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Strategies to Improve Music Perception in Cochlear Implantees

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1. Introduction

Cochlear implants have been an effective device for the management of patients with total or profound hearing loss over the past few decades. Significant improvements in speech and language can be observed in implantees following rehabilitation. In spite of remarkable linguistic perception, however, it is difficult for these patients to enjoy music although we did see some "superstars" for music performance in our patients. This article aimed to clarify current opinions on the strategies to improve music perception ability in this population of subjects. In part I, we included one of our previous work (Chen et al., 2010) talking about the effect of music training on pitch perception in prelingually deafened children with a cochlear implant. In part II, other factors related to the improvement of music perception in cochlear implantees were discussed, including residual hearing, bimodal hearing, and coding strategies. Evidences from results of our researches and from literature review will both be presented.

2. Part I: Music training improves pitch perception in prelingually deafened children with cochlear implants

2.1 Introduction

Cochlear implants have been an effective device for the management of deaf children over the past few decades. Significant improvements in speech and language can be observed in implanted children following rehabilitation. In spite of remarkable linguistic perception, however, it is difficult for these children to enjoy music (Galvin et al., 2007; McDermott, 2004). 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 (Gfeller & Lansing, 1991). Recognition of timbre depends, at least partly, on the

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discrimination of pitch in terms of fundamental frequency (Gfeller et al., 2002). The ability to differentiate pitch thus plays an important role in perception of music for implanted children. Fundamental traits of pitch acoustically transmitted to the auditory pathway of cochlear implantees via the apparatus are much less precise than those of normal-hearing subjects (Sucher & McDermott, 2007). 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 (McDermott, 2004). Efforts have been made to improve pitch resolution of cochlear implants for tonal languages and music perception (Busby & Plant, 2005; Firszt et al., 2007; Hamzavi & Arnoldner, 2006). However, the conclusions have been indecisive.

Neural correlates crucial for music processing have been demonstrated in cochlear implantees in an electroencephalographic study (Koelsch et al., 2004). Furthermore, magnetoencephalographic evidence of auditory plasticity has been noted in sudden deafness (Li, 2003, 2006). This plasticity facilitates tone perception in cochlear implantees, which can be mirrored by the progressive optimization of neuromagnetic responses evoked by auditory stimuli after implantation (Pantev et al., 2006). 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 cochlear implantees (Pantev et al., 1998). In fact, musical training has been found to be associated with improved pitch appraisal abilities in normal-hearing subjects, and comparatively poor music performance in cochlear implantees might be ascribed in part to an inadequate exposure to music (Sucher & McDermott, 2007). However, few studies exist on music performance in implanted children, and the effect of training on music perception in prelingually deafened children with cochlear implants has not been addressed. In the present study, twenty-seven prelingually deafened children with monaural cochlear implant were recruited to investigate whether or not musical education improved pitch perception. Thirteen subjects received structured training on music before and/or after implantation. Music perception was evaluated by using a test-set of pitch differentiation. To mirror real-world auditory environments, pure tones were presented using a tuned piano. Effect of age, gender, pitch-interval size, age of implantation, and type of cochlear implant were also addressed.

2.2 Patients and methods

2.2.1 Subjects

Twenty-seven subjects with congenital/prelingual deafness of profound degree (eighteen males and nine females; 5~14y/o, mean=6.7) were studied (Table 1). No other neurological deficits were identified. Thirteen subjects used Nucleus24 (Cochlear™, Australia)(left=6, right=7), thirteen subjects used Clarion (Advanced Bionics™, USA)(left=7, right=6), and one subject 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). Thirteen subjects 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 instruments-playing. They attended classes with normal-hearing children. Subject 4 and 5 have 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 Institutional Ethics Committee of Cheng-Hsin General Hospital.

No	Gender	Age (yr)	Age* (mo)	Device	DuM (mo)	DuC (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

No, participant number; Age, y/o; Age*, age at implantation; Device, type of cochlear implant; DuM, duration of musical training (months); DuC, duration of cochlear implant use (months); HA, 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.

Table 1. General data for all participants.

