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A Longitudinal Study of Speech Perception Skills and Device Characteristics of Adolescent Cochlear Implant Users

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Abstract

Background—For pediatric cochlear implant (CI) users, CI processor technology, map characteristics and fitting strategies are known to have a substantial impact on speech perception scores at young ages. It is unknown whether these benefits continue over time as these children reach adolescence.

Purpose—To document changes in CI technology, map characteristics, and speech perception scores in children between elementary grades and high school, and to describe relations between map characteristics and speech perception scores over time.

Research Design—A longitudinal design with participants 8–9 years old at session 1 and 15–18 years old at session 2.

Study Sample—Participants were 82 adolescents with unilateral CIs, who are a subset of a larger longitudinal study. Mean age at implantation was 3.4 years (range: 1.7 – 5.4), and mean duration of device use was 5.5 years (range: 3.8–7.5) at session 1 and 13.3 years (range: 10.9–15) at session 2.

Data Collection and Analysis—Speech perception tests at sessions 1 and 2 were the Lexical Neighborhood word Test (LNT-70) and Bamford-Kowal-Bench sentences in quiet (BKB-Q), presented at 70 dB SPL. At session 2, the LNT was also administered at 50 dB SPL (LNT-50) and BKB sentences were administered in noise with a +10 dB SNR (BKB-N). CI processor technology type and CI map characteristics (coding strategy, number of electrodes, map threshold levels [T levels], and map comfort levels [C levels]) were obtained at both sessions. Electrical dynamic range [EDR] was computed [C level – T level], and descriptive statistics, correlations, and repeated-measures ANOVAs were employed.

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Results—Participants achieved significantly higher LNT and BKB scores, at 70 dB SPL, at ages 15-18 than at ages 8-9 years. Forty-two participants had 1-3 electrodes either activated or deactivated in their map between test sessions, and 40 had no change in number of active electrodes (mean change: -0.5; range: -3 to +2). After conversion from arbitrary clinical map units to charge-per-phase in nanocoulombs (nC), no significant difference was found for T levels across time. Average C levels decreased by 19 nC. Seventy-three participants (89%) upgraded their CI processor technology type. At both sessions, significant correlations were found between EDR and all speech perception measures except LNT-50 (r range: .31 to .47; $p < 0.01$). Similarly, at both sessions, significant correlations were also found between C levels and all speech perception measures (r range: .29 to .49; $p < 0.01$). And, at session 2, a significant correlation was found between processor technology type and the LNT-50 scores ($r = .38$; $p < 0.01$).

Conclusions—Significant improvement in speech perception scores over time was observed between elementary grades and high school for children who had used a CI since preschool. On average, T level current requirements (nC) and electrode function remained stable for these long-term pediatric users. Analyses of maps did not allow for the determination of the exact cause of C level reductions, though power limitations in new processor systems and changes in perceived loudness over time are possible. Larger EDRs and higher map C levels were associated with better speech perception scores. Use of newer speech processor technology was associated with better speech perception scores at a softer level.

Keywords

Pediatric; cochlear implants; speech perception

INTRODUCTION

Cochlear implant (CI) systems are implantable devices that are designed for individuals receiving minimal benefit from traditional amplification. CIs consist of an implantable array of stimulating electrodes positioned into the cochlea, a receiver/stimulator placed in the mastoid and an external speech processor that is worn behind the ear. Since CIs became commercially available for children in the late 1980s, studies have documented steady improvements in benefits, especially related to perceiving and understanding speech (Staller, Beiter, Brimacombe, Mecklenburg, & Arndt, 1991;Osberger, Fisher, & Kalberer, 2000). Variables that have been shown to contribute to successful speech perception skills in children include younger age at implant, placement in a spoken language environment and device characteristics (Geers, Brenner, & Davidson, 2003; Fryauf-Bertschy, Tyler, Kelsay, Gantz, & Woodworth, 1997). Technological advances in speech coding strategies, CI hardware and optimization of the map stimulation levels by audiologists are among the device characteristics that have been associated with improved speech perception skills (Geers et al., 2003).

