Classification of Noise and Environmental Stimuli by the Auditory Impression of Cochlear Implant Users

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Abstract

In the present study, we investigated how cochlear implant (CI) users recognize noise and environmental stimuli by comparing the auditory impression to subjects with normal hearing (NH).

Methods: Subjects comprised the CI group and the NH group. There were 8 patients with CIs (4 males and 4 females, mean age 68.8 years, range 57-86 years) in the CI group. Thirty-two subjects (18 males and 14 females, mean age 67.4 years, range 61-83 years) with normal hearing were included in the NH group. The semantic differential (SD) method was used to measure the auditory impression to each sound stimulus using 14 bipolar adjective pairs. Each examinee evaluated 14 bipolar adjective pairs for 38 sound stimuli at two sound intensities of 65 dB and 75 dB. A hierarchical cluster analysis using the Ward method was performed using a matrix of the average score in each group composed of 38 sound stimuli and 14 bipolar adjective pairs as the rows and columns, respectively. A factor analysis was conducted to explore the difference in the structure of auditory impression for the sound stimuli.

Results: The cluster compositions differed between the groups. This finding indicated that the auditory impression of the CI group differed from that of the NH group. There were three variables among 14 adjective pairs to describe the auditory impression evaluation of 38 sound stimuli, whereas the CI group demonstrated two variables. The contribution of each variable was dependent on the sound intensity. The characteristics of factors I and II were monotonous and dynamic in time and frequency, respectively. The results indicated that CI users distinguished two different sound structures by the auditory impression compared to three in the NH group.

Discussion: We performed a factor analysis to explore the variables in the auditory impression. Three factors, pleasantness, sharpness and powerfulness, are experienced by the NH group, whereas only two variables are experiences by the CI group. A change in the sound intensity can affect factor loading in each factor. According to acoustic analysis, the characteristics of factors I and II are monotonous and dynamic in time and frequency, respectively. The stimulus spectrum could be referred to as the skeletonized spectrum. This might explain why fewer variables are necessary to explain the auditory impression in CI users. Thus, the temporal change may be the most important factor to distinguish the difference.

Key words: Noises and Environmental sounds, Auditory impression, Cochlear Implant, Cluster analysis, Factor analysis

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Introduction

The cochlea is a peripheral auditory sensory organ that transduces sound into an electrical neural signal of auditory neurons. The central nervous system recognizes various sounds by processing the neural signal. For a patient with a hearing impairment, a hearing aid (HA) amplifies the sound to stimulate the cochlea. However, signal transmission compensation is limited when the hearing impairment is severe. A cochlear implant (CI) was developed to overcome this limitation. The CI transforms sound signals into electrical stimulation to auditory neurons. The CI has only 22 electrodes for the instantaneous stimulation of a certain amount of neurons. In contrast, there are 3500 inner hair cells in the normal cochlea. Each inner hair cell stimulates 20 neurons and encodes the sound into a neural signal [1]. Therefore, the amount of information carried by the CI might be far less than that at the physiological condition. As a result, the strategy for transduction is focused on the information of speech sound. However, a CI user hears environmental sound and noise in everyday life. These sounds are considered to interfere with speech information. A directional microphone, noise suppression program or cut-off function have been used to exclude these sounds. We previously experienced that congenital deaf children with CI can distinguish environmental sounds, although they demonstrate difficulty in understanding language. Therefore, they can avoid dangerous situations by recognizing environmental noise [2]. CI users with acquired deafness experience stress due to the loss of surrounding sound in everyday life [3].

Recent developments in CIs have increased the recognition of environmental sounds and musical instruments. Several studies have reported the importance of surrounding sound recognition for hearing impaired patients and CI users [4]-[6]. In the present study, we investigated how CI users recognize environmental sounds and noise by comparing the auditory impression in CI users with that in subjects with normal hearing.

Subjects and Methods

Hearing test

The hearing level (HL) was measured in an anechoic chamber. The background noise level was measured using a sound level meter (Type BZ5003®, Brüel & Kjær, Nærum, Denmark). The level was maintained to be equal to or less than 20 dB SPL. Pure tone audiometry was performed using a commercial audiometer (AA -71®, RION, Tokyo, Japan). The hearing test in the sound field was measured at one meter away from the front of a loud speaker (ECLIPSE TD508MK-3®, Fujitsu Ten, Kobe, Japan) connected to the audiometer (AA-76®, RION, Tokyo, Japan). The HL in the sound field was calibrated by measuring the sound pressure level at the height of one meter from the floor. The data for calibration were taken at each frequency before all experiments.