2.2.2 Experiment paradigm

Experiments were conducted in an acoustically-shielded room using a tuned piano (YAMAHA™, Japan). Subjects sat upright with eyes open, facing away from the piano at a distance of about 1 meter, and were instructed to attend to the auditory stimuli during experiments. A modification of a two-alternative forced choice task was used. Each test-stimulus consisted of two sequential piano tones, ranging from C (256 Hz) to B (495 Hz). To avoid 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 different 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 two notes was thus between prime degree (two same notes, e.g."C-C") and major-seventh degree (eleven semitones, e.g."C-B"), either ascending or descending in direction. A total of 49 (7x7) tone-pairs were delivered to a subject in one experiment. The task was divided into two stages depending on the response. Each time after presentation of the stimuli, the subject would be asked whether the two notes were the same (i.e.,prime degree) or not. When the two notes were the same, the answer was recorded as correct or incorrect. When the two notes were different and the answer was incorrect, the answer was recorded as incorrect. When the two notes were different and the answer was correct, the subject would then be asked if 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 subjects on their answers. Each tone-pair was presented five times. To avoid the effect of random guessing of the results, the answer needed to be correctly answered at least three times (≥60% correct) for a single tone-pair recognition response to be recorded as correct. The correct rate for each subject was obtained by averaging the number of correct responses across the number of total tone pairs (49). The programming of speech processors for each subject varied, based on the speech intelligibility programs optimal for respective users.

2.2.3 Data analysis

Statistical analysis was performed using the software of SAS8.1 (SAS Institute Inc., USA). Performance of pitch perception in terms of correct rate was grouped into six sets for statistical analysis: overall, prime degree, ascending interval, ascending interval larger than perfect-fourth degree (five semitones, e.g."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 using analysis of variance. Differences of correct rate for pitch perception (cutoff value=50%) in terms of age were evaluated by dividing subjects into two groups: subjects >6 and subjects ≤6 y/o. Gender and age differences in overall task performance of pitch perception were evaluated using t-test. Correlations between pitch perception and period of musical training, age of implantation, or type of cochlear implant were evaluated using simple correlation analysis for three conditions respectively: all subjects, subjects divided into two groups by age (>6 and ≤6 y/o), and subjects divided into two groups by duration of cochlear implant use (>18 and ≤18 months). Threshold for statistical significance was set at $P < 0.05$.

2.3 Results

2.3.1 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 subjects (13 male and 2 female, mean age=7.3 y/o) accomplished the test with a correct rate ≥50% (i.e., chance level). When subjects were divided by gender/age, boys/subjects >6 y/o tended to accomplish the test with a correct rate ≥50% than girls/subjects ≤6 y/o, respectively. The mean correct rate of overall task performance was better for boys (56%)/subjects >6 y/o (58%) than for girls (45%)/subjects ≤6 y/o (49%), respectively, although the difference was insignificant (p=0.237 for gender, p=0.243 for age; Table 2). There were no differences in the performance of pitch perception between various conditions of pitch-interval size (F(5,156)=0.342, p=0.887; Figure 1).

Pitch Interval	Total		Gender				Age			
			Boy		Girl		> 6 yrs		≦ 6 yrs	
	≧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

Age, y/o; Correct rate at cutoff value of 50% for pitch perception; 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.

Table 2. Differences in correct rate for pitch perception (cutoff value=50%) by gender and age.