Speech coding strategies, processor technology and speech perception

The introduction of speech coding strategies, such as spectral peak (SPEAK) and continuous interleaved stimulation (CIS), resulted in improved speech perception for both adults and children compared to performance with earlier speech processing strategies (Wilson, Lawson, Finley, & Wolford, 1991; Geers, Brenner, & Davidson, 1999). Specifically, Geers et al. (2003) documented that longer use of the SPEAK coding strategy with the updated Spectra processor was related to better speech perception skills in a nationwide sample of pediatric cochlear implant users and the benefits of SPEAK over MPEAK were documented for pediatric CI users listening in background noise (Geers, Brenner & Davidson, 1999). Another study (Meyer & Svirsky, 2000) found that children who were implanted at a younger age and used newer speech coding strategies, achieved higher levels of speech perception skills in a shorter amount of time than reported in previous studies.

Speech processor features such as automatic gain control and preprocessing strategies have resulted in greater access and comfort for a variety of speech levels from soft to loud. The electrical dynamic range (EDR) and the input dynamic range (IDR) are critical to this process. The EDR is the difference between threshold and maximum comfort level for electrical stimulation on individual electrodes, and the IDR is the intensity range of acoustic signals coded by the speech processor and delivered to individual channels. CI processors employing wider IDRs have been shown to improve vowel, consonant, word and sentence recognition for signals presented at a softer level (Davidson et al., 2009; Holden, Skinner, Fourakis, & Holden, 2007; Santarelli et al., 2009). In a large pediatric study of long-term Nucleus CI system users, researchers found that children using more recent processors such as the ESPrit 3G and Freedom demonstrated better speech perception scores at soft input levels (50 dB SPL) compared to those using older technology processors (ESPrit 22 and Spectra) (Davidson, Geers, & Brenner, 2010).

Map characteristics, CI programming and Speech perception

In the mapping process, threshold (T) and comfort (C) levels are measured on individual electrodes based on subjective responses from the patient. These measurements are then used to find an optimal EDR (C level – T level) that allows for audibility of soft sounds and ensures that loud sounds are not perceived as too loud. T levels that are programmed too low could result in reduced audibility, especially for soft speech sounds, and C levels that are set too high could result in tolerance issues for louder inputs. A study by Geers et al. (2003) revealed that cochlear implant maps characterized by maximum number of active electrodes, wide EDR, and optimal growth of loudness as measured by a loudness scaling task were associated with pediatric CI users' ability to hear and understand speech. Likewise, a study of adult Nucleus 22 users found that better open- set speech recognition was associated with a wider EDR after 1 year of use. However, this relation was not maintained for subsequent years (Waltzman, Cohen and Shapiro, 1991) Similarly, studies in adults have demonstrated that cochlear implant mapping procedures, loudness scaling judgments, and sound-field thresholds are necessary for an optimized fitting and good speech perception (Skinner, Holden, & Holden, 1997).

