good user (PBK=25%). All adults were considered to be successful implant users based on scores of 65% of greater on the open-set Central Institute for the Deaf (CID) test.

2. Apparatus

All subjects were tested individually inside a single-walled IAC sound isolated booth. Subjects were seated 1.25 meters from a sin-

Table 2
Subject Characteristics

Subject	Sex	Age	Ear Implanted	Cause of Hearing Loss	Duration of Deafness (years)	Duration of Prosthesis Use (years)	Strategy	Most Recent Speech Perception Score
Implant Users								
Implant child 1	M	13	R	Congenital (unknown)	11.02	2.83	SPEAK	PBK=words 24% Phonemes 56%
Implant child 2	F	12	R	Congenital (unknown)	7.47	5.08	SPEAK	PBK = words 72% Phonemes 79%
Implant child 3	F	13	R	Congenital (unknown)	4.27	9.00	SPEAK	PBK = words 84% Phonemes 94%
Implant child 4	F	12	R	Congenital (unknown)	3.22	9.00	SPEAK	PBK = words 68% Phonemes 76%
Implant adult 1	M	42	R	Ototoxicity (sudden)	2.00	7.33	SPEAK	CID=98%
Implant adult 2	F	58	R	Rubella (gradual)	26.0	5.58	SPEAK	CID=86%
Normally-hearing								
Normal 1	M	24						
Normal 2	M	23						
Normal 3	F	22						
Normal 4	F	21						
Normal 5	F	24						
Normal 6	M	23						
Normal 7	F	31						
Normal 8	F	23						
Normal 9	M	26						
Normal 10	F	33						

gle JBL Studio Monitor 4406 loudspeaker positioned at eye-level. They responded by means of a response box consisting of 3 buttons with one light above each button. On each trial, the lights were activated in series, accompanying the presentation of a series of three tones. The pure tones, which were generated by a Tucker Davis Technologies (TDT) System II using Siggen software, were presented using the program Psychosig by TDT, and responses were collected using the same program.

3. Stimuli

All tones were continuous sine waves of 300ms duration with 50ms rise and decay times. The average intensity level was 75 dB(A) at the listener's head. The interstimulus interval was 500ms. The three reference tone frequencies were 560Hz, 2041 Hz, and 5754 Hz corresponding to bandwidth frequencies allocated to electrodes 18 (apical), 11 (middle) and 4 (basal), respectively, in the cochlear implant users.

4. Procedure

A three-alternative, forced-choice paradigm was used to measure sound frequency difference limens. A trial consisted of three tones presented in sequence: two of the three tones were the same frequency and one was different. Subjects were asked to identify the tone that sounded different using the response box. Subjects received three practice trials with feedback and all could perform the required task prior to beginning the experiment. Subjects did not receive feedback during the experiment. For subjects scoring greater than or equal to 70.7% correct on 30 trials, the difference between the reference tones and the comparison tone was reduced by half. For subjects who scored less than 70.7% correct on 30 trials, this difference was doubled. Psychometric functions were generated based on percentage scores for all comparison tone frequencies, and the frequency at which a listener could tell the tones apart 70.7% of the time was determined.[15]

Analysis of Cochlear Implant Electrode Stimulation

The implant electrode stimulation evoked by the pure tones with a Spectra[22] processor programmed with a typical BP+1 MAP and a HS4 headset was analyzed using SCILab Version 1.4b developed by The Swiss Cochlear Implant Laboratory. All tones were presented free-field and interfaced with the analysis program through the Dual Processor Interface.

Data Analysis

T-tests were used to test differences between sound frequency discrimination abilities in subjects with normal hearing and those with implants. One-way repeated measures ANOVA and post-hoc comparisons using Student Neuman Keuls Method at $p<0.05$ were performed within both groups to test effects of reference tone frequency on frequency discrimination. Mann-Whitney Rank Sum Tests were used to test whether implant subjects could perform sound frequency discrimination differently than expected based on the frequency allocation table.[9]

Results

1. Effect of group on frequency discrimination

Mean frequency difference limens (DL) are plotted in Figure 1. In general, cochlear implant users did not discriminate sound frequencies as well as normally hearing individuals on low-frequency ($p<0.005$), mid-frequency ($p<0.01$), and high frequency ($p<0.05$) reference tones. They did, however, perform significantly better for the low frequency reference tone than would be expected by frequency-to-electrode allocation tables ($p<0.005$). Since ranges of tones are assigned to each electrode, cochlear implant users should only be able to discriminate a reference tone and a comparison tone presented to the lowest bound of an adjacent electrode. Table 3 shows electrode boundaries and reference tone frequencies. Expected difference limens were 190 [750 (upper bound) - 560 (reference tone)], 292 (2333 – 2041), and 976 (6730 – 5754) for low, mid and high frequency reference tones respectively. All six implanted individuals were able to discriminate two tones lying within a bandwidth allocated to one electrode at the apical end of the electrode ($p<0.005$). Four were able to do this for two tones in a mid frequency bandwidth allocated to an electrode in the middle of the implanted array and also for two high frequency tones allocated to the same electrode located at the basal end. However, as a group, the implant users did not perform differently than expected for the mid frequency reference tone ($p>0.05$) or the high frequency reference tone ($p>0.05$).

