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Musical Training Improves Pitch Perception in Prelingually Deafened Children With Cochlear Implants

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WHAT'S KNOWN ON THIS SUBJECT: The comparatively poor music appreciation in patients with cochlear implants might be ascribed to an inadequate exposure to music; however, the effect of training on music perception in prelingually deafened children with cochlear implants remains unknown.

WHAT THIS STUDY ADDS: Musical training improves pitch perception in prelingually deafened children with cochlear implants. Incorporation of a structured training program on music perception early in life and as part of the postoperative rehabilitation program for these children would be beneficial.

abstract

OBJECTIVE: The comparatively poor music appreciation in patients with cochlear implants might be ascribed to an inadequate exposure to music; however, the effect of training on music perception in prelingually deafened children with cochlear implants remains unknown. This study aimed to investigate whether previous musical education improves pitch perception ability in these children.

METHODS: Twenty-seven children with congenital/prelingual deafness of profound degree were studied. Test stimuli consisted of 2 sequential piano tones, ranging from C (256 Hz) to B (495 Hz). Children were asked to identify the pitch relationship between the 2 tones (same, higher, or lower). Effects of musical training duration, pitch-interval size, current age, age of implantation, gender, and type of cochlear implant on accuracy of pitch perception were evaluated.

RESULTS: The duration of musical training positively correlated with the correct rate of pitch perception. Pitch perception performance was better in children who had a cochlear implant and were older than 6 years than in those who were aged ≤6 years (ie, preschool). Effect of pitch-interval size was insignificant on pitch perception, and there was no correlation between pitch perception and the age of implantation, gender, or type of cochlear implant.

CONCLUSIONS: Musical training seems to improve pitch perception ability in prelingually deafened children with a cochlear implant. Auditory plasticity might play an important role in such enhancement. This suggests that incorporation of a structured training program on music perception early in life and as part of the postoperative rehabilitation program for prelingually deafened children with cochlear implants would be beneficial. A longitudinal study is needed to show whether improvement of music performance in these children is measurable by use of auditory evoked potentials. *Pediatrics* 2010;125:e000 AQ:A-B

Cochlear implants have been an effective device for the treatment of deaf children for the past few decades. Significant improvements in speech and language can be observed after rehabilitation in children with an implant. Despite remarkable linguistic perception, however, it is difficult for these children to enjoy music.[1,2] Essential attributes of music include rhythm, timbre, and pitch. Previous studies have shown that perception of rhythm is easier than timbre and pitch for cochlear implant users.[3] Recognition of timbre depends, at least partly, on the discrimination of pitch in terms of fundamental frequency.[4] The ability to differentiate pitch thus plays an important role in perception of music for children with an implant. Fundamental traits of pitch that are acoustically transmitted to the auditory pathway of individuals with cochlear implants via the apparatus are much less precise than those of individuals with normal hearing.[5] Built-in restrictions for pitch perception in contemporary systems of cochlear implants arise from the electrical model of temporospatial stimulation, which in turn leads to a finite spectral resolution.[1] Efforts have been made to improve pitch resolution of cochlear implants for tonal languages and music perception[6–8]; however, the conclusions have been indecisive.

Neural correlates that are crucial for music processing have been demonstrated in individuals with cochlear implants in an electroencephalographic study.[9] Furthermore, magnetoencephalographic evidence of auditory plasticity has been noted in sudden deafness.[10,11] This plasticity facilitates tone perception in individuals with cochlear implants, which can be mirrored by the progressive optimization of neuromagnetic responses that are evoked by auditory stimuli after implantation.[12] Considering limitations of cochlear implant processing strategies for pitch differentiation, education might have a major effect on improvement of music processing by inducing plastic changes in the central auditory pathway of individuals with cochlear implants.[13] In fact, musical training has been found to be associated with improved pitch appraisal abilities in individuals with normal hearing, and comparatively poor music performance in individuals with cochlear implants might be ascribed in part to an inadequate exposure to music[5]; however, few studies exist on music performance in children with cochlear implants, and the effect of training on music perception in prelingually deafened children with cochlear implants has not been addressed. In this study, 27 prelingually deafened children with monaural cochlear implants were recruited for investigation of whether musical education improved pitch perception. Thirteen children received structured training on music before and/or after implantation. Music perception was evaluated by using a test set of pitch differentiation. For mirroring real-world auditory environments, pure tones were presented by using a tuned piano. Effect of age, gender, pitch-interval size, age of implantation, and type of cochlear implant were also addressed.

