



## Research Paper

# Temporal and spectral contributions to musical instrument identification and discrimination among cochlear implant users

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Received 2 June 2016; received in revised form 16 August 2016; accepted 5 September 2016

**KEYWORDS**

Music;  
Timbre;  
Cochlear implant;  
Envelope;  
Fine-structure

**Abstract** *Objective:* To investigate the contributions of envelope and fine-structure to the perception of timbre by cochlear implant (CI) users as compared to normal hearing (NH) listeners.

*Methods:* This was a prospective cohort comparison study. Normal hearing and cochlear implant patients were tested. Three experiments were performed in sound field using musical notes altered to affect the characteristic pitch of an instrument and the acoustic envelope. Experiment 1 assessed the ability to identify the instrument playing each note, while experiments 2 and 3 assessed the ability to discriminate the different stimuli.

*Results:* Normal hearing subjects performed better than CI subjects in all instrument identification tasks, reaching statistical significance for 4 of 5 stimulus conditions. Within the CI population, acoustic envelope modifications did not significantly affect instrument identification or discrimination. With envelope and pitch cues removed, fine structure discrimination performance was similar between normal hearing and CI users for the majority of conditions, but some specific instrument comparisons were significantly more challenging for CI users.

*Conclusions:* Cochlear implant users perform significantly worse than normal hearing listeners on tasks of instrument identification. However, cochlear implant listeners can discriminate

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Peer review under responsibility of Chinese Medical Association.



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<http://dx.doi.org/10.1016/j.wjorl.2016.09.001>

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Please cite this article in press as: Prentiss SM, et al., Temporal and spectral contributions to musical instrument identification and discrimination among cochlear implant users, World Journal of Otorhinolaryngology-Head and Neck Surgery (2016), <http://dx.doi.org/10.1016/j.wjorl.2016.09.001>

differences in envelope and some fine structure components of musical instrument sounds as well as normal hearing listeners. The results indicated that certain fine structure cues are important for cochlear implant users to make discrimination judgments, and therefore may affect interpretation toward associating with a specific instrument for identification.

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## Introduction

Cochlear implant processors are predominantly designed to transmit cues relevant to speech. With current processor technology many users attain scores on speech recognition tests close to those of their normal hearing counterparts, particularly in quiet. However, despite advancements in processing technology, music perception and enjoyment remain challenging and, in many cases, the perceived quality of music degrades post-implantation from prior-to-deafness.<sup>1</sup> Music and speech share some acoustic similarities, but music appreciation involves perception of additional acoustic cues that may not be perceived accurately, or at all, by the cochlear implant user.

Fundamental elements of music include rhythm, melody and timbre. Rhythm is the regular recurrence of a stimulus over time. In music, it represents the temporal pattern, or the tempo, of a song and is often represented as beats per minute.<sup>2,3</sup> Rhythm is the element of music that is most accurately conveyed in cochlear implant processors,<sup>4</sup> to the extent that cochlear implant users can discriminate rhythmic patterns as well as normal hearing listeners.<sup>1,3,5–7</sup>

The ability to recognize rhythmic cues is important to recognizing melody; however, melody recognition also requires accurate pitch perception. The organization of varying pitches within a distinct rhythmic pattern creates melodies<sup>3,8</sup> and requires the listener to recognize the direction and magnitude of pitch changes.<sup>2</sup> Pitch perception and/or pitch pattern discrimination are challenging tasks for cochlear implant users<sup>2–5,9,10</sup> resulting in significantly poorer performance than normal hearing listeners on tests of melody recognition.<sup>3,5</sup>

The most complicated component underlying music perception is timbre. Timbre perception is the ability to distinguish two sounds of the same pitch, duration and loudness played by two different instruments.<sup>11</sup> Timbre is multidimensional and characterized by the envelope of the sound as well as the fine-structure of the frequency spectrum.<sup>1,3</sup> The physical structure of the instrument (e.g., big/small, straight/convoluted, brass/wood/string) and mode of playing (e.g., blowing/plucking/striking/bowing) define the envelope of the sound, as well as the spectral distribution of the harmonics and the relative relationship to the fundamental frequency.<sup>12,13</sup>