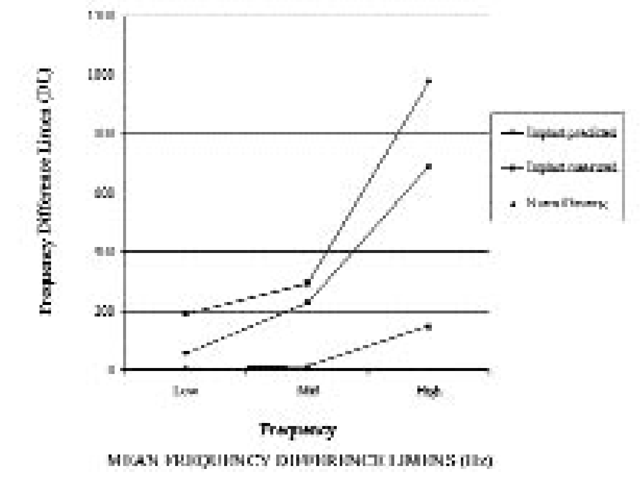

Figure 1. Cochlear implant users did not perform as well as normally hearing individuals. However, they did perform better than predicted by frequency-to-electrode allocation tables. Mean frequency difference limens (df) increased with increasing frequency of probe tone.

2. Effect of reference tone frequency on frequency discrimination

For normal listeners, mean frequency difference limens increased significantly with increasing frequency of the reference tone ($p<.0005$). Post-hoc pairwise comparisons testing revealed that there were significant differences in performance between high and mid as well as high and low reference tone frequencies ($p<0.05$). However, the difference between low and mid probe tone frequencies was not significant ($p>0.05$). Although this trend was also evident in cochlear implant users, it was not significant ($p>0.05$). Individual frequency difference limens for cochlear implant users (Table 4) are plotted in Figure 2. Interestingly, neither of the adult cochlear implant users exhibited a difference in frequency discrimination between the low, mid, and high reference tone tasks.

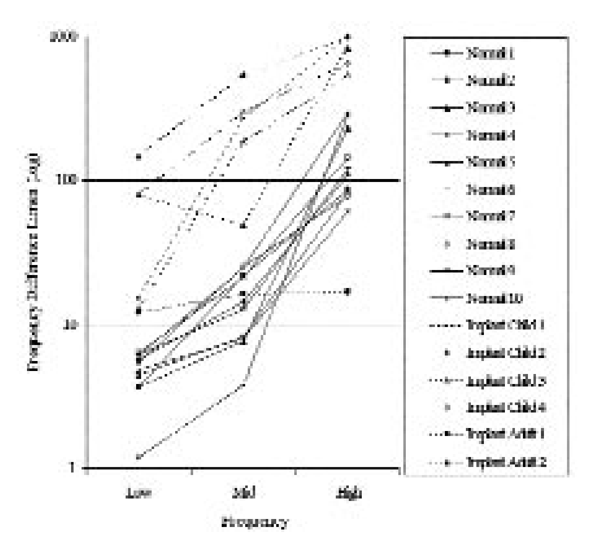

Figure 2. Individual frequency difference limens (df) increased with increasing frequency of probe tone. Neither of the adult cochlear implant users exhibited this trend.

3. Electrode Stimulation pattern evoked by pure tones in sound field

The number of stimulations provided per electrode for each of the three pure reference tone frequencies is plotted in Figure 3. The large number of stimulations for electrode 20 are considered artifact from the low frequency hum of the computer. It is interesting to note that for each pure tone, more than one electrode was stimulated. For example, even though a 560 Hz pure tone should in theory be encoded by electrode 18, it evoked stimulation in as many as ten electrodes ranging from electrode 20 to electrode 6. Similar results were observed at 2041Hz (mid-frequency reference) and 5754Hz (high frequency reference).

Electrode stimulation was also compared for pure tones that were discriminable from the reference tones at a rate of 70.7% by at least 3 of the 6 cochlear implant users in Figure 4. Reference tones yielded different patterns of electrode stimulation than comparison tones at low and mid frequencies. The high frequency reference tones yielded different numbers of stimulations than comparison tones.