METHODS

Subjects

Twenty-seven children with congenital/prelingual deafness of profound degree (18 boys and 9 girls; age 5 to 14 years [mean: 6.7 years]) were studied (Table 1). No other neurologic deficits were identified. Thirteen children used Nucleus24 (Cochlear, Australia; left = 6, right = 7), 13 used Clarion (Advanced Bionics; left = 7, right = 6), and 1 used Med-El (MED-EL, Austria) cochlear implant system (right). Elapsed time for the evaluation of pitch perception after cochlear implantation ranged from 10 to 69 months (mean: 29 months). Thirteen children attended the same style of structured music classes at YAMAHA Music School (2–36 months; mean: 13.2). The programs included training of listening, singing, score reading, and instrument playing. They attended classes with children who had normal hearing. Subjects 4 and 5 had had musical education before the implantation. The study conformed to the Declaration of Helsinki. Written informed consent was obtained from parents with a protocol approved by the institutional ethics committee of Cheng-Hsin Rehabilitation Medical Center.

Experiment Paradigm

Experiments were conducted in an acoustically shielded room by using a tuned piano (YAMAHA, Japan). Children sat upright with eyes open, facing away from the piano at a distance of ~1 m and were instructed to attend to the auditory stimuli during experiments. A modification of a 2-alternative forced-choice task was used. Each test stimulus consisted of 2 sequential piano tones, ranging from C (256 Hz) to B (495 Hz). For avoidance of the possible effect of intensity variation on the test, the loudness was monitored on site by a sound-pressure meter and was maintained within 70 ± 6 dB SPL for loudness matching of various pitch tones. The first note was any of the following: C, D (294 Hz), E (330 Hz), F (349 Hz), G (392 Hz), A (440 Hz), or B. Once the first note was determined, the second note was presented randomly from C to B. The interval of 2 notes was thus between prime degree (2 same notes; eg, C–C) and major-seventh degree (11 semitones; eg, C–B), either ascending or descending in direction. A total of 49 (7 × 7) tone pairs were delivered to a child in 1 experiment. The task was divided into 2 stages depending on the response. Each time after

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TABLE 1 General Data for All Children

Child	Gender	Age of Child, y	Age at Implantation, mo	Device	Duration of Musical Training, mo	Duration of Cochlear Implant Use, mo	HA	Correct Rate, %					
								O	P	A	A>5	D	D>5
1	F	6	20	Clarion	0	48	Y	45.3	37.1	45.7	40.0	48.6	46.7
2	M	5	42	Clarion	3	17	Y	56.1	60.0	41.9	46.7	64.8	80.0
3	M	6	36	Nucleus	12	33	Y	44.6	42.9	55.2	76.7	26.7	40.0
4	M	10	78	Nucleus	36	11	Y	60.7	48.6	52.4	53.3	70.5	76.7
5	F	10	64	Nucleus	30	22	Y	88.2	94.3	91.4	93.3	80.0	93.3
6	F	6	53	Nucleus	0	10	Y	36.4	40.0	31.4	30.0	41.9	36.7
7	M	8	57	Clarion	0	34	Y	50.5	65.7	55.2	53.3	41.0	46.7
8	M	6	36	Nucleus	0	33	N	48.2	5.7	52.4	66.7	52.4	50.0
9	M	6	54	Clarion	24	26	Y	55.7	57.1	71.4	73.3	41.0	33.3
10	M	5	17	Nucleus	0	46	Y	46.9	40.0	43.8	53.3	51.4	43.3
11	F	6	58	Nucleus	3	13	Y	46.2	42.9	41.9	46.7	55.2	33.3
12	F	7	29	Nucleus	6	55	Y	52.1	94.3	28.6	73.3	67.6	10.0
13	M	8	22	Nucleus	0	69	Y	52.5	45.7	43.8	50.0	61.0	63.3
14	F	5	37	Nucleus	0	19	N	17.4	25.7	20.0	26.7	8.6	20.0
15	F	6	48	Nucleus	0	23	Y	69.2	68.6	67.6	83.3	67.6	66.7
16	F	5	32	Nucleus	0	24	Y	38.7	97.1	27.6	33.3	34.3	30.0
17	M	8	65	Clarion	0	25	Y	56.1	94.3	68.6	76.7	33.3	26.7
18	M	5	30	Med El	0	31	Y	55.4	62.9	55.2	70.0	50.5	50.0
19	M	6	37	Nucleus	2	31	Y	56.1	88.6	61.0	63.3	44.8	33.3
20	M	8	68	Clarion	14	36	N	37.4	42.9	37.1	36.7	38.1	30.0
21	M	6	45	Clarion	0	33	Y	46.2	20.0	41.9	36.7	56.2	66.7
22	M	6	36	Clarion	14	16	Y	68.2	82.9	72.4	80.0	54.3	73.3
23	M	14	163	Clarion	0	17	Y	89.2	97.1	95.2	93.3	79.0	90.0
24	F	5	53	Clarion	6	15	N	9.5	17.1	9.5	23.3	5.7	0.0
25	M	5	34	Clarion	0	30	N	50.2	5.7	30.5	30.0	81.0	83.3
26	M	5	32	Clarion	20	35	Y	92.5	100.0	91.4	93.3	90.5	93.3
27	M	8	86	Clarion	2	22	Y	36.4	0.0	41.0	40.0	41.9	40.0