Map Characteristics over Time

Changes in map T and C levels have been documented over time in both adults and children. Changes in these levels are likely a result of both physiological changes in the cochlea and behavioral changes related to experience with electrical stimulation and reliability of responses (Henkin, Kaplan-Neeman, Muchnik, Kronenberg, & Hildesheimer, 2003a, 2003b; Hughes et al., 2001; Kawano, Seldon, Clark, Ramsden, & Raine, 1998; Shapiro & Waltzman, 1995). Children in particular have demonstrated changes in electrical stimulation levels during the first 2 years of cochlear implant use. Shapiro & Waltzman (1995) found that over half of their sample of 22 children using the Nucleus 22 CI system demonstrated significant increases or decreases in T levels during their first year of implant use. Henkin et al (2003a) examined T and C levels as well as the EDRs of 37 pediatric Nucleus 22 users over a 2- year period. They found that T levels increased significantly during the first year of implant use and stabilized during the second year while significant increases in C levels and EDRs continued throughout the 2-year period. Studies examining adult Nucleus 22 users over time have revealed variable results. A retrospective review of T and C levels of adult subjects who had used their CI from 2-7.5 years revealed significant changes in T and C levels when the most recent programs were compared to those obtained at 6 months post-implant (Butts, Hodges, Dolan-Ash, & Balkany, 2000). Three of the 5 subjects that had used their CI for longer than 5 years exhibited the greatest change in T and C levels over time. For all subjects, changes in T and C levels for the basal and medial electrodes were significant while changes in the apical region were not. Another study of 18 adult subjects documented no significant changes in T levels or EDRs when levels from year 1 were compared to those from year 5 (Waltzman, Cohen, & Shapiro, 1991). Subsequent studies of CI systems that use monopolar stimulation have generally shown that levels stabilize within the first 2 years of use for children and within the first year of CI use for adults, however these studies only followed subjects up to 2 years post-initial stimulation (Henkin et al., 2006; Henkin, et al., 2003a; Hughes, et al., 2001). Changes in both the T and C/M (comfort C or most comfortable M) levels as well as the EDR are apparent across the pediatric and adult populations. It is unclear however if stabilization periods are permanent or if further changes occur after long-term use and external-processor upgrades.

The primary aims of this study are to, 1) document changes in CI technology, map characteristics, and speech perception scores at two test sessions, roughly 8 years apart and, 2) to describe relations between map characteristics and speech perception scores over time.

METHODS

Participants

Eighty-two adolescent participants (40 female; 42 male) with unilateral Cochlear Nucleus 22 internal CI systems (Cochlear Americas Corporation, Centennial, CO) took part in this study. None of the participants wore a hearing aid in the opposite ear. Participants were a subset of a larger longitudinal study of 112 participants who were tested in a previous research study at some point between 1996 and 2000 (session 1) when they were between 8.0 and 9.11 years of age. These participants were tested again, at some point, between 2004 and 2008 (session 2) when the students ranged in age from 15.5 to 18.5 years (Geers, et al., 2011). Participants met the following criteria: copies of CI maps available at both test sessions, use of the N-22 internal CI system at both sessions, and no internal device failures. Fourteen children from the original sample had device failures and 16 children either used an internal CI system other than the N-22 or did not have maps available at both sessions. The mean age at implantation was 3.4 years (range: 1.7 – 5.4), and the mean duration of device use was 5.5 years (range: 3.8 – 7.5) at session 1 and 13.3 years (range: 10.9 – 15) at session 2.

Equipment/Test Environment

For each test session, the participant was seated 3 feet at a 0 degree azimuth from the loudspeaker. Speech perception stimuli were presented via a laptop computer connected to an Anchor Model AN-100 loudspeaker. For calibration of the speech stimuli, a type 2 sound level meter was placed at the level of the child's implant microphone and levels were measured in dB SPL (C weighted).

Test Materials and Procedures

The Lexical Neighborhood Test (LNT) (Kirk, Pisoni, & Osberger, 1995) consists of 50 monosyllabic words per list; 25 of which are high frequency words with limited lexical neighbors (labeled “easy”) and 25 that are lower frequency words with many lexical neighbors (labeled “hard”). The LNT word list was administered in quiet at 70 dB SPL at sessions 1 and 2 (LNT-70) and in quiet at 50 dB SPL at session 2 (LNT-50).

The Bamford-Kowal-Bench (BKB) (Bamford & Wilson, 1979) sentence test is an open-set sentence test consisting of 16 sentences with 50 key words. These sentences contain vocabulary, grammar and sentence length suitable for hearing impaired individuals between the ages of 8-15 years. The BKB was administered in quiet at 70 dB SPL at sessions 1 and 2 (BKBQ) and at 60 dB SPL in the presence of 50 dB SPL multi-talker background (10 dB signal- to- noise ratio-SNR) at session 2 (BKB-N).