The envelope of a musical note can be described by the rise time (i.e., attack) and release time, as well as the sustained portion (i.e., duration);<sup>14</sup> the former two shaping the envelope and the latter representing the fine structure and harmonics (Fig. 1). Timbre perception requires the ability to detect subtle changes in the envelope and fine

structure. Cochlear implants emphasize the transmission of speech cues, which is heavily dependent on the envelope of sound,<sup>15</sup> thereby providing less emphasis on the fine structure cues pertinent to music perception. Studies of instrument identification have revealed that timbre perception marks the greatest distinction between normal hearing and hearing with cochlear implants. That is, while instrument identification is a very challenging task for cochlear implant users, it is uniquely an easy task for normal hearing listeners.<sup>16</sup> Cochlear implant users can correctly identify instruments playing notes approximately 45% of the time while normal hearing listeners usually identify above 90%.<sup>5,6,16</sup>

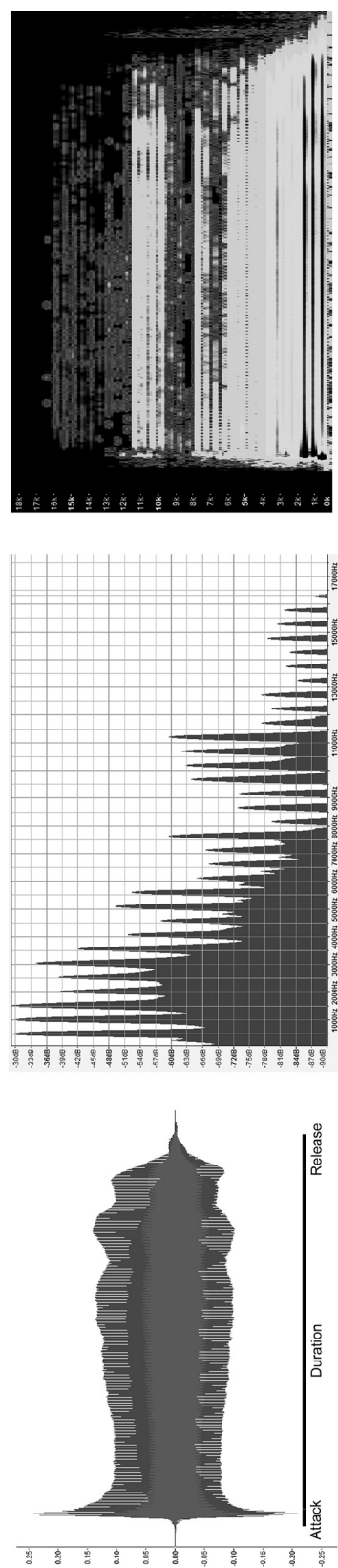
It remains unclear why timbre is not satisfactorily perceived by cochlear implant users, and whether the cause of this arises from: 1) poor processing by the external device; 2) poor transmission of processed information across the electrode-nerve interface; 3) poor perception (i.e., interpretation) by the acoustically-deprived central auditory system; or a combination of these. The purpose of this study was to investigate perception of timbre components by cochlear implant users as compared to normal hearing listeners. Specifically, this study investigated whether envelope and fine-structure cues important for instrument identification are perceived by cochlear implant users, and if so, whether the cues are perceived similar to normal hearing listeners.

## Materials and methods

Experiments were performed to interrogate different aspects of timbre perception. Experiment 1 investigated whether CI users can identify an instrument (i.e., different timbre cues) as well as subjects with normal hearing. Experiments 2 and 3 investigated whether the appropriate cues are heard by the CI user independent of whether they are correctly associated with a specific musical instrument. These experiments were designed to determine whether acoustic cues associated with timbre perception are interpreted by the auditory system, or are underrepresented by the implant itself, either through processing of the acoustic signal or an inability to transmit in high enough fidelity to the auditory nerve.<sup>17</sup>

### Experiment 1: instrument identification envelope cues

Ten adult cochlear implant users, ages 21–81 years (avg 58, SD 19), and 8 normal hearing controls, ages 30–63 years



**Fig. 1** Example of a single musical note. A: envelope of the note over time showing the attack, duration and release; B: frequency analysis showing the formants and harmonics composing the note; C: spectrogram showing the intensity of sound (brighter is higher intensity) at different frequencies (y-axis) over time (x-axis).

(avg 43, SD 11) participated in the first experiment (Table 1). Subjects identified five different instruments in five conditions based on a major scale. The five instruments tested represented brass, wind and string instruments and included: trumpet, alto-saxophone, clarinet, flute and violin. In the first condition, scales were presented in the instrument's natural, characteristic frequency range ("native condition"). For the second condition, each instrument scale was transposed to a G4 major scale to eliminate characteristic pitch cues, and is referred to as the "normalized" condition. Additional conditions were created to investigate the effects of envelope cues on instrument identification. The envelopes of each note within the scale were digitally modified in Adobe Audition 3.0 (San Jose, CA) in the following ways: 1) removing the attack and preserving the middle and release (AttRem); 2) removing the release and preserving the attack and middle (RelRem); or 3) removing both the attack and release leaving only the middle of the note (AttRelRem). Each note within the scale was played for 1 s in duration. Examples of the envelope modifications are shown in Fig. 2.