HA indicates use of hearing aid in the other ear; Correct rate, percentage of correct response for pitch-interval differentiation; O, overall correct rate; P, correct rate for prime pitch interval; A, correct rate for ascending interval; A>5, correct rate for ascending interval over 5 semitones; D, correct rate for descending interval; D>5, correct rate for descending interval over 5 semitones.

presentation of the stimuli, the child would be asked whether the 2 notes were the same (ie, prime degree). When the 2 notes were the same, the answer was recorded as correct or incorrect. When the 2 notes were different and the answer was incorrect, the answer was recorded as incorrect. When the 2 notes were different and the answer was correct, the child would then be asked whether the second tone was higher or lower than the first tone, and this subsequent answer was recorded as correct or incorrect. There was no feedback to children on their answers. Each tone pair was presented 5 times. For avoidance the effect of random guessing of the results, the answer needed to be answered correctly at least 3 times (≥60% correct) for a single tone pair recognition response to be recorded as correct. The correct rate for each child was obtained by averaging the number of correct responses across the number of total tone pairs (49). The programming of speech processors for each child varied, on the basis of the speech intelligibility programs that were optimal for respective users.

Data Analysis

Statistical analysis was performed by using the software of SAS 8.1 (SAS Institute Inc, Chicago, IL). Performance of pitch perception in terms of correct rate was grouped into 6 sets for statistical analysis: overall, prime degree, ascending interval, ascending interval larger than perfect-fourth degree (5 semitones; eg, C–F), descending interval, and descending interval larger than perfect-fourth degree. Differences in the performance of pitch perception by pitch-interval size were analyzed by using analysis of variance. Differences of correct rate for pitch perception (cutoff value: 50%) in terms of age were evaluated by categorizing children into 2 groups: those who were older than 6 years and those who were aged ≤6 years. Gender and age differences in overall task performance of pitch perception were evaluated by using *t* test. Correlations between pitch perception and period of musical training, age of implantation, or type of cochlear implant were evaluated by using simple correlation analysis for 3 conditions, respectively: all children (Table 2), children categorized into 2 groups by age (>6 and ≤6 years; Table 3), and children categorized into 2 groups by duration of cochlear implant use (>18 and ≤8 months; Table 4). Threshold for statistical significance was set at $P < .05$.

TABLE 2 Correlation Between Variables and Correct Rate of Pitch Perception

Variable	0		P		A		A>5		D		D>5	
	r^2	P	r^2	P	r^2	P	r^2	P	r^2	P	r^2	P
Duration of musical training, mo	0.389	.045[a]	0.238	.232	0.402	.038†	0.366	.061	0.271	.172	0.303	.124
Device	0.046	.818	−0.085	.675	0.111	.581	−0.099	.624	0.026	.897	0.149	.459
Age at implantation	0.293	.138	0.146	.466	0.381	.050	0.229	.251	0.154	.445	0.226	.257

0 indicates overall correct rate; P, correct rate for prime pitch interval; A, correct rate for ascending interval; A>5, correct rate for ascending interval over 5 semitones; D, correct rate for descending interval; D>5, correct rate for descending interval over 5 semitones.