Subjects

The subjects comprised the CI group and the normal hearing (NH) group. There were 8 patients with CIs (4 males and 4 females, mean age 68.8 years, range 57-86 years) in the CI group. The characteristics of the CI group are listed in Table 1. In all patients, the strategy for sound processing was ACE®, and the input frequency range was between 188 and 7938 Hz. Thirty-two subjects (18 males
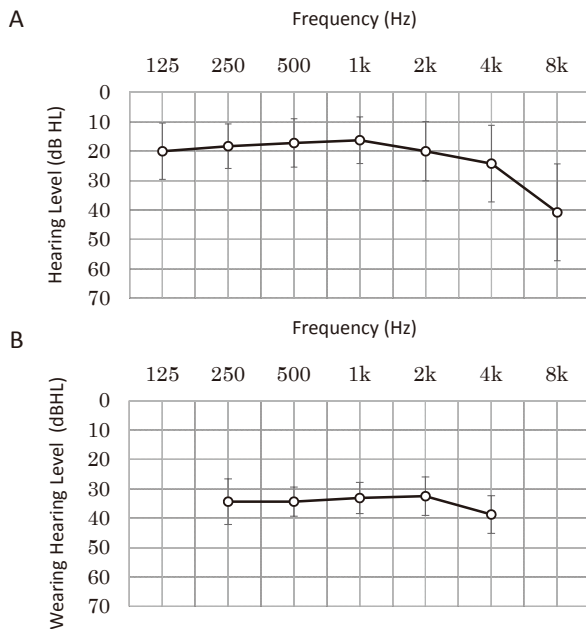
Table 1. Details of cochlear implant (CI) group

#	Age	Dur.	CI	Proc.	Freq	Ch
C2	75	3.9	CI24RE ®	Freedom ®	500	22
C3	68	6.5	CI24R (CS) ®	Freedom ®	900	22
C4	58	2.0	CI24RE ®	CP910 ®	900	22
C5	77	1.5	CI422 ®	CP810 ®	900	22
C6	67	8.6	CI24R (CS) ®	CP910 ®	900	22
C7	69	2.0	CI422 ®	CP810 ®	900	20
C9	57	1.9	CI422 ®	CP900 ®	900	22
C10	78	7.8	CI24R (CS) ®	CP810 ®	720	22

Abbreviation; Age, test age (year-old). Dur., duration for implant use (years). CI; type of cochlear implant. Proc., speech processor. Freq, stimulation frequency (Hz). Ch, number of channels used. Strategy and frequency range employed in all cases were ACE® and 188-7938 Hz.

and 14 females, mean age 67.4 years, range 61-83 years） with normal hearing were included in the NH group. All subjects were employed by the National Silver Human Resources Centers Association®. Normal hearing was defined as a HL value of less than or equal to 40 dB HL. The HL was calculated as follows: the sum of HL at 500 Hz, the valued was doubled at 1 kHz, and that at 2 kHz was divided by four.

Figure 1A shows the average and standard deviation of the HL in the NH group for 8 frequencies, 125, 250, 500, 1000, 2000, 4000 and 8000 Hz. Aided HL values of CI users were measured at 6 frequencies,250, 500, 1000, 2000 and 4000 Hz, in the sound field（Figure 1B）.

Fig. 1 Hearing level（HL）of NH group（A）and aided HL of CI group（B）.
Empty circle and bar represented mean and ±SD of HL.

Test materials

Test materials for the experiments, such as the environmental noise, were prepared from research material of sound stimuli reported by Tanaka et al. [7]（shown in Table 2）. Sound stimuli 1-28 were taken from the DVD version of the architecture and environment sound library（edited by the Architectural Institute of Japan）. Sound stimuli 29-33 were originally created by Tanaka and Shiraishi [7] Sound stimulus 34 was obtained from the hearing aid compatible evaluation CDTY-89. Sound stimuli 35-38 were created using an acoustic signal processing software（Adobe Audition 2.0®, Adobe Systems

Table 2. List of sound source

1	A string quartet
2	Environmental sounds inside a Bus
3	Environmental sounds inside a Car
4	The siren of an ambulance in the streets
5	A road traffic noise
6	A road traffic noise of the rain
7	Environmental sounds inside a bullet train（Shinkansen）
8	Environmental sounds inside a subway
9	The noise of an adjacent factory
10	Hydraulic excavato
11	Hand drill
12	A hair dryer
13	A refrigerator
14	The sound of the washing machine
15	Dewatering washing machine
16	The whine of a vacuum cleaner
17	Ventilation fan
18	Warning sound of the railroad crossing
19	Noise of a fast-food restaurant
20	Concourse
21	Jazz music
22	Roar of waves
23	Sound of a stream
24	Buzz of cicada（Crypto tympana facialis, Kumazemi）
25	Buzz of cicada（Kaempfer cicada, Ninizemi）
26	Cricket chirping
27	The rumbling of thunder
28	Music of trees
29	Sound of a bag made of thin plastic material
30	Sound of many keys
31	Sound of crumpling a piece of paper into a ball
32	The sound that washes the dishes
33	Applause
34	Babble
35	Speech noise
36	White noise
37	Pink noise
38	Hoth Noise

Inc., San Francisco, CA, USA）. Each sound stimulus was sampled at a frequency of 44.1 kHz. The stimuli were saved on a personal computer（PC）（Dynabook R732 / 39HB®, Toshiba, Tokyo, Japan）as a 16-bit RIFF waveform Audio Format（WAV）file. The duration of all sound stimuli were cut to10 seconds and converted into monaural sound using the auditory signaling processing software program [8].