Map Characteristics and Speech Processors

Speech processor and map characteristics were documented at each test session. The CI processor technology type was documented and ranked from 5 = most recent to 1 = oldest (Table 1). CI map characteristics included the coding strategy, number of active electrodes, map T and C levels as well as the map EDR. Arbitrary clinical map units were converted to charge-per-phase in nanocoulombs (nC) to allow appropriate comparisons of the T levels, C levels and EDRs across different speech processors (i.e. MSP or Spectra at session 1 to ESPirit 22, ESPirit 3G or Freedom at session 2). These conversions were made using tables provided by Cochlear Americas. Table 1 lists the number of participants who used each type speech processor at session 1 and at session 2.

Statistical Analysis

Speech perception results, map T and C levels, EDR and number of electrodes were compared for each subject at session 1 and 2 using analysis of variance (ANOVA). Correlational analyses were used to examine relations between processor/map variables and speech perception.

RESULTS

Speech Perception

Figures 1 and 2 show individual scores and group mean scores plotted for sessions 1 and 2 for the LNT-70 and BKB-Q tests respectively. Group mean scores on both the LNT-70 and BKB-Q tests increased significantly from session 1 to session 2. Figure 1 demonstrates that group mean LNT-70 increased from 50% (SD= 25.3) at session 1 to 62% (SD= 23.2) at session 2 ($F(1,79) = 48.62$, $p<.0001$). Figure 2 shows BKB-Q scores increased from 63% (SD=24.3) at session 1 to 81% (SD= 26.4) at session 2 ($F(1,81)= 57.24$, $p<.0001$). At session 2, the group mean LNT score decreased significantly from 62 % (SD=23.2) to 48% (SD=24.3) when the level was decreased from 70 to 50 dB SPL ($F(1,81) =51.32$, $p<.0001$). Also at session 2, the group mean BKB score is significantly affected by the presence of noise. The mean BKB group score decreased significantly from 81% (SD=26.4) to 52% (SD=26.2) with the addition of multi-talker babble at 10 dB SNR ($F(1, 81)= 220.36$, $p<.0001$). Individual scores for all tests are provided in Appendix A.

CI Characteristics

Seventy-three out of eighty-two participants (89%) took advantage of technology updates to the speech processors and upgraded to newer devices (e.g., from Spectra to ESPrit or Freedom). Nine participants remained Spectra users at session 2. Eight children used the MPEAK coding strategy and 74 used SPEAK at session 1 and all children utilized the SPEAK coding strategy at session 2. The average number of active electrodes in a child's map at session 1 was 18.7 (SD, 2.1; range 6-21) and 18.3 (SD, 1.6; range 5-20) at session 2. Figure 3 shows that of the eighty-two participants, forty-two had between 1 to 3 electrodes either activated or deactivated from session 1 to session 2. The remaining forty had the same number of active electrodes at both sessions (mean change: -0.5; range: -3 to +2). The average T level, C level (in nanocoulombs) and EDR for sessions 1 and 2 are shown in Table 2. The average T level at session 1 was 33 nC (SD=13; range 13-84) and the average C level was 119 nC (SD= 61; range 77-317). The average T and C levels at session 2 were 30 nC (SD=12; range 14-87) and 100 nC (SD= 45; range 29-219) respectively. No significant differences were found for T levels ($F(1,81) = 3.42$, $p = .07$). The decrease in the C level from 119 to 100 and the resulting decrease in EDR from 87 to 70 were both significant (C Level-($F(1,81)= 11.60$, $p < .01$; EDR-($F(1,81) = 10.30$, $p < .01$). A graph showing the relation between arbitrary clinical units and charge per phase in nC is shown in appendix B. Note that charge per phase is limited to ~239 nC for the ESPirit 22, ESPirit 3G and Freedom processors compared to 700 nC for the Spectra and MSP processors. Individual speech perception scores and map characteristics at sessions 1 and 2 can be found in Appendix A.