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[a] Threshold for statistical significance by using simple correlation analysis was set at $P < .05$.

TABLE 3 Correlation Between Variables and Correct Rate of Pitch Perception Adjusted for Age (>6 or ≤6 Years)

Variable	0		P		A		A>5		D		D>5	
	r^2	P	r^2	P	r^2	P	r^2	P	r^2	P	r^2	P
>6 y (*n* = 9)												
Duration of musical training, mo	0.293	.445	0.012	.975	0.145	.710	0.074	.850	0.459	.214	0.442	.234
Device	−0.261	.497	−0.169	.664	0.120	.758	−0.183	.637	−0.660	.053	−0.253	.511
Age at implantation	0.493	.178	0.115	.768	0.635	.066	0.358	.344	0.252	.513	0.492	.178
≤6 y (*n* = 18)												
Duration of musical training, mo	0.435	.071	0.382	.118	0.618	.006[a]	0.584	.011[a]	0.098	.698	0.151	.550
Device	0.132	.602	−0.101	.691	0.070	.783	−0.110	.663	0.231	.357	0.338	.170
Age at implantation	−0.189	.453	−0.122	.631	−0.126	.619	−0.117	.645	−0.176	.486	−0.254	.310

0 indicates overall correct rate; P, correct rate for prime pitch interval; A, correct rate for ascending interval; A>5, correct rate for ascending interval over 5 semitones; D, correct rate for descending interval; D>5, correct rate for descending interval over 5 semitones.

[a] Threshold for statistical significance by using simple correlation analysis was set at $P < .05$.

TABLE 4 Correlation Between Variables and Correct Rate of Pitch Perception Adjusted for Duration of Cochlear Implant Use (>18 or ≤18 Months)

Variable	0		P		A		A>5		D		D>5	
	r^2	P	r^2	P	r^2	P	r^2	P	r^2	P	r^2	P
>18 mo (*n* = 20)												
Duration of musical training, mo	0.564	.010[a]	0.353	.127	0.625	.003[a]	0.549	.012[a]	0.295	.207	0.305	.191
Device	−0.005	.983	−0.201	.396	0.071	.767	−0.240	.308	0.064	.787	0.114	.632
Age at implantation	0.020	.932	−0.051	.832	0.238	.312	0.064	.787	−0.163	.492	−0.043	.859
≤18 mo (*n* = 7)												
Duration of musical training, mo	0.133	.776	−0.057	.903	0.072	.878	0.078	.868	0.216	.642	0.265	.566
Device	0.169	.717	0.402	.371	0.246	.594	0.369	.415	−0.109	.816	0.194	.677
Age at implantation	0.595	.159	0.539	.212	0.657	.109	0.603	.152	0.500	.253	0.421	.346

0 indicates overall correct rate; P, correct rate for prime pitch interval; A, correct rate for ascending interval; A>5, correct rate for ascending interval over 5 semitones; D, correct rate for descending interval; D>5, correct rate for descending interval over 5 semitones.

[a] Threshold for statistical significance by using simple correlation analysis was set at $P < .05$.

RESULTS

Differences of Correct Rate for Pitch Perception by Pitch-Interval Size, Gender, and Age

Overall, the correct rate for pitch perception varied between 9.5% and 92.5% (Table 1). Fifteen children (13 boys and 2 girls; mean age: 7.3 years) accomplished the test with a correct rate ≥50% (ie, chance level). When children were categorized by gender/age, boys and children who were older than 6 years tended to accomplish the test with a correct rate ≥50% than girls and children who were aged ≤6 years, respectively. The mean correct rate of overall task performance was better for boys (56%) and for children who were older than 6 years (58%) than for girls (45%) and for children who were aged ≤6 years (49%), respectively, although the difference was insignificant ($P = .237$ for gender, $P = .243$ for age; Table 5). There were no differences in the performance of pitch perception among various conditions of pitch-interval size ($F_{5,156} = 0.342$, $P = .887$; Fig 1).

Correlation Between Pitch Perception and Period of Musical Training, Age of Implantation, or Type of Cochlear Implant

For all children combined, the duration of musical training positively correlated with the correct rate of overall ($r^2 = 0.389$, $P = .045$) and ascending pitch-interval ($r^2 = 0.402$, $P = .038$; Table 2) perception. There was no correlation be- **T5**
tween pitch perception and the age of implantation or type of cochlear implant.