Experimental setup

A schematic diagram of the experimental setup is shown in Fig. 2. All experiments were performed in the anechoic room. The presentation of the stimuli and recording of the responses were performed using the PC. The output from the PC was amplified by a power amplifier (KIT11101A®, Kyushu Inter-Tec, Fukuoka, Japan) to present the tasks by the loud speaker (ECLIPSE TD508MK-3®). The examinee sat in front of the speaker, in the same condition as the hearing test in the sound field. The visual component of the task was shown by the display located next to the speaker. The task was presented in increments of 0.1 dB, and the sound intensity of the output was adjusted to 65 dB and 75 dB of an equivalent continuous A-weighted sound pressure level (L_{Aeq}) of 10 seconds measured by the sound level meter (Type BZ5003®) at the location where the examinee was.
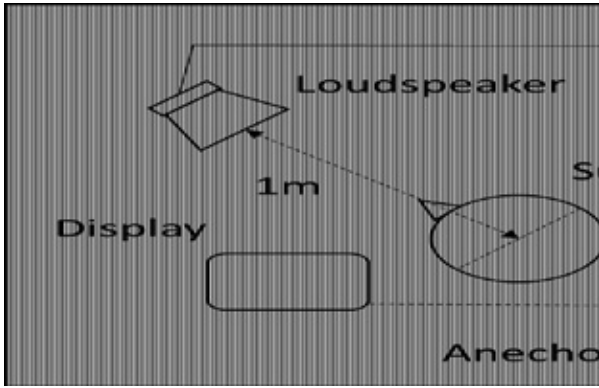

Fig. 2 Layout for the experiment.

Evaluation of the auditory impression

The semantic differential (SD) method was used to measure the auditory impression to each sound stimulus using 14 bipolar adjective pairs (Table 3). There were 7 grades in the scale between two bipolar adjectives (Fig. 3). Each examinee evaluated the auditory impression of each sound stimulus by pointing to the scale on the display
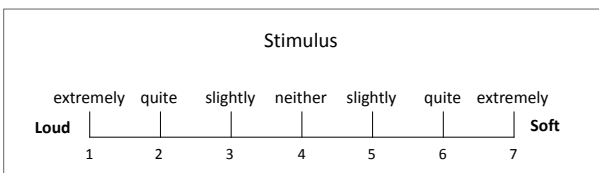

Fig. 3 Representative of visual analogue scale for semantic differential (SD) method.
Examinee estimated the level of each stimulus sound and chose appropriate number between 1 and 7.

Table 3. Adjective used for auditory impression evaluation

Loud	–	Soft
Annoying	–	Not annoying
Clean	–	Dirty
Easy	–	Hard
Wooden	–	Metallic
Pure	–	Complex
Sharp	–	Dull
High-pitched	–	Low-pitched
Strong	–	Weak
Powerful	–	Undertone
Comfortable	–	Uncomfortable
Pleasant	–	Unpleasant
Noisy	–	Calm
Stable	–	Unstable

with a mouse. The order of the presentation of the stimuli and 14 bipolar adjective pairs were randomized in each examination. Each examinee evaluated 14 bipolar adjective pairs for 38 sound stimuli at the two sound intensities of 65 dB and 75 dB. Each examination took approximately 90 minutes.

Acoustic analysis

The amplitudes of the sound wave in the time and frequency power spectra were evaluated in the acoustic analysis. The temporal sound amplitude was recorded using the acoustic signal processing software (Adobe Audition 2.0®). The power spectrum evaluated by the frequency analysis was measured by the sound level meter (Type BZ5003®).

Statistical analysis

Statistical analyses were performed using the JMP software program (SAS, Cary, NC, USA). A hierarchical cluster analysis using the Ward method was performed using a matrix of the average score in each group composed of 38 sound stimuli and 14 bipolar adjective pairs as the rows and columns, respectively. The unit of the horizontal axis of the dendrogram was the Euclidean distance. A factor analysis was conducted to explore the difference in the structure of the auditory impression for sound stimuli. A principal component analysis was used for factor extraction. To interpret factor loadings, loadings were set to 0.6 or higher to confirm independent variables using the varimax method for the rotation of factors. The relative weight of each variable in the component was identified by the factor score coefficient. The value of

the coefficient was used to show the contribution of the variable to the auditory impression.