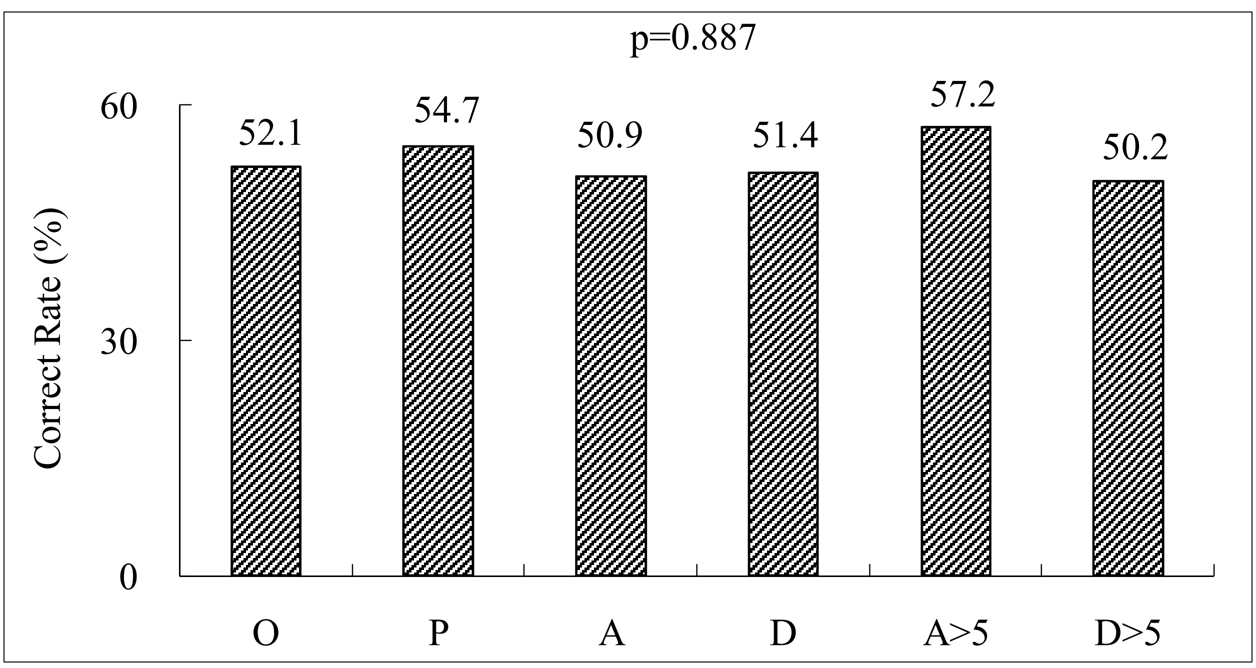

Fig. 1. Differences of correct rate for pitch perception by pitch-interval size. There were no differences in the performance of pitch perception between various conditions of pitch-interval size (F(5,156) = 0.342, p=0.887). O, overall correct rate; P, correct rate for prime pitch interval; A, correct 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.

2.3.2 Correlation between pitch perception and period of musical training, age of implantation, or type of cochlear implant (Table 3, 4a~d)

For all subjects combined, the duration of musical training positively correlated with the correct rate of overall (r^2=0.389, p=0.045) and ascending pitch-interval (r^2=0.402, p=0.038) perception. There is no correlation between pitch perception and the age of implantation or type of cochlear implant.

To assess the effect of age on the significance of correlation, additional analysis was conducted with children separated by age >6 and ≤6 y/o (i.e., preschool). For children >6 y/o, there is no correlation between pitch perception and duration of musical training, age of implantation, or type of cochlear implant. For children ≤6 y/o, the duration of musical training strongly correlated with correct rate of ascending pitch-interval (r^2=0.618, p=0.006) and ascending pitch-interval over 5 semitones (r^2=0.584, p=0.011) perception; there is no correlation between pitch perception and age of implantation or type of cochlear implant.

	O		P		A		A>5		D		D>5	
Variable	r^2	p	r^2	p	r^2	p	r^2	p	r^2	p	r^2	p
DuM(mo)	0.389	0.045†	0.238	0.232	0.402	0.038†	0.366	0.061	0.271	0.172	0.303	0.124
Device	0.046	0.818	-0.085	0.675	0.111	0.581	-0.099	0.624	0.026	0.897	0.149	0.459
Age*	0.293	0.138	0.146	0.466	0.381	0.050	0.229	0.251	0.154	0.445	0.226	0.257

Threshold for statistical significance using simple correlation analysis was set at P < 0.05 (denoted as †). r^2, correlation coefficient; DuM, duration of musical training (months); Device, type of cochlear implant; Age*, age at implantation; 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.

Table 3. Correlation between variables and correct rate of pitch perception.