To assess the effect of age on the significance of correlation, we conducted ad- **F1**

TABLE 5 Differences in Correct Rate for Pitch Perception (Cutoff Value: 50%) by Gender and Age

Pitch Interval	Total		Gender				Age			
			Boy		Girl		>6 y		≤6 y	
	≥50%	<50%	≥50%	<50%	≥50%	<50%	≥50%	<50%	≥50%	<50%
O	15	12	13	5	3	6	7	2	8	10
P	13	14	9	9	4	5	5	4	8	10
A	13	14	11	7	2	7	5	4	8	10
A>5	16	11	13	5	3	6	7	2	9	9
D	15	12	11	7	4	5	5	4	10	8
D>5	12	15	10	8	2	7	4	5	8	10

O indicates overall correct rate; P, correct rate for prime pitch interval; A, correct rate for ascending interval; A>5, correct rate for ascending interval over 5 semitones; D, correct rate for descending interval; D>5, correct rate for descending interval over 5 semitones.

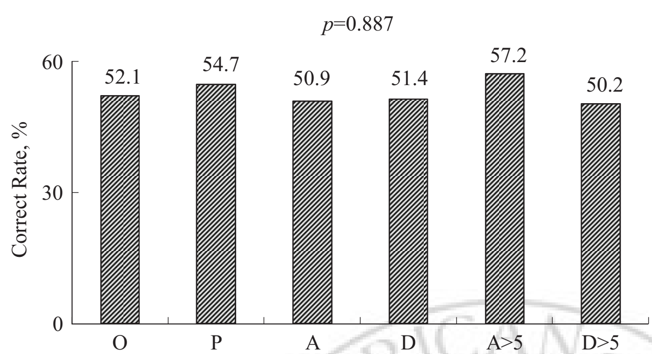

FIGURE 1
Differences of correct rate for pitch perception by pitch-interval size. There were no differences in the performance of pitch perception between various conditions of pitch-interval size ($F_{5,156}$ = 0.342, P = .887). O indicates overall correct rate; P, correct rate for prime pitch interval; A, correct rate for ascending interval; A > 5, correct rate for ascending interval over 5 semitones; D, correct rate for descending interval; D > 5, correct rate for descending interval over 5 semitones.

ditional analysis with children separated by age >6 and ≤6 years (ie, preschool). For children who were older than 6 years, there was no correlation between pitch perception and duration of musical training, age of implantation, or type of cochlear implant. For children who were aged ≤6 years, the duration of musical training strongly correlated with correct rate of ascending pitch-interval perception (r^2 = 0.618, P = .006) and ascending pitch-interval perception over 5 semitones (r^2 = 0.584, P = .011; Table 3); there was no correlation between pitch perception and age of implantation or type of cochlear implant.

Because some patients who were older than 6 years had had a longer period of music training, we conducted additional analysis with children by duration of cochlear implant use >18 and ≤18 months to assess the effect of implant use duration on the significance of correlation. For children with duration of implant use >18 months, the duration of musical training significantly correlated with correct rate of overall (r^2 = 0.564, P = .010) and ascending pitch-interval (r^2 = 0.625, P = .003) perception; there was no correlation between pitch perception and age of implantation or type of cochlear implant. For children with duration of implant use ≤18 months, there was no correlation between pitch perception and duration of musical training, age of implantation, or type of cochlear implant (Table 4).

DISCUSSION

Insignificant Effect of Pitch-Interval Size on Pitch Perception

In this study, the size of the pitch interval did not considerably affect the performance of pitch perception in prelingually deafened children with a cochlear implant (Fig 1, Table 1). For the pitch perception of descending interval of >5 semitones, however, the correct rate was lower than for that of descending interval of ≤5 semitones. This finding was paradoxic because it is reasonable to infer that a larger pitch interval is easier to perceive correctly than a smaller one. It might suggest a general intricacy in pitch perception of descending interval for cochlear implant users of all ages, because scores of "falling" melodic contour perception was much lower than those of a "rising" one (even lower than chance level) for adults with cochlear implants in 1 previous study.[2]