Ethics

The methods used in the present study were approved by the ethical community of Fukuoka University Hospital. Informed consent was obtained from each examinee.

Results

Subject characteristics

The speech intelligibility of the CI group was 25-76% for a single syllable （mean 53.6 ± 16.6%）. The duration of deafness was between 0.4 to 2.8 years （mean 1.4 ± 0.7 years）, and the duration of implantation was 1.5 to 8.6 years （mean 4.2 ± 2.9 years）.

Hierarchical cluster of the sound stimuli

A hierarchical cluster analysis of the sound stimuli was performed using the Ward method. Tasks were presented at the sound level of 75 dB HL. The rows and columns of the analyzed matrix comprised 38 sound stimuli, and the average score of the auditory impression of 14 adjective pairs was evaluated by the semantic differential method. Figures 4 and 5 demonstrate the dendrograms for the NH and CI groups, respectively. The numbers of clusters in the NH and CI groups were 26 and 35, respectively, at a Euclidean distance equal or less than 1. The numbers of clusters were 10 and 6, respectively, at a Euclidean distance equal or less than 3. The compositions of the clusters differed between the groups. This indicated that the auditory impression of the CI group was different from that of the NH group.
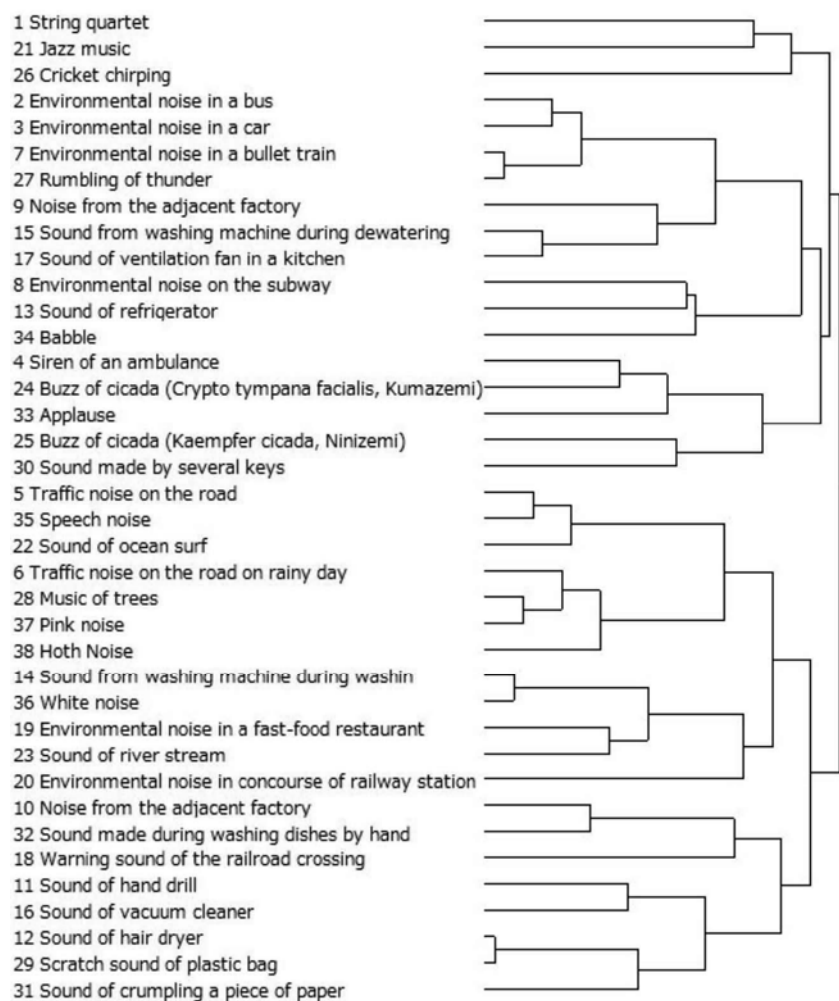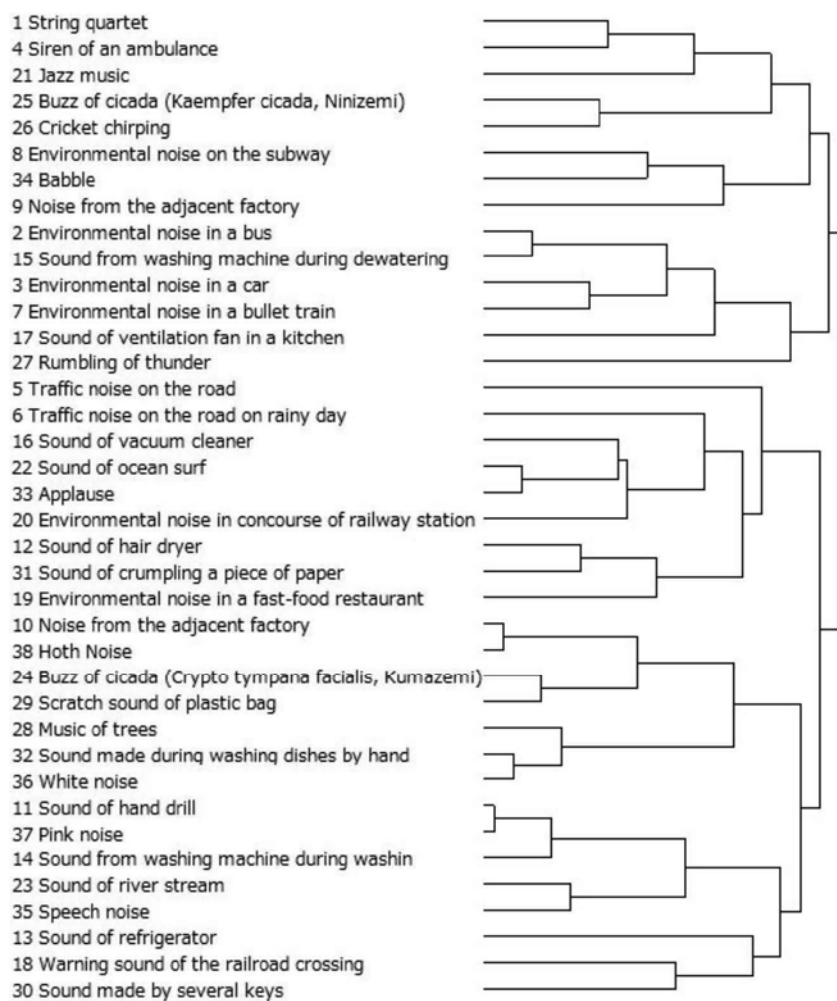