Correlational Analyses

Significant correlations between the dynamic range and all speech perception measures except LNT-50 (LNT-70, BKB-Q and BKB-N) were found at session 1 and 2 (r range: .31 to .47; $p < .01$). All speech perception measures except LNT-50 were also found to have significant correlations with C levels at both sessions (r range: .29 to .49; $p < .01$). Lastly a significant correlation between processor technology type and the LNT-50 scores ($r = .38$; $p < .01$) was found at session 2. All correlations for session 1 and 2 are provided in Appendix C.

DISCUSSION

Past studies had revealed significant changes in electrical stimulation levels for both adults and children. However, most of these studies only examined changes over a 1-2 year period. This population of Nucleus 22 users allowed us to examine stimulation levels over a period of 7-9 years. Since the majority of children had upgraded from a body-worn processor to an ear-level processor, conversion from clinical units to nanocoulombs was necessary to compare T and C levels across different processors. On average the current (nC) requirements decreased 3 nC for the T levels and 19 nC for the C levels from session 1 to session 2. The average decrease of 19 nC in the C levels and resulting decrease in the EDR, may be due to a reduction of maximum current levels across electrodes imposed by ear-level processors compared to body-worn processors or to changes in perceived/tolerated loudness over time. An analysis of individual electrodes revealed that ~15% of the children had some number of electrodes (1-18 electrodes per map) with C levels greater than 239 nC at session 1. Upgrades to ear-level processors could, then, have resulted in a reduction in C levels across some portion of electrodes, and consequent decrease in the across-electrode C level average computed for this analysis. Changes in perceived/tolerated loudness level can neither be confirmed nor ruled out due to the fact that maps were analyzed post-hoc and details of the actual programming session were unavailable. Though wider EDRs did remain positively associated with better speech perception outcomes, the reduction in C levels and EDRs observed over the two test sessions was not enough to negatively affect speech perception scores. The average number of active electrodes in the map remained stable at 18 electrodes. For most children, the reasons for deactivating electrodes in the map were related to changes in programming modes and speech coding strategies, due to processor upgrades, rather than electrode malfunction. This suggests that current requirements and overall electrode function remain stable for these pediatric CI users over a period of about 8 years.

Speech perception scores improved significantly between elementary grades and high school for these children who had used a CI since preschool. Perception of speech in demanding listening conditions was a challenge as evidenced by the significant decrease in word and sentence scores at soft levels and in noise. An average decrease in scores of 29 and 14 percentage points were obtained for noise and reduced level respectively. These results are similar to studies from adult CI recipients showing that listening in noise presents the greatest challenge followed by listening at soft input levels (Firszt et al., 2004; James et al., 2002). While it has been observed that increases in speech perception scores over time are highly associated with concomitant changes in speech production and language abilities (Davidson, Geers, Blamey, Tobey, & Brenner, 2011), map and processor characteristics also appear to contribute to speech perception skills. Larger EDRs across electrodes and higher map C levels were associated with better speech perception scores on both the LNT and BKB tests, and the use of upgraded speech processors resulted in improved speech perception abilities at softer levels (e.g. 50 dB SPL).

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Appendix

Appendix A

CI processor and map data, and speech perception scores for each participant at both Sessions.

	Session 1					Session 2						
		Map levels		Speech scores			Map levels		Speech scores			
Subj ID	Tech	T (nC)	C (nC)	LNT70	BKBQ	Tech	T (nC)	C (nC)	LNT50	LNT70	BKBQ	BKBN
96103	2	23	120		78	2	38	219	20	70	96	74
96105	2	45	158		88	3	32	139	14	74	98	70
97103	2	26	71	76	47	3	36	138	44	72	100	64
97105	2	46	208	64	92	3	40	88	42	72	92	74
97107	2	34	89	34	16	4	34	77	54	56	84	58
97109	2	18	28	64	76	3	18	29	60	80	98	50
97112	2	21	47	8	0	3	45	105	22	44	44	12
97113	1	18	80	68	90	3	23	83	30	86	100	26
97114	1	30	317	24	74	3	20	110	26	70	90	70
97115	2	34	60	32	28	4	26	67	72	56	82	34
97204	2	22	247	78	82	4	31	137	84	72	98	58
97205	2	35	142	70	98	4	31	141	24	76	96	22
97206	1	45	88	16	4	2	17	67	8	16	26	8
97207	2	20	43	30	57	3	23	49	26	42	86	44
97208	2	36	157	30	16	4	39	128	12	48	84	54
97211	2	24	53	20	8	3	31	101	6	50	48	12
97212	1	19	72	54	48	4	21	91	52	44	82	64
97214	2	20	27	0	0	3	23	32	0	4	0	0
97301	2	36	180	38	78	4	21	99	68	64	94	66
97302	2	39	195	58	33	4	37	121	66	74	80	48
97306	2	33	74	38	78	3	29	80	24	64	96	48
97307	2	37	153	62	94	3	35	156	28	86	100	40
97309	2	42	191	58	100	2	43	178	72	80	100	62
97310	2	26	104	0	0	3	24	149	4	2	2	2
97312	2	29	63	16	0	3	52	126	18	24	12	8