Scales were randomly presented at 65 dB SPL in each of the five conditions (native, normalized, attack removed, release removed and attack and release removed) via soundfield using the modified Musical Sounds in Cochlear Implants (Mu.S.I.C.) software.<sup>18</sup> Subjects were seated in a sound attenuated booth 1 m from the speaker at 0° azimuth with a computer screen below the speaker. This experiment was designed as a 5-alternative forced choice task where pictures of the 5 instruments (flute, clarinet, alto-saxophone, trumpet and violin) were displayed on the computer screen and subjects were instructed to click on the instrument they perceived.

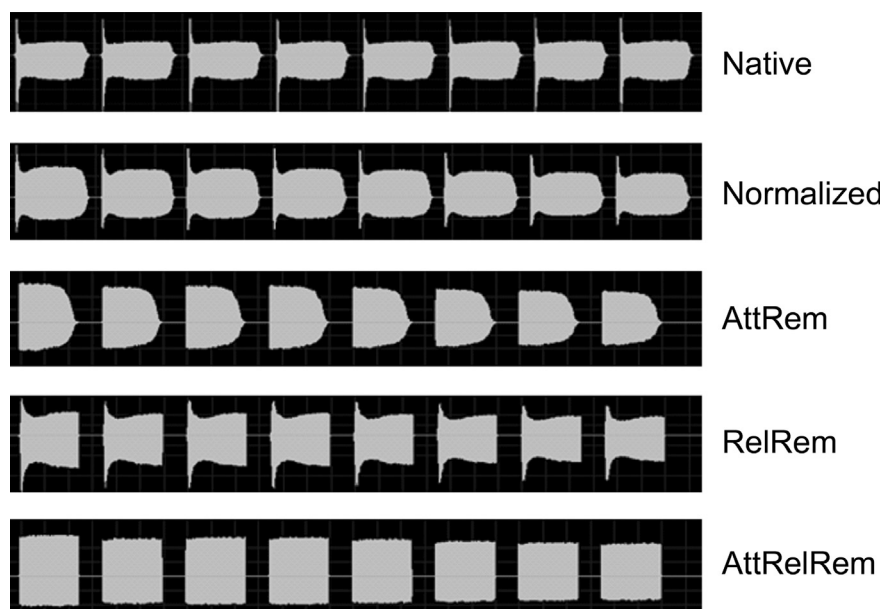
## Experiment 2: timbre envelope discrimination

Whereas experiment 1 was an instrument identification task requiring subjects to both perceive and interpret the auditory signal, experiment 2 simply interrogated whether a difference between stimuli could be detected. Twenty-five cochlear implant users, ages 18–82 years (avg 59, SD 16), and 7 normal hearing listeners, ages 31–56 years (avg 44, SD 10), participated in this experiment (Table 2). E-prime software (Psychology Software Tools, Inc., Sharpsburg, PA) was used for stimulus delivery and recording of behavioral responses. Stimuli consisted of individual 1-s notes from the instruments (trumpet, clarinet, flute or saxophone) presented in pairs as a discrimination task to discern whether a difference in instruments could be perceived. These instruments were chosen based on our preliminary research demonstrating that these were the most difficult to discriminate for both cochlear implant and normal hearing listeners. The envelopes of the instrument notes were digitally manipulated using Adobe Audition to create four conditions similar to that described in experiment 1. The first condition was the "native" condition where notes were selected from the instrument's natural characteristic range: trumpet (G4), alto-saxophone (G4), clarinet (C5) and flute (G5). To eliminate characteristic pitch cues, the second condition involved transposing the notes to a common note, C5 ("normalized"). The envelope

**Table 1** Demographics for subjects in experiments 1 and 3.

Subject	Age at test	Age of onset of severe-profound HL	Age of implantation	Time since implant	Duration of deafness	Etiology	Rate of onset	Listening configuration	Device
<b>CI</b>									
C1	46	31	46	0.5	15	Nerve damage at birth	Progressive	CI	C
C2	79	64	79	0.6	15	Unknown	Progressive	CI	C
C3	76	49	72	4	27	Unknown	Progressive	CI	M
C4	60	19	55	4	41	Measles	Sudden	CI	C
C5	81	78	81	0.5	3	Age	Progressive	CI	A
C6	42	0	33	0.8	42	Familial	Congenital	CICI	A
C7	21	1	10	11	20	CV issues as newborn	Progressive	CICI	C
C8	63	56	57	6	7	Unknown	Progressive	CICI	C
C9	56	44	49	7	12	Infection	Progressive	CICI	C
C10	59	43	46	13	16	Maternal HPB	Progressive	CICI	M
Avg (SD)	58 (19)		53 (22)		20 (13)				
<b>NH</b>									
N1	30								
N3	30								
N4	43								
N5	49								
N15	37								
N17	40								
N18	48								
N19	63								
Avg (SD)	43 (11)								