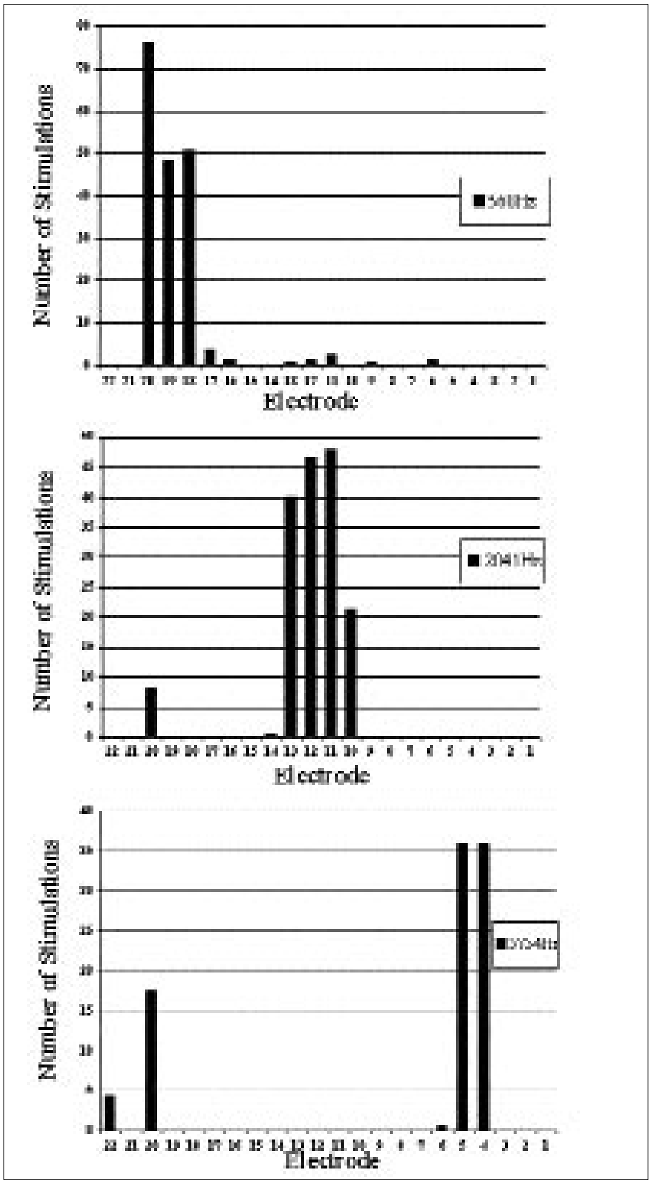

Figure 3. Electrode activation at 560 Hz, 2401 Hz, and 5754 Hz pure probe tone frequencies.

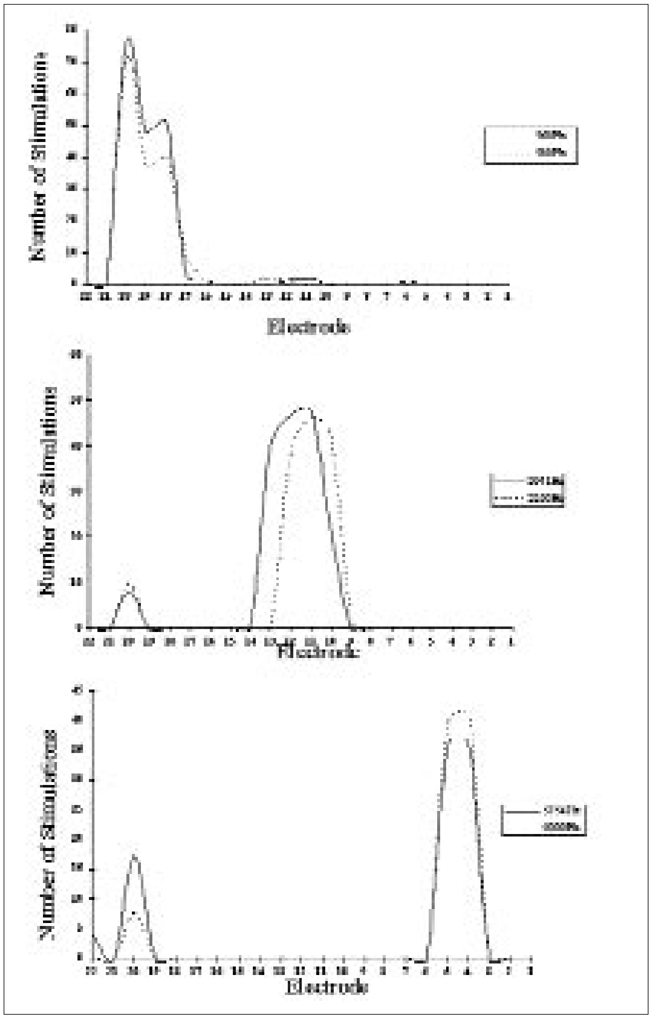

Figure 4. Comparison of electrode activation at 560 Hz and 580 Hz, 2041 Hz and 2250 Hz, and 5754 Hz and 6000 Hz pure tone frequencies.