Fig. 4 Dendrogram of sound source analyzed by hierarchical clustering in NH group.

Fig. 5 Dendrogram of sound source analyzed by hierarchical clustering in CI group.

Structural difference in the auditory impression in CI users

A factor analysis was used to explore the difference in the structure of the auditory impression between NH and hearing through a CI. Table 4 shows the results of the NH group. There were three variables among 14 adjective pairs to describe the auditory impression evaluation of 38 sound stimuli. The NH group included subjects with cochlear damage, i.e., prescubysis. A comparison was performed between the NH group and the inner ear disorder group (data not shown). No difference in the number of factors was noted. Thus, these subjects were included in the NH group.

On the other hand, there were two variables in the CI group (Table 5). The factor analysis was divided into 1-3 factors for each CI user, i.e., 3 factors for three users, two factors for four users and 1 factor for one user. There was no significant correlation between the number of factors and the speech intelligibility, duration of deafness, or HL of the factor analysis (data not shown). We therefore considered each group to be a homogeneous group in the experiments.
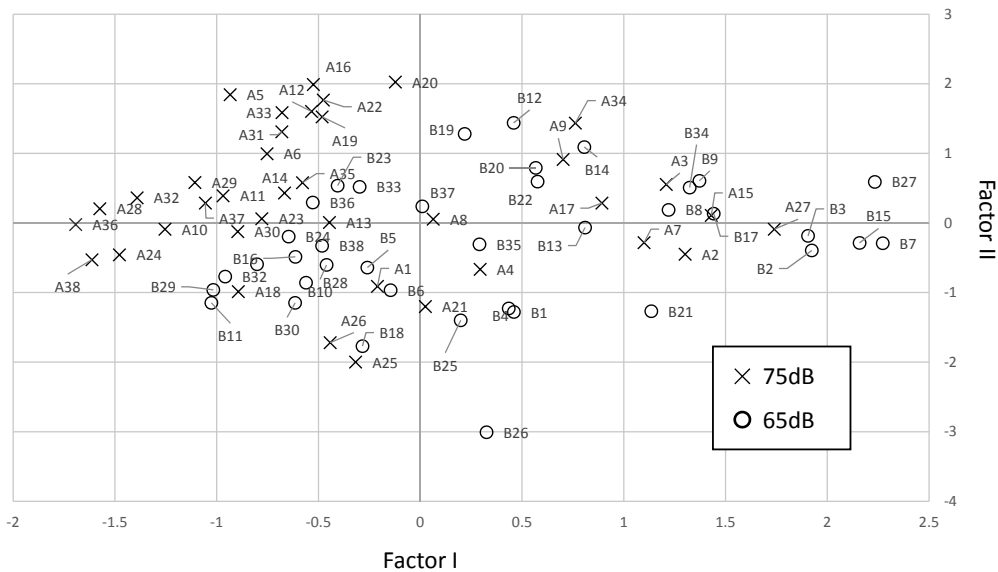
Figure 6 demonstrates a scattered diagram of the contribution of both factors for various sound stimuli in CI users. The sounds were presented at two different sound intensities of 65 dB and 75 dB. When the sound intensity increased, the scores of factor I significantly decreased ($P<0.01$, Mann-Whitney U test). Conversely, the scores of factor II significantly increased ($P<0.05$, Mann-Whitney U test). The contribution of each variable was dependent on the sound intensity.