All ages and times are reported in years. ANSD = auditory neuropathy spectrum disorder; EVA = enlarged vestibular aqueduct; OM = otitis media; CMV = cytomegalovirus; CV = cardiovascular; Cx26/30 = connexin 26/30 mutation; CI = unilateral cochlear implant alone; HL = severe to profound hearing loss; CICI = bilateral cochlear implants; CIHA = bimodal configuration with a cochlear implant on one ear and hearing aid on the contralateral ear; A = Advanced Bionics; C = Cochlear; M = MED-EL.



**Fig. 2** Example of the 5 conditions used in experiment 1 for assessing the envelope contributions to identification of musical instruments. Native is the note played in the instruments characteristic frequency range, normalized is the note transposed to G4, AttRem is the attack of the note removed, RelRem is the release of the note removed, AtRelRem is the attack and release of the note removed leaving only the fine-structure duration portion of the note.

**Table 2** Demographics for subjects in experiment 2.

Subject	Age at test	Age of severe to profound HL	Age of implant	Duration of deafness	Length of device use	Etiology	Listening configuration	Device
<b>CI</b>								
C1	47	31	46	16	1	Congenital	CI	C
C2	79	64	79	15	1	Unknown	CI	C
C3	76	44	72	32	4	Unknown	CI	M
C4	60	19	55	41	5	Measles	CI	M
C5	82	78	81	4	1	Unknown	CI	A
C6	43	0	33	43	10	Congenital	CICI	A
C8	63	56	57	7	6	Unknown	CICI	C
C10	60	43	46	17	14	Maternal HPB	CICI	M
C11	75	73	74	2	1	Familial	CI	M
C12	64	58	58	6	6	Chicken pox	CI	A
C13	18	0	4	18	14	Ushers	CI	C
C14	71	48	61	23	10	Otosclerosis	CI	M
C15	60	56	57	4	3	Unknown	CI	M
C16	58	55	57	3	1	Nerve damage	CI	M
C17	70	60	70	10	1	Industrial noise	CI	C
C18	66	54	66	12	1	Familial	CI	C
C19	63	60	62	3	1	Unknown	CI	A
C20	53	37	52	16	1	Occupational noise exposure	CI	C
C21	63	42	57	21	6	Noise exposure	CI	C
C22	52	37	44	15	8	Guillain-Barre Syndrome	CI	M
C23	69	59	61	10	8	Otosclerosis	CICI	C
C24	21	14	19	7	2	Meningitis	CICI	C
C25	42	37	41	5	1	Unknown	CICI	C
C26	61	34	57	27	4	Nerve damage	CICI	C
C27	56	44	49	12	7	Unknown	CICI	C
Avg (SD)	59 (16)	44 (20)	54 (17)	15 (11)				
<b>NH</b>								
N1	31							
N3	31							
N4	44							
N5	50							
N20	50							
N21	44							
N22	56							
Avg (SD)	44 (10)							

All ages and times are reported in years. ANSD = auditory neuropathy spectrum disorder; EVA = enlarged vestibular aqueduct; OM = otitis media; CMV = cytomegalovirus; Cx26/30 = connexin 26/30 mutation; CI = unilateral cochlear implant alone; HL = severe to profound hearing loss; CICI = bilateral cochlear implants; CIHA = bimodal configuration with a cochlear implant on one ear and hearing aid on the contralateral ear; A = Advanced Bionics; C = Cochlear; M = MED-EL.

of the transposed note was then modified to remove the attack time (AttRem) and then both the attack and release time (AttRelRem). To save time, the condition in which the release of the note was removed was not used in this task based on our findings from experiment 1 indicating no significant differences in performance between the AttRem and RelRem removed conditions (see [Results](#)).

Pairs of notes were presented for the same or different instruments. The notes within each pair had undergone the same envelope modification, and were 500 ms in duration separated by a 500 ms gap of silence. A trial consisted of 256 pairs of stimuli, providing 4 iterations of all instrument and modified-envelope combinations. Subjects were

instructed to determine if the sounds were the same or if they were different. Performance was quantified by calculating D-prime ( $D'$ ) based on hit and false-alarm rates. Larger  $D'$  values indicate better discrimination performance.