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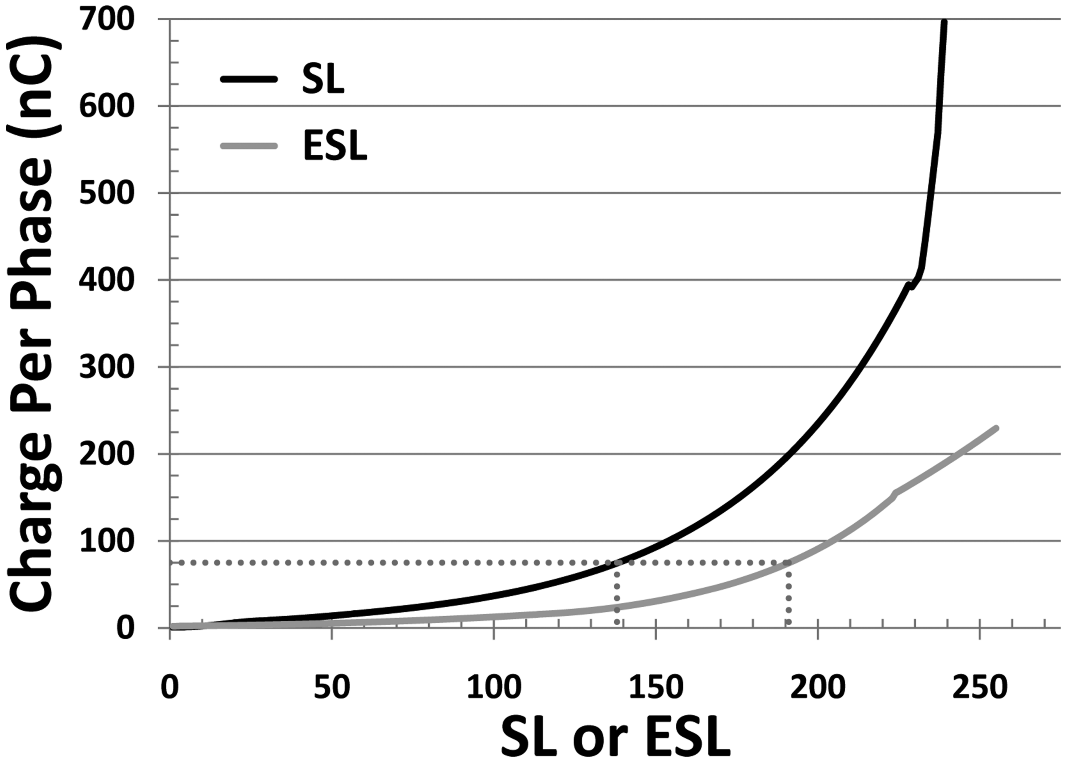
	Session 1					Session 2						
		Map levels		Speech scores			Map levels		Speech scores			
Subj ID	Tech	T (nC)	C (nC)	LNT70	BKBQ	Tech	T (nC)	C (nC)	LNT50	LNT70	BKBQ	BKBN
97314	2	13	46	4	4	2	18	34	6	4	16	0
97316	1	36	90	28	22	3	21	55	40	54	72	26
98105	2	38	141	46	64	4	16	73	60	72	94	40
98108	2	21	178	68	96	4	25	171	68	80	98	86
98109	1	26	76	0	0	3	19	41	4	8	12	0
98113	2	28	157	76	85	4	33	134	58	66	100	56
98202	2	48	112	38	24	4	56	114	14	34	56	30
98205	2	29	172	58	84	2	28	114	62	60	100	58
98210	1	34	57	22	2	3	23	76	14	30	68	38
98212	2	16	46	16	12	4	21	52	48	48	80	56
98213	2	46	132	44	48	4	41	151	20	38	66	34
98215	1	39	183	22	18	2	27	69	30	18	62	30
98301	2	28	55	44	72	3	27	80	60	66	100	58
98304	2	21	67	52	66	4	14	32	50	56	82	68
98312	2	37	108	12	24	4	62	139	28	62	78	36
99101	2	39	130	68	98	4	21	50	78	80	96	62
99103	2	33	173	74	98	4	27	97	80	80	100	84
99105	2	39	181	60	94	2	39	150	66	78	100	66
99106	2	34	175	72	96	4	21	127	50	58	86	72
99114	2	34	81	36	16	4	34	80	46	70	84	42
99201	2	22	105	54	86	4	23	69	70	62	82	68
99204	2	37	178	66	86	4	30	76	44	84	88	80
99207	2	15	102	34	62	3	18	126	56	74	98	68
99210	2	33	84	70	72	4	32	91	56	68	88	48
99211	2	51	134	42	72	4	21	82	56	74	96	40
99213	2	27	46	0	0	4	28	34	0	0	0	0
99214	2	32	87	74	90	4	22	59	64	76	100	84
99303	2	36	197	74	98	4	31	144	80	88	96	94
99304	2	34	291	80	98	5	57	170	84	76	100	62
99306	2	38	154	80	98	4	44	168	52	86	88	66
99307	2	27	93	64	64	4	23	127	48	66	88	54
99310	2	13	32	42	56	4	24	50	64	72	100	52
99312	2	35	69	66	84	4	39	153	60	64	90	50
99314	2	21	166	42	82	3	20	121	36	56	72	60
99315	2	14	31	0	6	4	27	45	22	32	42	12
200101	2	51	140	64	78	5	25	104	52	42	78	32
200102	2	69	140	80	100	2	87	198	54	80	100	96
200103	2	22	76	84	100	4	23	33	64	76	96	88
200104	2	30	79	90	98	4	25	65	84	82	100	98
200105	2	17	38	86	98	4	21	29	76	78	96	64