Table 4. Factor loadings of auditory impression evaluation by the mean of factor analysis with varimax rotation in NH group

		I	II	III	Communality
Clean	- Dirty	**0.98**	-0.12	-0.04	0.94
Pleasant	- Unpleasant	**0.93**	-0.30	-0.07	0.95
Comfortable	- Uncomfortable	**0.93**	-0.32	-0.05	0.97
Pure	- Complex	**0.92**	0.22	0.08	0.92
Annoying	- Not annoying	**-0.78**	0.40	0.43	0.91
Stable	- Unstable	**-0.75**	0.42	0.46	0.96
Easy	- Hard	**0.70**	-0.42	-0.51	0.96
Wooden	- Metallic	0.24	**-0.95**	-0.04	0.95
Noisy	- Calm	-0.33	**0.88**	0.27	0.95
High-pitched	- Low-pitched	-0.46	**0.79**	0.34	0.81
Sharp	- Dull	0.29	**0.77**	0.53	0.97
Loud	- Soft	-0.23	0.27	**0.90**	0.96
Powerful	- Undertone	0.03	0.03	**0.90**	0.96
Strong	- Weak	-0.17	0.52	**0.81**	0.95
Contribution of factor ratio		41.1	28.7	24.3	94.1
Accumulation contribution ratio		41.1	69.7	94.1	

Table 5. Factor loadings of auditory impression evaluation by the mean of factor analysis with varimax rotation in CI group

		I	II	Communality
Noisy	- Calm	**0.94**	-0.22	0.88
Annoying	- Not annoying	**0.90**	-0.24	0.92
Strong	- Weak	**-0.90**	0.02	0.79
Easy	- Hard	**0.88**	-0.31	0.91
Wooden	- Metallic	**0.88**	0.10	0.88
Stable	- Unstable	**0.88**	-0.38	0.81
Clean	- Dirty	**0.87**	-0.40	0.79
High-pitched	- Low-pitched	**-0.86**	0.41	0.87
Comfortable	- Uncomfortable	**0.85**	-0.36	0.88
Loud	- Soft	**0.85**	-0.41	0.85
Pleasant	- Unpleasant	**-0.79**	0.43	0.87
Powerful	- Undertone	**-0.74**	0.56	0.81
Sharp	- Dull	0.03	**0.94**	0.92
Pure	- Complex	-0.52	**0.72**	0.92
Contribution of factor ratio		65.8	20.6	86.4
Accumulation contribution ratio		65.8	86.4	

Fig. 6 Scattered diagram of contribution of both factors for various sound sources of CI users.
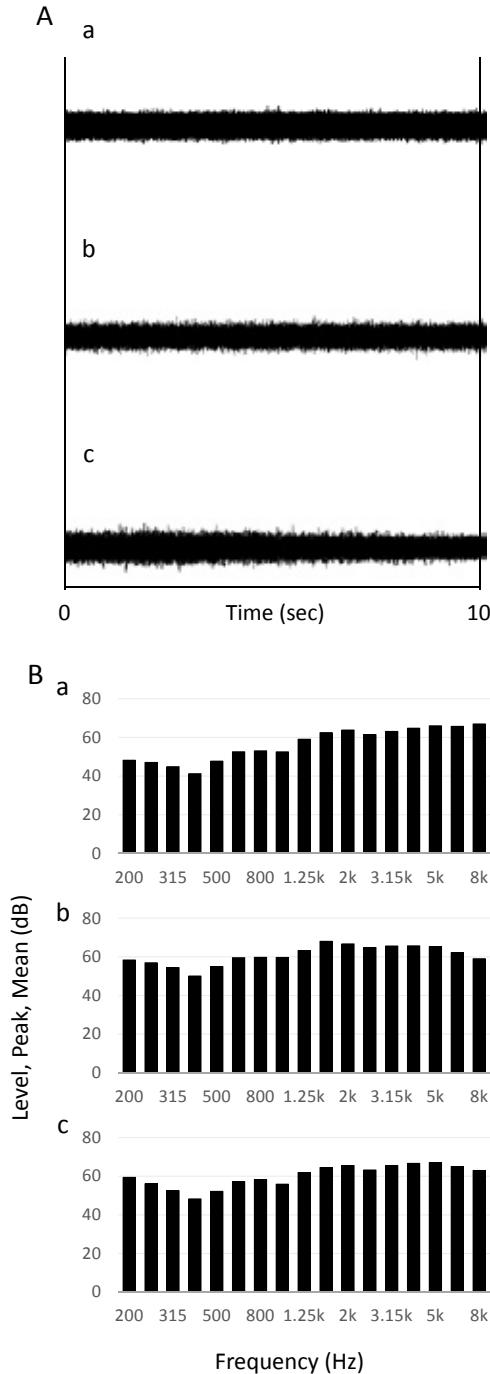Horizontal and vertical bars were factors I and II, respectively. A and B represented 75dB and 65dB of stimulus sound intensity, respectively. Each number corresponded to the sound source number in Table 2. When sound intensity became higher, the scores of factor I significantly decreased（*P<0.01*）. On contrary, the scores of factor II significantly increased（*P<0.05*）.