Various factors have been reported to affect the pitch perception in children with implants. The insignificant effect of pitch-interval size on the differentiation tasks in this study could be ascribed partly to the channel setting of sound frequency and/or tone perception changes caused by cochlear implants.[14,15] Obvious disparity could occur between frequencies that are assigned to electrodes and those that are actually perceived by cochlear recipients, possibly related to the channel setting of frequency during mapping.[15] After appropriate mapping, pitch perception via cochlear implants might still have great spectral variations for years, which can echo the extent of damage of peripheral innervation patterns in the early stage and plasticity-dependent modifications in the later stage of implant use.[14] In fact, effect of musical training was much more significant for pitch perception of ascending interval of >5 semitones in children with duration of cochlear implant use of >18 months. Our results showed that a duration ≤18 months of cochlear implant use might not be long enough for the plasticity-dependent adaptation of aforementioned disparity to happen (Table 4).

Another possibility for better results with smaller intervals is the use of loudness instead of pitch cues for tone discrimination. It has been shown that a musical note at the center of a frequency band for 1 electrode may be louder than that at the edge of the frequency band[16]; besides, a musical note at the edge of the band may activate 2 electrodes instead of 1.[17] The way these different musical intervals align with the frequency ranges allocated to each electrode (ie, MAPs) potentially provide additional cues for tone discrimination; however, it has been revealed that electrode activation differences did not influence recognition performance with low-frequency (104–262 Hz) and middle-frequency (207–523 Hz) melodies.[16] Because the frequency range in our study lies between 256 and 495 Hz, electrode activation differences did not seem to be a confounding factor.

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One more plausible explanation is the abnormal frequency-coding resolution that results from the disorganization of tonotopic maps in the auditory cortices of prelingually deafened children. Topographically arranged representations of frequency-tuning maps (ie, tonotopy) have been known to exist in the auditory system.[18] The orderly maps of tonotopy start at the cochlea and continue through to the auditory cortex. Mechanisms underlying the development of tonotopic maps remain unknown. In previous studies, however, deprivation of auditory input as a result of cochlear ablation and/or misexpression of essential proteins in the auditory pathway in neonatal birds and mammals were shown to affect the normal development of tonotopic maps.[18–21] This might in turn lead to a diminished capacity of the auditory system to decode the acoustic information in terms of frequency resolution,[18,19,21] which could underpin our finding of the insignificant effect for pitch-interval size on the differentiation tasks.

Musical Training Improves Pitch Perception

One major and novel finding in this study is that the duration of musical training correlates with music perception in prelingually deafened children with a cochlear implant; that is, higher scores for the performance of pitch perception positively correlated with a longer duration of musical training in children with implants. Furthermore, the performance for the perception of ascending interval was significantly enhanced after the musical training (Table 2).

Our finding was in line with a previous study, in which structured training was suggested to have a positive correlation with recognition and appraisal of the timbre of musical instruments by postlingually deafened cochlear implant recipients.[4] After 12 weeks of training, implant recipients who were assigned to the training group showed significant improvement in timbre recognition and appraisal compared with the control group. The effect of training in music perception of prelingual cochlear implantees, however, was not addressed in the aforementioned study. As far as we know, our research is the first study to report such a finding of enhanced music perception by musical training in prelingually deafened children with cochlear implants.

Mechanisms underlying the enhanced performance of pitch perception after musical training in prelingually deafened children with cochlear implants remain unclear. One possibility is the modification of disorganized tonotopy through auditory plasticity in the central auditory pathway of our subjects. The reinstatement of afferent input via cochlear implantation could consequently launch a cascade of plastic changes in the auditory system. Such reorganization, probably coupled with essential changes in neurotransmission or neuromodulation, might assist in reducing additional deterioration in the nervous system that results from cessation of electrical input as a result of cochlear damage.[22,23] This might reverse the disrupted tonotopic maps toward a relatively "normal" organization,[24] which in turn may lead to better development of frequency tuning in the auditory cortices. In children with normal hearing, improved music perception via music education has been revealed by increased auditory evoked fields, possibly as a result of a greater number and/or synchronous activity of neurons.[13] With the intervention of musical training, it seemed that the modified organization of tonotopy in prelingually deafened children could also be further optimized for a more delicate resolution of frequency spectrum, as is indexed by a better performance of pitch perception in this study.