### Experiment 3: timbre fine structure discrimination

Experiment 3 was designed to assess fine structure discrimination of timbre. The subjects for experiment 3 were the same described in experiment 1 ([Table 1](#)). Stimuli for this task used single notes of the trumpet (T), alto-

saxophone (S), clarinet (C), flute (F) and violin (V). All notes for this experiment were normalized to a C5 and digitally modified to remove both the attack and release times preserving only the middle of the note. Thus, this experiment focused on the discrimination of fine structure as pitch and envelope cues were removed.

To determine whether continuity of stimulation between notes affected discrimination performance, the note pairs were either presented with 0.5 s of silence in between, or the pairs were concatenated (i.e., no silence between notes). In both conditions Adobe Audition was used to ensure that the two stimuli were of same pitch and loudness and ensure absence of any other audible cues indicating that the note had changed. An example of 'spaced' and 'concatenated' note pairs are shown in Fig. 3. Using the same E-prime software as for experiment 2, note pairs were randomly selected as first and second stimuli and 4 iterations of all instrument combinations were presented.

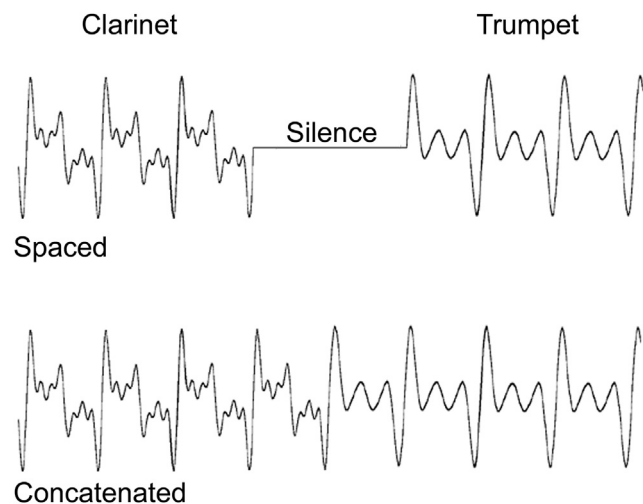
### Statistical analysis

Percent correct scores for instrument identification in experiment 1 and  $D'$  values for discrimination in experiments 2 and 3 were compared between cochlear implant and normal hearing listeners.  $T$ -tests were performed to determine whether there were statistically significant differences, defined as  $P < 0.05$ .

## Results

### Experiment 1: instrument identification envelope cues

This experiment investigated components of the acoustical envelope important in identifying instruments for both native- and normalized-pitch conditions. Cochlear implant



**Fig. 3** Example of the stimuli used in experiment 3 in which two notes of the same pitch and loudness are presented to assess the ability to distinguish a difference. One test used a 0.5 s gap of silence between presentations and the other test concatenated the notes to assess whether a change was detected.

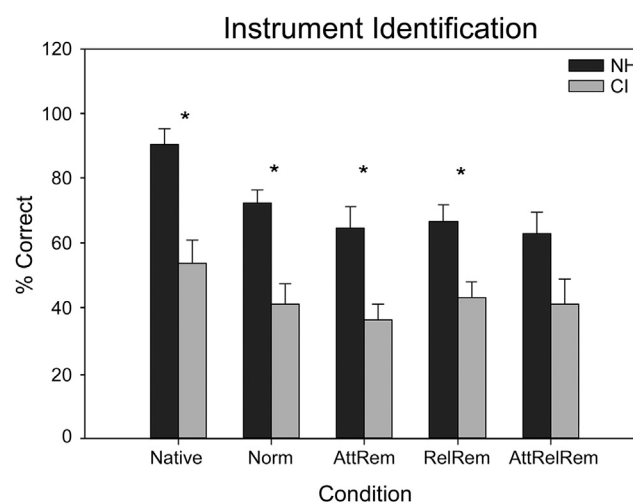
users performed statistically significantly poorer than normal hearing subjects on instrument identification for 4 of 5 conditions; the condition of both attack and release removed showed the same trend and approached statistical significance (Fig. 4).