Since some patients >6 y/o have had a longer period of music training, additional analysis was conducted with children separated by duration of cochlear implant use >18 and ≤18

	O		P		A		A>5		D		D>5	
Variable	r^2	p	r^2	p	r^2	p	r^2	p	r^2	p	r^2	p
DuM(mo)	0.293	0.445	0.012	0.975	0.145	0.710	0.074	0.850	0.459	0.214	0.442	0.234
Device	-0.261	0.497	-0.169	0.664	0.120	0.758	-0.183	0.637	-0.660	0.053	-0.253	0.511
Age*	0.493	0.178	0.115	0.768	0.635	0.066	0.358	0.344	0.252	0.513	0.492	0.178

Correlation between variables and correct rate of pitch perception (> 6 years old, n=9).

	O		P		A		A>5		D		D>5	
Variable	r^2	p	r^2	p	r^2	p	r^2	p	r^2	p	r^2	p
DuM(mo)	0.435	0.071	0.382	0.118	0.618	0.006†	0.584	0.011†	0.098	0.698	0.151	0.550
Device	0.132	0.602	-0.101	0.691	0.070	0.783	-0.110	0.663	0.231	0.357	0.338	0.170
Age*	-0.189	0.453	-0.122	0.631	-0.126	0.619	-0.117	0.645	-0.176	0.486	-0.254	0.310

Correlation between variables and correct rate of pitch perception (≤ 6 years old, n=18).

For description, see Table 3.

Table 4a. and 4b. Correlation between variables and correct rate of pitch perception adjusted for age (> 6 or ≤ 6 years old).

	O		P		A		A>5		D		D>5	
Variable	r^2	p	r^2	p	r^2	p	r^2	p	r^2	p	r^2	p
DuM(mo)	0.564	0.010†	0.353	0.127	0.625	0.003†	0.549	0.012†	0.295	0.207	0.305	0.191
Device	-0.005	0.983	-0.201	0.396	0.071	0.767	-0.240	0.308	0.064	0.787	0.114	0.632
Age*	0.020	0.932	-0.051	0.832	0.238	0.312	0.064	0.787	-0.163	0.492	-0.043	0.859

Correlation between variables and correct rate of pitch perception (Duration of cochlear implant use > 18 months, n=20).

	O		P		A		A>5		D		D>5	
Variable	r^2	p	r^2	p	r^2	p	r^2	p	r^2	p	r^2	p
DuM(mo)	0.133	0.776	-0.057	0.903	0.072	0.878	0.078	0.868	0.216	0.642	0.265	0.566
Device	0.169	0.717	0.402	0.371	0.246	0.594	0.369	0.415	-0.109	0.816	0.194	0.677
Age*	0.595	0.159	0.539	0.212	0.657	0.109	0.603	0.152	0.500	0.253	0.421	0.346

Correlation between variables and correct rate of pitch perception (Duration of cochlear implant use ≤ 18 months, n=7).

For description, see Table 3.

Table 4c. and 4d. Correlation between variables and correct rate of pitch perception adjusted for duration of cochlear implant use (> 18 or ≤ 18 months).

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=0.010) and ascending pitch-interval (r^2=0.625, p=0.003) perception; there is no correlation between pitch perception and age of implantation or type of cochlear implant. For children with duration of implant use ≤18 months, there is no correlation between pitch perception and duration of musical training, age of implantation, or type of cochlear implant.

2.4 Discussion

2.4.1 Insignificant effect of pitch-interval size on pitch perception

In the present study, the size of the pitch interval did not considerably affect the performance of pitch perception in subjects of prelingually deafened children with a cochlear implant (Figure 1, Table 1). For the pitch perception of descending interval >5 semitones, however, the correct rate was lower than for that of descending interval ≤5 semitones. This finding was paradoxical since it's reasonable to infer that a larger pitch interval is easier to perceive correctly than a smaller one. It might imply a general intricacy in pitch perception of descending interval for cochlear implant users of all age, since scores of "falling" melodic contour perception was much lower than those of "rising" one (even lower than chance level) for adult cochlear implantees in one previous study (Galvin et al., 2007; McDermott, 2004).

Various factors have been reported to affect the pitch perception in implanted children. The insignificant effect of pitch-interval size on the differentiation tasks in the present study could be ascribed partly to the channel-setting of sound frequency and/or tone perception changes caused by cochlear implants (Nardo et al., 2007; Reiss et al., 2007).