Effect of Age and Duration of Cochlear Implant Use on Pitch Perception

In this study, the performance of pitch perception was better in children who had cochlear implants and were older than 6 years than in those who were aged ≤6 years (Table 5). This might be attributable to the younger children's not understanding the test itself. Actually, some of our older children seemed to have had longer training periods (Table 1). Our finding was in line with previous studies in which older children with cochlear implants tended to score higher on tonal language performance.[25,26] At least partly, this could also be attributed to the aforementioned influence of auditory plasticity. In an operational context, the generally longer duration of auditory rehabilitation and thus more cognitive experiences of acoustic stimulation led to the enhanced skills for musical perception of our older children with longer duration of cochlear implant use (Table 4). Nevertheless, the effect of musical training was much more significant for children who are aged ≤6 years than for those who were older than 6 years (Table 3). The seeming gender effect observed in Table 5 might actually be attributable to the age effect, because the mean age of boys (6.9 years) was larger than that of girls (6.2 years), although the difference was not significant (P = .404, t test). Our finding thus verified that later pitch sensations in children with implants possibly reflected higher level and/or experience-dependent plastic changes in the auditory pathway[14] and that musical training in the sensitive period (≤6 years of age) would be beneficial for development of pitch sensations.[27]

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Limits of This Study

Although pitch ranking was assessed, testing intervals that were used in this research may be too small for the evaluation of real-world music appreciation. It has been reported that postlingual cochlear implantees were generally less accurate in identification of formerly well-known music pieces than were individuals with normal hearing.[28] Additional study with larger intervals/musical extracts is thus necessary to determine whether improvement of pitch discrimination could result in better music perception in prelingual cochlear implantees.

Although loudness was monitored to avoid the possible effect of intensity variation in this study, it is clear that loudness matching of various tones from a piano cannot be as precise as that of computerized sounds. Because musical training could improve loudness discrimination in individuals with normal hearing,[29] the training might also improve pitch differentiation by advancing use of available loudness differences that are created unintentionally by cochlear implant programming. Future research that uses computerized tones with a more precise matching of loudness and analyzing how the results relate to MAPs will be helpful to separate tone discrimination from loudness differences.

CONCLUSIONS

The ability to discriminate sounds was improved with musical experience in prelingually deafened children with cochlear implants. Children who had implants and attended music classes revealed significant differences compared with those without musical training. We suggest that structured training on music perception should begin early in life and be included in the postoperative rehabilitation program for prelingually deafened children with cochlear implants. Because auditory plasticity might play an important role in the enhancement of pitch perception, our research invites additional studies on a larger group of children with implants to correlate neuroelectrical changes over time from cochlear implantation and music performance. A longitudinal study is also needed to show whether such neuroelectrical responses change with improvement of music performance in prelingually deafened children with a cochlear implant.

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REFERENCES

1. McDermott HJ. Music perception with cochlear implants: a review. *Trends Amplif.* 2004;8(2):49–82
2. Galvin JJ 3rd, Fu QJ, Nogaki G. Melodic contour identification by cochlear implant listeners. *Ear Hear.* 2007;28(3):302–319
3. Gfeller K, Lansing CR. Melodic, rhythmic, and timbral perception of adult cochlear implant users. *J Speech Hear Res.* 1991;34(4):916–920
4. Gfeller K, Witt S, Adamek M, et al. Effects of training on timbre recognition and appraisal by postlingually deafened cochlear implant recipients. *J Am Acad Audiol.* 2002;13(3):132–145
5. Sucher CM, McDermott HJ. Pitch ranking of complex tones by normally hearing subjects and cochlear implant users. *Hear Res.* 2007;230(1–2):80–87
6. Firszt JB, Koch DB, Downing M, Litvak L. Current steering creates additional pitch percepts in adult cochlear implant recipients. *Otol Neurotol.* 2007;28(5):629–636
7. Hamzavi J, Arnoldner C. Effect of deep insertion of the cochlear implant electrode array on pitch estimation and speech perception. *Acta Otolaryngol.* 2006;126(11):1182–1187
8. Busby PA, Plant KL. Dual electrode stimulation using the nucleus CI24RE cochlear implant: electrode impedance and pitch ranking studies. *Ear Hear.* 2005;26(5):504–511
9. Koelsch S, Wittfoth M, Wolf A, Muller J, Hahne A. Music perception in cochlear implant users: an event-related potential study. *Clin Neurophysiol.* 2004;115(4):966–972
10. Li LPH, Shiao AS, Chen LF, et al. Healthy-side dominance of middle- and long-latency neuromagnetic fields in idiopathic sudden sensorineural hearing loss. *Eur J Neurosci.* 2006;24(3):937–946
11. Po-Hung Li L, Shiao AS, Lin YY, et al. Healthy-side dominance of cortical neuromagnetic responses in sudden hearing loss. *Ann Neurol.* 2003;53(6):810–815
12. Pantev C, Dinnesen A, Ross B, Wollbrink A, Knief A. Dynamics of auditory plasticity after