Acoustic analysis of the sound stimuli in each factor of the CI group

The calculated values of factors for sound stimuli are listed in Table 6. A negative value of both factors contributed more to describe the auditory impression.

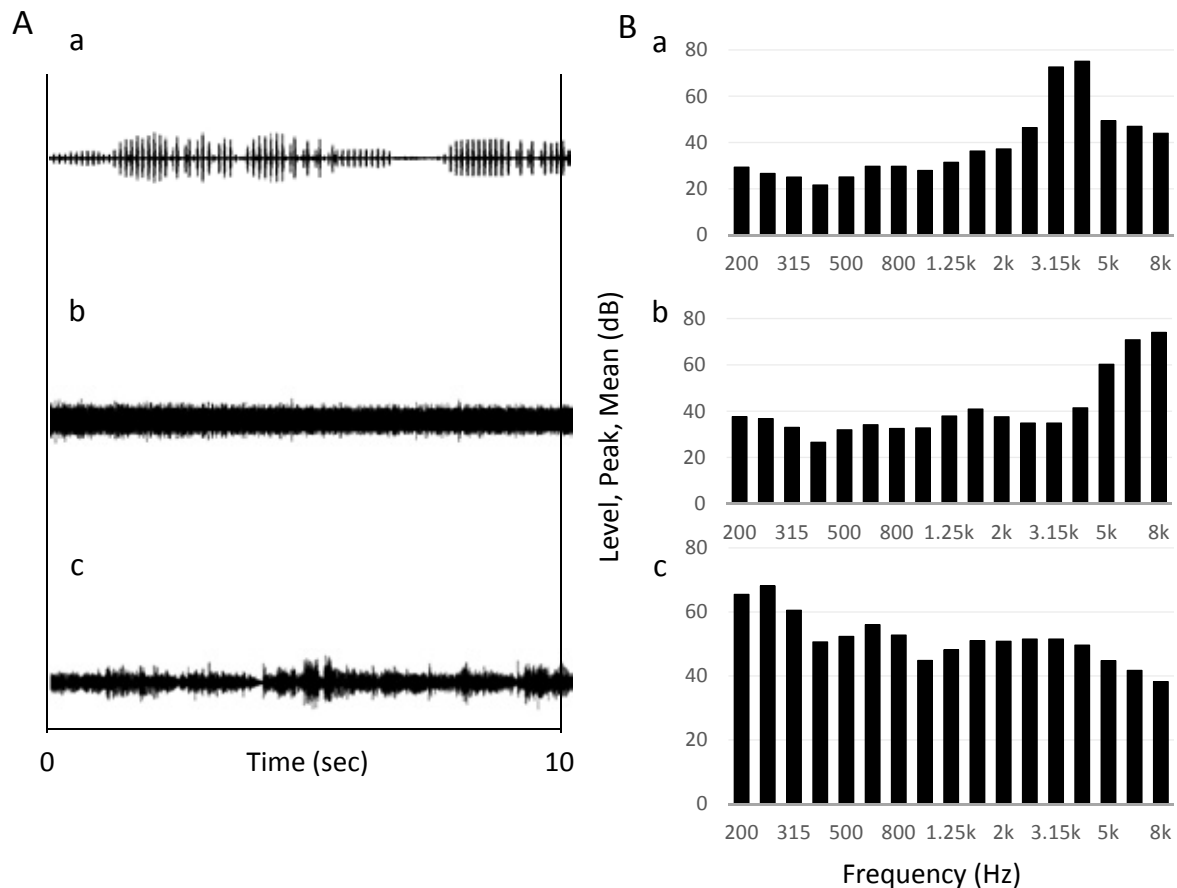Figure 7 shows the results of the acoustic analysis of three sound stimuli of factor I which were in the top 3 in the CI group. These stimuli were white noise, hoth noise and the music of trees. The amplitudes of the sound wave in the time and frequency power spectra of these three sound stimuli were monotonous. The sound stimuli of factor II were cricket chirping, cicada buzzing and jazz music. In contrast, cricket chirping and jazz music changed drastically over time. The frequency power spectra were different from those of factor I. Those of factor II exhibited a peak in a certain frequency band. The characteristics of

Fig. 7 Amplitude of sound wave in time (A) and frequency power spectrum (B) of three sound sources in an order of high value of factor I in CI.
a, white noise. b, hoth noise. c, music of trees.