Obvious disparity could occur between frequencies assigned to electrodes and those actually perceived by cochlear recipients possibly related to the channel-setting of frequency during mapping (Nardo et al., 2007). 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 innervations patterns in the early stage and plasticity-dependent modifications in the later stage of implant use (Reiss et al., 2007). In fact, effect of musical training was much more significant for pitch perception of ascending interval >5 semitones in children with duration of cochlear implant use >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 4c~d).

Another possibility for better results with smaller intervals might be 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 one electrode may be louder than that at edge of the frequency band (Singh et al., 2009). Besides, a musical note at the edge of the band may activate two electrodes instead of one (Donaldson et al., 2005). The way these different musical intervals align with the frequency ranges allocated to each electrode (i.e., MAPs) potentially provide additional cues for tones discrimination. However, it has been revealed that electrode activation differences did not influence recognition performance with low- (104–262Hz) and middle-frequency (207–523Hz) melodies (Singh et al., 2009). Since the frequency range in our study lies between 256 and 495Hz, electrode activation differences did not seem to be a confounding factor in our study.

One more plausible explanation is the abnormal frequency-coding resolution resulting from the disorganization of tonotopic maps in the auditory cortices of those prelingually deafened children. Topographically arranged representations of frequency-tuning maps (i.e.,tonotopy) have been known to exist in the auditory system (Huffman & Cramer, 2007). The orderly maps of tonotopy start at the cochlea and continue through to the auditory cortex. Mechanisms underlying the development of tonotopic maps remained unknown. In previous studies, however, deprivation of auditory input due to cochlear ablation and/or misexpression of essential proteins in the auditory pathway in neonatal birds and mammals have been shown to affect the normal development of tonotopic maps (Harrison et al., 1998; Huffman & Cramer, 2007; Yu et al., 2007; Zhang et al., 2005). This might in turn lead to a diminished capacity of the auditory system to decode the acoustic information in terms of frequency resolution (Harrison et al., 1998; Huffman & Cramer, 2007; Yu et al., 2007), which could underpin our finding of the insignificant effect for pitch-interval size on the differentiation tasks.

2.4.2 Musical training improving pitch perception

One major and novel finding in this study is that the duration of musical training correlates with music perception in subjects of 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 implanted children. Furthermore, the performance for the perception of ascending interval was significantly enhanced after the musical training (Table 3).

Our finding was in line with a previous study, in which structured training was suggested to have positive correlation with recognition and appraisal of the timbre of musical instruments by postlingually deafened cochlear implant recipients (Gfeller et al., 2002). After twelve weeks of training, those implant recipients assigned to the training group showed significant improvement in timbre recognition and appraisal compared to 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 present research is the first study ever reporting such 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 those prelingually deafened children with cochlear implants remained 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 further deterioration in the nervous system resulting from cessation of electrical input due to cochlear damage (Durham et al., 2000; Illing & Reisch, 2006). This might reverse the disrupted tonotopic maps toward a relatively "normal" organization (Guiraud et al., 2007), which in turn may lead to a better development of frequency tuning in the auditory cortices. In normal-hearing children, improved music perception via music education has been revealed by increased auditory evoked fields, possibly due to a greater number and/or synchronous activity of neurons (Pantev et al., 1998). With the intervention of musical training, it seemed that the modified organization of tonotopy in subjects of 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 the present study.

2.4.3 Effect of age and duration of cochlear implant use on pitch perception

In the present study, the performance of pitch perception is better in children with cochlear implants >6 y/o than those ≤6 y/o (Table 2). This might be due to the younger children not understanding the test itself. Actually, some of our older children appear to have 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 (Huang et al., 2005; Lee & van Hasselt, 2005). 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 lead to the enhanced skills for musical perception of our older children with longer duration of cochlear implant use (Table 4c~d). Nevertheless, the effect of musical training is much more significant for children ≤6 y/o than those >6 y/o (Table 4a~b). The seemingly gender effect observed in Table 2 might actually be due to the age effect, since the mean age of boys (6.9 y/o) was larger than that of girls (6.2 y/o), though the difference was not significant (p=0.404, t-test). Our finding thus verified that later pitch sensations in implanted children possibly reflected higher-level and/or experience-dependent plastic changes in the auditory pathway (Reiss et al., 2007), and that musical training in the sensitive period (≤6 y/o) would be beneficial for development of pitch sensations (Baharloo et al., 2000).