Discussion

Frequency Discrimination in Implant Users vs. Subjects with Normal Hearing

We found that cochlear implant users in our study did not discriminate sound frequency as well as normally hearing individuals. In normally hearing individuals, varying displacement of the basilar membrane of the cochlea due to an increase in stiffness along the membrane from base to apex allows for the cochleotopic coding of frequencies. The auditory pathway preserves this orderly frequency scale. Cochlear implants, however, bypass the basilar membrane and electrically stimulate auditory nerve fibers directly. Thus, cochlear implant users must rely on computerized processing strategies to encode sound, which may be suboptimal. Furthermore, cochlear implants encode sound based primarily on place pattern and are limited by the number of channels available. These factors, combined with spiral ganglion cell degeneration resulting from auditory deprivation[16] and the possibility of electrode insertion trauma[17] may explain the poorer performance by cochlear implant users in the present study.

Better Than Expected Frequency Discrimination in Implant Users

Cochlear implant users in our study performed better on tasks of sound frequency discrimination than shown by previous studies. For example, while the mean frequency difference limen for cochlear implant users at the 560 Hz reference tone was 58.146 Hz, frequency difference limens ranged from 12.2175 to 148.24 Hz. These results are better than those observed by Fujita and Ito who tested the abilities of adult cochlear implant users to discriminate musical intervals in the range 123-494 Hz by free-field stimulation, and found the best threshold of discrimination to be 4 semitones, with 3 of the 8 subjects not being able to differentiate 2 tones as much as 12 semitones (an octave) apart.[11] Within the range of frequencies tested by Fujita and Ito,[11] a frequency difference limen of 4 semitones can be anywhere from 30 to 100 Hz, and a frequency difference limen of 12 semitones can range from 130 to 247 Hz. The finding of smaller frequency difference limens in our study may be explained by the fact that all participants in the present study used the SPEAK processing strategy compared to only 1 of the 8 in the Fujita and Ito study (the others used MPEAK).[11] There is evidence to suggest that converting from MPEAK to SPEAK leads to significant improvements in speech perception and sentence recognition.[18]

We also found that cochlear implant users performed significantly better on tasks of sound frequency discrimination in the low frequencies than would be expected on the basis of frequency-to-electrode allocation tables. Because in the SPEAK encoding program there is no overlap between ranges of frequencies allocated to different electrodes, it may be hypothesized that a pure tone stimulates only the electrode to which it is assigned. However, we have shown that even though the 560 Hz pure tone was allocated to electrode 18 in our subjects, it activated as many as ten electrodes ranging from electrode 20 to electrode 6 in a typical device. This processing of pure tones helps explain how all six implanted individuals were able to discriminate two low frequency tones within a bandwidth allocated to one electrode and four were able to do this at the mid and high frequency reference "place pitch" encoding despite the fact that such a wide range of frequencies are assigned to such a small number of electrodes. Interestingly, Busby and Clark delivered biphasic current pulses directly through the Cochlear Limited prosthesis to three positions on the electrode array and found difference limens of less than one electrode in 6 of 16 subjects at apical (low), 5 of 16 at mid, and 3 of 16 at basal (high) frequency probe tones.[12]

Table 3
Frequency-To-Electrode Allocation and Reference Tone

Electrode	Lower bound	Probe tone	Upper bound (lower bound of adjacent electrode)
18 (low)	550	560	750
11 (mid)	2031	2041	2333
4 (high)	5744	5754	6730

Effect of Reference Tone

We found that mean sound frequency difference limens increased with increasing frequency of reference tones in normal-hearing individuals. This finding has been documented by Spetner and Olsho who examined frequency discrimination in normal-hearing 6-month-olds and adults.[19] In normal-hearing individuals, phase-locked excitation of the cochlear nerve that allows for temporal coding occurs only for low frequency stimuli (below approximately 1500 to 3000 Hz).[20,21] Since significant phase-locking does not occur at higher frequencies, information of such stimuli is limited to only place or excitation pattern.[22,23] Lack of temporal coding at higher frequencies may be one reason why poorer frequency discrimination occurs with increasing frequency of reference tones in individuals with normal hearing.