In the native condition, cochlear implant users scored an average of  $54\% \pm 7.3\%$  correct, while normal hearing listeners scored an average of  $90.6\% \pm 4.8\%$  correct ( $P < 0.01$ ). Scores declined for both groups in the normalized condition (i.e., characteristic pitch cues removed), with scores for the cochlear implant group of  $41.5\% \pm 6.2\%$  and normal hearing listeners of  $72.5\% \pm 4.0\%$  ( $P < 0.01$ ). Comparisons of performance between CI users and NH subjects for modified envelope conditions were as follows: AttRem: CI =  $36.5\% \pm 4.8\%$ , NH =  $65\% \pm 6.3\%$  ( $P < 0.01$ ); RelRem: CI =  $43.5\% \pm 4.9\%$ , NH =  $66.9\% \pm 5.1\%$  ( $P < 0.01$ ); and AttRelRem: CI =  $41.5 \pm 7.6\%$ , NH =  $63.1 \pm 6.5\%$  ( $P = 0.053$ ).

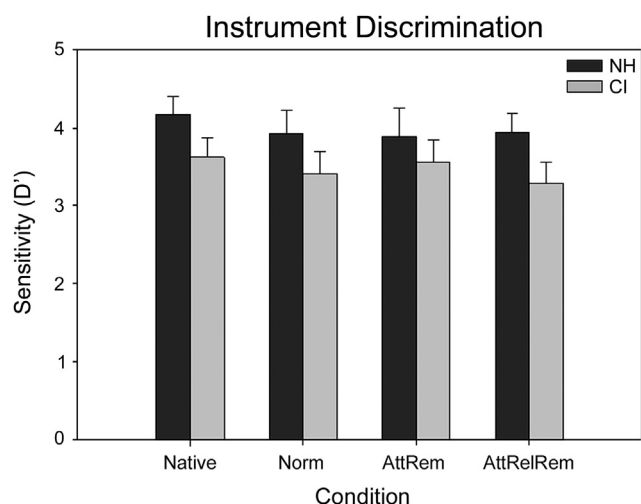
Within the normal hearing listeners, subjects performed significantly better in the native condition versus all other conditions (versus normalized,  $P = 0.01$ ; AttRem,  $P < 0.01$ ; RelRem,  $P < 0.01$ , AttRelRem,  $P < 0.01$ ). There were no significant differences in performance among the envelope-altered conditions. Within the cochlear implant group no significant differences between conditions, native and envelope-altered, were present.

### Experiment 2: timbre envelope discrimination

With the same envelope modifications described in experiment 1, this experiment investigated important components necessary in discriminating timbre as opposed to identifying timbre. In all listening conditions there was no statistically significant difference in performance between CI and NH subjects (Fig. 5).



**Fig. 4** Instrument identification using a scale with altered notes to remove envelope cues. Normal hearing subjects performed significantly better than those with cochlear implants. This suggests that normal hearing subjects interpret auditory cues better than cochlear implant users.

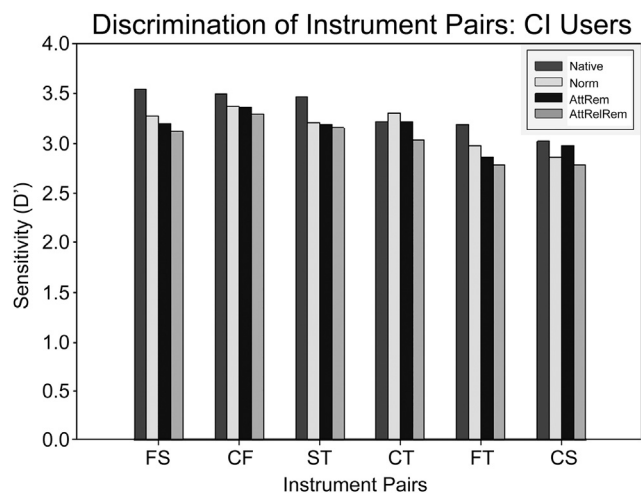


**Fig. 5** Instrument discrimination in four conditions. This tested the ability to hear a difference, rather than identify the instrument. There was no statistically significant difference in performance between normal hearing and cochlear implant subjects suggesting that both groups can perceive differences in envelope and fine structure similarly.

Both normal hearing listeners and cochlear implant users performed at similar levels regardless of envelope modification for each of the instrument pairings (Flute v. Sax, Clarinet v. Flute, Saxophone v. Trumpet, Clarinet v. Trumpet, Flute v. Trumpet and Clarinet v. Saxophone). In general, both groups performed well at discrimination between stimuli. Data for cochlear implant users are shown in Fig. 6.

### Experiment 3: timbre fine structure discrimination

In this experiment envelope and pitch cues were removed, thus requiring listeners to rely only on fine structure to discriminate differences between instrument sounds.



**Fig. 6** Discrimination of instrument differences in cochlear implant users by alteration of the envelope. The alteration of the envelope showed little effect on performance suggesting that fine-structure was perceived by CI users.