2.4.4 Limits of this study

While pitch ranking was assessed, testing intervals 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 normal-hearing subjects (Gfeller et al., 2005). Further study using larger intervals/musical extracts is thus necessary to see if improvement of pitch discrimination could result in a better music perception in prelingual cochlear implantees.

Though loudness was monitored to avoid the possible effect of intensity variation in this study, it is clear that loudness matching of different tones from a piano cannot be as precise as that of computerized sounds. Since musical training could improve loudness discrimination in normal-hearing subjects (Plath, 1968), the training might also improve pitch differentiation by advancing use of available loudness differences created unintentionally by cochlear implant programming. Future research using 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.

2.5 Conclusion

In summary, the ability to discriminate sounds was improved with musical experience in prelingually deafened children with cochlear implants. Implanted children attending 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 post-operative rehabilitation program for prelingually deafened children with cochlear implants. Since auditory plasticity might play an important role in the enhancement of pitch perception, our research invites further studies on a larger group of implanted children 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.

2.6 Acknowledgment

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2.7 Annotations

1. Section 2.2.3: The type of ANOVA used was repeated measure ANOVA.
2. Section 2.2.3: Normal distribution of data was confirmed by using Kolmogorov-Smirnov test.
3. Section 2.3.1: The power was 0.35 for the boys/girls comparison and 0.32 for the subjects >6 yr/subjects ≤6 yr comparison.

3. Part II: Other factors related to the improvement of music perception in cochlear implantees

3.1 Effect of residual hearing preservation on music perception in cochlear implantees

There are many factors that can influence functional outcomes post-cochlear implantation including surgical techniques, variability of array placement, device coding strategies, intensity of rehabilitation and pathology of hearing loss (Wilson & Dorman, 2008a, 2008b). In addition to the variability of functional outcomes, music appreciation in cochlear implant recipients is also variable, presumably for similar reasons. While it is not possible to differentiate between all of these, technological developments of cochlear implants aim to maximize an individual's ability to reach their maximum potential. As cochlear implant candidacy is expanded with improvements in technology, individuals with increasing levels of residual low-frequency hearing (e.g those with steeply sloping severe-profound hearing loss) fall within the candidacy range (Gantz et al., 2006). In this population, where hearing is retained after surgery, combined electric and acoustic stimulation can be used which may provide access to finer spectral resolution and temporal fine structure, enhancing music perception (Gantz et al., 2005; Kong et al., 2004). Techniques aimed to preserve residual hearing include the insertion of a short electrode array (Gantz et al., 2006; Gfeller et al., 2005) or partial or full insertion of a standard electrode array combined with a soft surgery technique to minimize intracochlear trauma (Fraysse et al., 2006; Gstoettner et al., 2004).

Short electrode arrays, including the research 10mm Iowa/Nucleus Hybrid-S Cochlear Implant, have been designed to facilitate electric and acoustic stimulation in individuals with residual hearing by only entering the descending cochlear basal turn (Gantz et al., 2005). Results reported as part of the multi-centre FDA clinical trial in 47 patients with the Nucleus Hybrid implant (Gantz et al., 2006) showed hearing preservation in 45 immediately after implantation, with hearing within 10dB of pre-operative thresholds maintained in 25 and within 30dB maintained in 22 for up to 3 years in some patients. Within this study, comparisons between long-term Hybrid-S users and long-term long array users who were matched on word understanding in quiet showed a difference in speech perception in noise (using both multi-talker babble and steady-state noise), suggesting that the Hybrid-S users perform better within a more realistic listening environment. Despite these benefits, Briggs and colleagues (Briggs et al., 2006) identified the possibility that shortening of the electrode array to 10mm may cause a place-frequency mismatch because only the basal portion of the cochlea will be stimulated, causing a disproportionately higher frequency percept than with a standard array. Further, should hearing not be preserved, then concerns have been raised that speech perception outcomes will be impaired for individuals who only receive electrical stimulation in such a limited region of the cochlea (Gstoettner et al., 2009). Nonetheless, in the clinical trial of the commercially-available 16mm Hybrid-L24, Lenarz et al. (Lenarz et al., 2009) showed good post-operative hearing preservation in 24 recipients implanted with a round-window surgical approach.