Table 6. The calculated values of factors for sound stimuli.

	Fac. I	Fac. II
White noise	**-1.69**	-0.02
Hoth Noise	**-1.61**	-0.53
Music of trees	**-1.57**	0.20
Buzz of cicada (Crypto tympana facialis, Kumazemi)	-1.48	-0.46
The sound that washes the dishes	-1.39	0.36
Hydraulic excavato	-1.25	-0.09
Sound of a bag made of thin plastic material	-1.11	0.58
Pink noise	-1.06	0.29
Hand drill	-0.97	0.39
A road traffic noise	-0.93	1.84
Sound of many keys	-0.90	-0.12
Warning sound of the railroad crossing	-0.89	-0.99
Sound of a stream	-0.78	0.06
A road traffic noise of the rain	-0.75	0.99
Sound of crumpling a piece of paper into a ball	-0.68	1.31
Applause	-0.68	1.59
The sound of the washing machine	-0.67	0.43
Speech noise	-0.58	0.58
A hair dryer	-0.53	1.60
The whine of a vacuum cleaner	-0.53	1.99
Noise of a fast - food restaurant	-0.48	1.53
Roar of waves	-0.48	1.77
A refrigerator	-0.45	0.01
Cricket chirping	-0.44	**-1.72**
Buzz of cicada (Kaempfer cicada, Ninizemi)	-0.32	**-2.00**
A string quartet	-0.21	-0.91
Concourse	-0.12	2.03
Jazz music	0.03	**-1.20**
Environmental sounds inside a subway	0.06	0.06
The siren of an ambulance in the streets	0.29	-0.67
The noise of anadjacent factory	0.70	0.91
Babble	0.76	1.44
Ventilation fan	0.89	0.29
Environmental sounds inside a bullet train (Shinkansen)	1.10	-0.28
Environmental sounds inside a Car	1.21	0.55
Environmental sounds inside a Bus	1.30	-0.45
Dewatering washing machine	1.43	0.11
The rumbling of thunder	1.74	-0.09

Fig. 8 Amplitude of sound wave in time（A）and frequency power spectrum（B）of three sound sources in an order of high value of factor I in CI.

a, cricket chirping. b, buzz of cicada（Kaempfer cicada, Ninizemi）. c, jazz music.

factors I and II were monotonous and dynamic in time and frequency, respectively. These results indicated that CI users distinguished two different sound structures by the auditory impression compared to three in the NH group.

Discussion

The present results of the hierarchical cluster analysis confirmed the previous findings in the NH group. The cluster components differed between the NH and CI groups. This finding indicated that the auditory impression of CI users was different from that of the NH group. This may be the result of a different mechanism to analyze the sound at the peripheral level.

A factor analysis was performed to explore the variables to explain the auditory impression. There were three factors for the NH group, pleasantness, sharpness and powerfulness. This finding was consistent with those previously reported by Tanaka and Shiraishi[7] and Namba and Kuwano[9, 10]. On the other hand, the number of

variables was two for the CI group. These results confirmed the difference in the auditory impression between the CI group and NH group. A change in the sound intensity affected factor loading in each factor. One factor decreased the value of factor loadings by increasing the sound intensity. Conversely, another factor increased the value by increasing the sound intensity. The fact that two factors behaved in opposing manners indicated that the sound intensity was one of components capable of affecting the auditory impression in CI users.

An acoustic analysis showed that the characteristics of factors I and II were monotonous and dynamic in time and frequency, respectively. CI users recognized sound by the transducing strategy. In the present experiments, the strategy was ACE® in all CI users. The speech processor analyzed sound in three components, intensity, frequency and temporary change. ACE® is an encoding system that corresponds to 8 channels of high intensity at every stimulus[11, 12]. The spectrum of the stimulus could be referred to as the skeletonized spectrum. This might

be the reason why fewer variables were necessary to explain the auditory impression in CI users. The main information carried by ACE® is a rough envelope of the power spectrum. This indicates that the temporal change is the most important aspect to distinguish the difference. The finding that the difference between factor I and factor II was the temporal change in the acoustic analysis is consistent with the characteristics of strategy. When the sound intensity is higher, then the sound source of factor I might become dynamic and that of factor II might become monotonous. CI users with different strategy should be analyzed to confirm this hypothesis.

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