Overall, cochlear implant users showed comparable discrimination performance compared to normal hearing listeners for the majority of instrument comparisons, and were only significantly poorer for the comparisons of TV, FS, CF and CS (Fig. 7). In the concatenated condition cochlear implant users had significantly more difficulty than normal hearing listeners in deciphering TV ( $P < 0.01$ ), FS ( $P = 0.02$ ) and CF ( $P = 0.04$ ). In the spaced condition similar instruments provided difficulty; the cochlear implant group performed significantly poorer than the normal hearing listeners in comparisons of FS ( $P = 0.050$ ), CF ( $P = 0.02$ ) and CS ( $P < 0.01$ ).

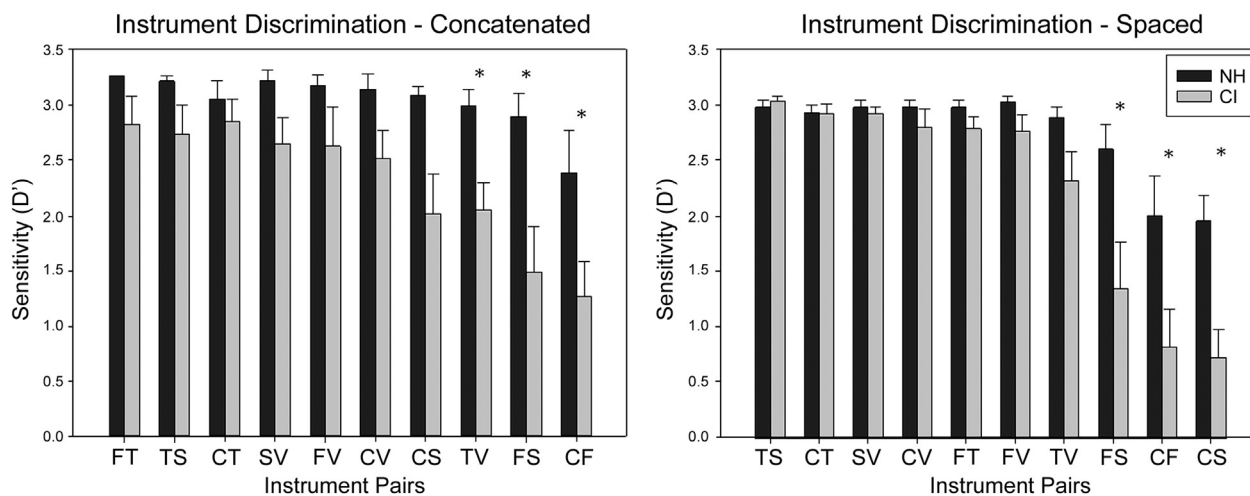
Whether the two stimuli were spaced or concatenated significantly affected the discrimination performance of the normal hearing group. Averaging across all instrument comparisons, the normal hearing group  $D'$  scores were significantly higher in the concatenated condition than the spaced condition ( $P = 0.01$ ), unlike cochlear implant users, who did not demonstrate a statistically significant difference in performance between the concatenated and spaced conditions.

### Discussion

The experiments designed for this study investigated the role of envelope and fine structure cues underlying the ability to both interpret and detect musical instrument stimuli among normal hearing and cochlear implant listeners. In general, CI users performed significantly poorer in the instrument identification task (i.e., interpretation); however, performed similarly to NH listeners for envelope discrimination and identification tasks and several fine structure discrimination tasks (i.e., detection). These findings suggest that most complex auditory cues are being perceived by CI users, but not necessarily interpreted correctly. In addition, it is possible that certain fine structure cues may be imperceptible to CI users that are critical for instrument identification.

Using unaltered whole notes to identify various instruments, CI users in this study showed consistently poorer performance compared to normal hearing listeners, consistent with results found in previous research.<sup>1,5</sup> When the envelope of the whole notes was altered (i.e., transposition out of characteristic range and removal of attack and/or release), performance for both groups declined, with CI subjects continuing to perform worse than normal hearing subjects. Ultimately, once all envelope information was removed (i.e., attack and release removed), performance between CI and NH listeners was no longer statistically different. This indicates that envelope cues are necessary in identifying instruments, for at least the normal hearing subjects in this study, which agrees with previous research suggesting that timbre judgments are based primarily on envelope cues as opposed to fine structure cues.<sup>13,19</sup>

Prior studies indicate that normal hearing listeners are able to utilize both envelope and fine structure cues interchangeably.<sup>13</sup> However, this study presented a situation where envelope cues were gradually removed until only the fine structure remained, at which point the performance of NH listeners was statistically similar to cochlear implant



**Fig. 7** Discrimination between fine-structure of two notes among normal hearing and cochlear implant users. Other than a few difficult pairings, cochlear implant users performed similarly to normal hearing subjects.

users. While the small number of subjects may account for the lack of a statistically significant difference in the fine-structure only condition (i.e., AttRelRem), the data suggest that in the absence of envelope cues normal hearing listener performance starts to approach that of cochlear implant users. Thus, normal hearing subjects do not necessarily interchange envelope and fine structure but, in fact, tend to make greater use of the envelope cues for identifying instruments. That is, when envelope cues are present normal hearing listeners identify instruments much better than cochlear implant listeners.