cochlear implantation: a longitudinal study. *Cereb Cortex.* 2006;16(1):31–36

13. Pantev C, Oostenveld R, Engelien A, Ross B, Roberts LE, Hoke M. Increased auditory cortical representation in musicians. *Nature.* 1998;392(6678):811–814
14. Reiss LA, Turner CW, Erenberg SR, Gantz BJ. Changes in pitch with a cochlear implant over time. *J Assoc Res Otolaryngol.* 2007;8(2):241–257
15. Nardo WD, Cantore I, Cianfrone F, Melillo P, Fetoni AR, Paludetti G. Differences between electrode-assigned frequencies and cochlear implant recipient pitch perception. *Acta Otolaryngol.* 2007;127(4):370–377
16. Singh S, Kong YY, Zeng FG. Cochlear implant melody recognition as a function of melody frequency range, harmonicity, and number of electrodes. *Ear Hear.* 2009;30(●●●): AQ: I 160–168
17. Donaldson GS, Kreft HA, Litvak L. Place-pitch discrimination of single- versus dual-electrode stimuli by cochlear implant users (L). *J Acoust Soc Am.* 2005;118(2):623–626
18. Huffman KJ, Cramer KS. EphA4 misexpression alters tonotopic projections in the auditory brainstem. *Dev Neurobiol.* 2007;67(12):1655–1668
19. Yu X, Sanes DH, Aristizabal O, Wadghiri YZ, Turnbull DH. Large-scale reorganization of the tonotopic map in mouse auditory midbrain revealed by MRI. *Proc Natl Acad Sci USA.* 2007;104(29):12193–12198
20. Zhang Y, Dyck RH, Hamilton SE, Nathanson NM, Yan J. Disrupted tonotopy of the auditory cortex in mice lacking M1 muscarinic acetylcholine receptor. *Hear Res.* 2005;201(1–2):145–155
21. Harrison RV, Ibrahim D, Mount RJ. Plasticity of tonotopic maps in auditory midbrain following partial cochlear damage in the developing chinchilla. *Exp Brain Res.* 1998;123(4):449–460
22. Durham D, Park DL, Girod DA. Central nervous system plasticity during hair cell loss and regeneration. *Hear Res.* 2000;147(1–2):145–159
23. Illing RB, Reisch A. Specific plasticity responses to unilaterally decreased or increased hearing intensity in the adult cochlear nucleus and beyond. *Hear Res.* 2006;216–217:189–197
24. Guiraud J, Besle J, Arnold L, et al. Evidence of a tonotopic organization of the auditory cortex in cochlear implant users. *J Neurosci.* 2007;27(29):7838–7846
25. Lee KY, van Hasselt CA. Spoken word recognition in children with cochlear implants: a five-year study on speakers of a tonal language. *Ear Hear.* 2005;26(4 suppl):30S–37S
26. Huang CY, Yang HM, Sher YJ, Lin YH, Wu JL. Speech intelligibility of Mandarin-speaking deaf children with cochlear implants. *Int J Pediatr Otorhinolaryngol.* 2005;69(4):505–511
27. Baharloo S, Service SK, Risch N, Gitschier J, Freimer NB. Familial aggregation of absolute pitch. *Am J Hum Genet.* 2000;67(3):755–758
28. Gfeller K, Olszewski C, Rychener M, et al. Recognition of “real-world” musical excerpts by cochlear implant recipients and normal-hearing adults. *Ear Hear.* 2005;26(3):237–250
29. Plath P. Influence of training effect on the loudness differentiation-threshold in normal hearing persons [in German]. *Arch Klin Exp Ohren Nasen Kehlkopfheilkd.* 1968;190(3):286–290