A standard commercially available electrode array has also been used for hearing preservation with full or partial insertion of the array using an atraumatic surgical technique (Roland, 2005). Using a prospective multicenter study, Fraysse et al. (Fraysse et al., 2006) compared changes in hearing threshold levels after 27 patients were implanted with the Nucleus 24 Contour Advance perimodiolar electrode array. Of these, 12 were implanted with a soft surgery technique using a 17mm insertion depth. The authors demonstrated that preservation of hearing thresholds was more successful when the soft surgery technique was used with median changes in average hearing thresholds between 250-500Hz measured at 40dB for the entire group and 23dB for the soft surgery group. Success in hearing preservation has also been reported using partial insertion of other electrode arrays, including the MED-EL C40+ implant (Gstoettner et al., 2004; Skarzynski et al., 2007). However delayed loss of residual hearing has been reported in some instances even when an atraumatic surgical technique is used (Fraysse et al., 2006; Gstoettner et al., 2006).

In contrast to the standard length electrode array, Skarzynski and Podskarbi-Fayette (Skarzynski & Podskarbi-Fayette, 2010) reported on the Nucleus® Straight Research Array (Cochlear Ltd), an atraumatic electrode array. The main characteristics of this array that are different from the usual straight or Contour Advance arrays are that it is thinner and smoother which aim to reduce intracochlear trauma and kinking of the proximal end during insertion with a 20mm insertion. This study showed that of nine patients who had low-frequency residual hearing ≤50dBHL at 500Hz, the mean increase in thresholds at this frequency was 19dB. Similarly, Gstoettner and colleagues (Gstoettner et al., 2009) reported on the outcomes of 9 patients implanted with the MED-EL Flex EAS (with increased flexibility of the array) showing that 4 patients had full hearing preservation and 5 showed partial preservation. However, Baumgartner et al (Baumgartner et al., 2007) reported hearing preservation in 10 of 16 patients fitted with the MED-EL Flex^{soft} at 1 month post-implantation but this declined to only 4 patients at 6 months post-implantation, suggesting variable outcomes which may or may not reflect the array *per se,* or the surgical technique or the underlying pathology or combination of the above.

To date, only limited evidence exists to support the possibility that any of these techniques result in improved music perception for implant recipients. Gfeller and colleagues (Gfeller, 2005, 2006) compared music perception in 17 normally-hearing adults, 39 with a conventional long array (from Cochlear Ltd, Advanced Bionics and Ineraid) and 4 patients with a Hybrid-S Cochlear Implant (Cochlear Ltd). The results showed that Hybrid-S recipients and NH listeners performed significantly better than those with a standard-electrode array on recognizing real-world songs with no lyrics and instrument recognition (with no significant difference observed with device or processing strategy for the standard-electrode array group). Nonetheless, it does indicate the possibility of combined electrical and acoustic stimulation for improved musical recognition in cochlear implant recipients.

3.2 Effect of bimodal hearing and/or bilateral implantation on music perception in cochlear implantees

It has long been known that bimodal hearing is better than unimodal hearing for patients with hearing impairment in terms of speech/language perception. With respect to music perception, bimodal hearing was also revealed to be superior to unimodal hearing for prelingually deafened children in one of our previous studies (Chen et al., in submission). Scores for pitch differentiation were generally higher for the condition of "simultaneous use of both hearing aid as well as cochlear implant" than that of "utilization of cochlear implant only" in the same subject, although the differences were not statistically significant enough which could possibly be ascribed to the small sample size. The performance of pitch-interval differentiation was furthermore shown to be superior in subjects with longer duration of hearing aids use and longer duration of hearing aids use prior to the cochlear implantation.