If we now accept that normal hearing listeners recognize instruments better than cochlear implant users in the presence of envelope cues, we can examine the concepts of whether cochlear implant users are unable to perceive envelope cues or whether they perceive envelope cues but do not interpret them well. Experiment 2 used similar stimulus conditions to those in experiment 1, but interrogated whether a difference could be perceived. There was no statistically significant difference between groups in discrimination performance for all conditions. Thus, both cochlear implant and normal hearing listeners respond to envelope cues similarly when discriminating between instruments.

The small overall variability in performance among CI users with envelope modification (Fig. 5) indicates that envelope plays little role in discriminating between sounds in this experiment. In that case, fine-structure would perhaps be the primary cue helping to distinguish differences. While the fairly consistent downward trend in performance when envelope is modified for each instrument pairing (Fig. 6) may suggest that envelope plays some role in discriminating between sounds, it is beyond these experiments to quantify the relative contributions of envelope and fine structure to discrimination.

Instrument identification is a combination of envelope and fine structure perception. We have thus far demonstrated that envelope changes are interpreted better by normal hearing listeners than cochlear implant users, and overall discrimination performance is similar between

groups. The final experiment, experiment 3, interrogated whether fine-structure perception follows a similar pattern. All envelope and native pitch cues were removed leaving only fine structure. Normal hearing and cochlear implant subjects showed statistically similar results in the ability to perceive a difference between the signals for most instrument pairs. This statistical relationship was seen in both concatenated and spaced experiments. Some instrument pairs proved problematic for all subjects, although were significantly more difficult to discriminate for CI users. Overall, this suggests that cochlear implant users perceive differences in fine structure analogous to normal hearing listeners, although there are likely key fine structure elements that CI users are missing.

An interesting finding in experiment 3 was that spacing the stimuli apart, rather than concatenating the sounds, affected cochlear implant and normal hearing listeners differently. For cochlear implant users, there were no significant changes in  $D'$  scores when stimuli were spaced or concatenated; however, normal hearing subjects could more accurately detect changes in timbre when the stimuli were concatenated. This may be reflective of the dramatic envelope modification to generate these stimuli (i.e., removal of attack and decay). The concatenated portion of this experiment may represent a pure comparison of fine-structure while the spaced component may be clouded by the complex interaction between envelope and fine-structure in contributing to timbre. The nature of this difference will require further investigation.

A unique strength of this study was the gradual removal of envelope cues from musical instrument stimuli to probe the differential effects of envelope and fine-structure information. Another strength is the interrogation of, not only instrument identification, which has been frequently studied, but also instrument discrimination. The latter allows us to distinguish the ability to perceive a signal versus the ability to interpret the signal correctly. A weakness in this study was the use of different subjects in the different experimental groups as well as the variety of processors, processing strategies and internal devices. This prevents



the analyses from identifying whether specific processing strategies or particular devices are better at providing the subtle acoustical differences between stimuli used in this study. However, it allows some degree of generalization across a variety of cochlear implant listeners.

## Conclusions

Cochlear implant users continue to lag behind normal hearing listeners with instrument identification; however, cochlear implant listeners can discriminate differences in envelope and some fine structure components of musical instrument sounds as well as normal hearing listeners. Certain fine structure cues were very difficult for CI users to perceive, and to a significantly greater extent than normal hearing listeners. This indicates that current processors, or current electrode-neural interfaces, may not present some of the critical fine-structure signals necessary for music appreciation. Further investigation will help determine whether the signal is present but too degraded or the chronically deprived auditory system can no longer interpret such signals.

## Conflicts of interest

Dr. Friedland was a member of the MED-EL Surgical Advisory Board, Dr. Runge is a Research Consultant for MED-EL Corp., Novartis Corp., and Frequency Therapeutics Inc. For all other authors no conflicts of interest were reported.

## Funding

Investigator-initiated Institutional Award: MED-EL Corp, Project # 3305019.

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Edited by Yuxin Fang