Table 4
Frequency Difference Limens (DL)

Subject	Low frequency	Mid frequency	High frequency
Normal 1	3.668	21.882	86.510
Normal 2	5.713	14.205	111.930
Normal 3	3.720	7.688	231.816
Normal 4	6.051	24.730	300.843
Normal 5	4.802	8.083	61.262
Normal 6	6.206	12.651	121.216
Normal 7	4.410	8.128	82.586
Normal 8	5.358	24.991	78.500
Normal 9	6.399	21.395	144.680
Normal 10	1.188	3.731	289.440
Implant Child 1	15.360	269.700	1082.000
Implant Child 2	148.240	546.050	1009.400
Implant Child 3	12.900	184.140	538.480
Implant Child 4	79.733	299.000	653.346
Implant Adult 1	12.218	16.241	16.816
Implant Adult 2	80.426	49.610	827.351

While there was a trend towards mean sound frequency difference limens increasing with increasing frequency of reference tones in cochlear implant users, the results were not significant. Better performance at low frequencies compared with high frequencies on tasks of discrimination has been described in studies using direct stimulation of implanted electrodes. Pijl and Schwarz found scores on musical interval matching tasks to be significantly higher at apical (low frequency) electrode locations compared to basal (high frequency) locations.[24] This was confirmed by McDermott and McKay who demonstrated that the closest similarity in pitch interval between implanted and normal-hearing individuals occurred at the more apically-located electrode 19.[10] This may be explained by frequency-to-electrode allocation for the spectral peak strategy (SPEAK), whereby frequency bands are linearly distributed in the low frequencies and logarithmically distributed thereafter.[1] Busby and Clark,[12] however, found mixed results, with some subjects demonstrating apical limens larger than mid or basal limens, and other subjects demonstrating basal limens larger than mid and apical. All of these studies, however, utilized direct stimulation of electrodes rather than free-field presentation of stimuli that were used in the present study.

Electrode Stimulation Pattern Evoked by Pure Tones in Sound Field

The number of stimulations per electrode for each of the three pure reference tone frequencies decreased with increasing frequency of reference tones. While the 560Hz pure tone stimulated as many as 10 electrodes, the 2041Hz and 5754 Hz pure tones stimulated only 6 and 5 electrodes respectively. Patterns of electrode stimulation for reference tones and for comparison tones that were just discernable from the reference tones were visibly different. Moreover, differences were more pronounced in the electrodes activated by low frequency tones than for those stimulated by high frequency tones. Therefore, stimulation with low frequency pure tones may provide extra place cues that theoretically may otherwise not be present by stimulation with higher frequency pure tones. This may account for the significantly better than expected performance in the low frequencies.

Clinically, pure tones presented in the sound field are used to measure sound frequency specific hearing acuity for individuals using implants. However, since we have demonstrated that a pure tone presented to a cochlear implant may activate as many as ten electrodes, this practice cannot provide an accurate assessment of specific locations along the electrode array. Thus, while cochlear implant users in our study were able to discriminate frequencies beyond the theoretical capabilities of their implants, they may have been using cues other than frequency. The wide variability in sound frequency difference limens obtained for subjects of similar backgrounds using similar processing strategies, suggests that additional factors other than those investigated may have affected frequency discrimination. With respect to music perception, however, the ability of cochlear implant users to discriminate sound frequencies better than otherwise predicted by frequency-to-electrode allocation tables suggests that cochlear implants can be used not only for hearing speech, but for hearing musical tones as well. Perhaps future processing strategies will be better able to highlight the important aspects of music, so that cochlear implant users will one day be able to switch their processor to “music mode” to assist them in appreciating music to its fullest.

Acknowledgements

The authors would like to thank Dr. Marianne Fallon for her insight during the review of this manuscript, and Jane Figueiredo for her assistance with the collection of data.

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– CORRECTION –

The UTMJ apologizes to
Alex Vesely, Hiroshi Sasano, George Volgyesi, Ron Somogyi, Janet Tesler, Ludwik Fedorko,
Jonathan Grynspan, Adrian Crawley, Joseph A. Fisher, and David Mikulis,
the authors of “Mapping of Cerebrovascular Reactivity Using Square Wave Changes in End-Tidal PCO2”,
published in Magnetic Resonance in Medicine volume 45, pages 1011-1013 (2001).
Figure 3 of said article was reproduced in the December 2001 issue of the UTMJ (Figure 1, page 20)
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