Our study was congruent with one recent research in which bimodal hearing was noted to be better than hearing with bilateral cochlear implantation regarding music perception in patients with post-lingual deafness (Cullington & Zeng, 2011). The mechanisms underlying the superior effect of bimodal hearing on music perception over unimodal hearing and hearing with bilateral cochlear implantation remained unknown. One possibility is that the low-frequency cues inherent in hearing aids can compensate for the insufficiency of low-frequency cues built-in in the contemporary systems of cochlear implant in terms of pitch discrimination (Cullington & Zeng, 2011). Another more plausible explanation is that the auditory signals transmitted by hearing aids are analog in format (Chen et al., in submission). The acoustic information enclosed is thus much more abundant than that conveyed via the "digital" devices of cochlear implant, which in turn could sound more like that a normal-hearing subject would percept.

A usable high-frequency hearing gain by using hearing aids sometimes leads to a longer duration of hearing aids use prior to the cochlear implantation (Chen et al., in submission). The implanted ear will continue to benefit the implantees with a good high-frequency hearing gain even after the cochlear implantation. Since the neuronal architects serving auditory perception are hardwired to fine-tune to subtle differences in the auditory environment (Illing & Reisch, 2006), longer duration of hearing aids use will enable our subjects to become more familiar with the presented tone pairs, which would consecutively lead to a better capability of pitch-interval differentiation.

3.3 Coding strategies

In current commercially available cochlear implant systems, four main sound coding strategies are utilized (Wilson & Dorman, 2008a, 2008b). These are: (i) SPEAK (spectral peak strategy) (ii) CIS (continuous interleaved sampling); (iii) ACE (advanced combination encoder), which extracts both spectral and temporal cues; and (iv) *n of m* (number of maxima spectral speech extractor). However, it is proposed by some researchers that two main limitations affect music perception: (1) low-frequency fine structure information is poorly represented by envelope–based strategies; and (2) insufficient numbers of independent effective channels exist to deliver fine structure due to current spread and electrode interactions (conventional arrays have been 12-22 channels). More recently, considerable attention has been focused on the development of *novel* strategies to address this. These include the development of virtual channels through current steering (Firszt et al., 2007), and fine structure processing which intends to increase access to spectral and temporal fine structure (Hochmair et al., 2006). While such strategies are continually being improved to facilitate improved music perception and appreciation, limited empirical evidence currently exists to support the role of virtual channels or fine structure coding at this stage (Berenstein et al., 2008; Firszt et al., 2007). Nonetheless, they continue to represent possibilities for the future.

3.4 Conclusion

In summary, only limited evidence exists to support the possibility that factors such as residual hearing, bimodal hearing, and coding strategies result in improved music perception for implant recipients to date. However, they continue to represent opportunities for the future. The importance of techniques aimed to preserve residual hearing thus cannot be overemphasized in cochlear implantation. Further studies are also needed to show the longitudinal effect of bimodal hearing and newly developed coding strategies to benefit music performance in cochlear implantees.

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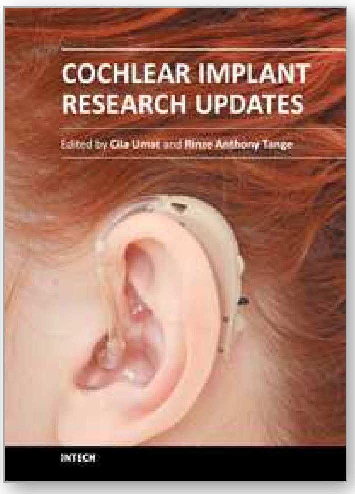

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For many years or decades, cochlear implants have been an exciting research area covering multiple disciplines which include surgery, engineering, audiology, speech language pathology, education and psychology, among others. Through these research studies, we have started to learn or have better understanding on various aspects of cochlear implant surgery and what follows after the surgery, the implant technology and other related aspects of cochlear implantation. Some are much better than the others but nevertheless, many are yet to be learnt. This book is intended to fill up some gaps in cochlear implant research studies. The compilation of the studies cover a fairly wide range of topics including surgical issues, some basic auditory research, and work to improve the speech or sound processing strategies, some ethical issues in language development and cochlear implantation in cases with auditory neuropathy spectrum disorder. The book is meant for postgraduate students, researchers and clinicians in the field to get some updates in their respective areas.