	Session 1					Session 2							
		Map levels		Speech scores			Map levels		Speech scores				
Subj ID	**Tech**	**T (nC)**	**C (nC)**	**LNT70**	**BKBQ**	**Tech**	**T (nC)**	**C (nC)**	**LNT50**	**LNT70**	**BKBQ**	**BKBN**
200106	2	41	182	84	86	4	43	88	74	88	100	66
200107	2	85	162	88	100	5	45	144	80	84	100	80
200108	2	27	134	36	90	4	37	108	58	58	88	60
200116	2	21	94	12	0	5	19	52	40	48	72	46
200202	2	31	213	64	94	4	28	168	58	84	96	90
200203	2	64	178	68	98	4	57	176	84	92	94	96
200204	2	40	173	70	98	5	16	139	82	86	98	76
200207	2	75	169	38	64	4	17	68	52	78	92	30
200210	2	31	155	78	100	3	31	155	82	92	100	94
200211	2	35	123	62	98	3	19	63	56	78	92	94
200212	2	25	50	20	8	4	19	50	22	32	36	16
200214	2	17	63	72	98	4	24	83	90	94	100	64
200215	2	42	136	54	66	4	28	115	66	42	68	24
200305	2	23	57	68	100	2	35	80	52	80	100	82
200310	2	37	136	70	90	4	19	55	30	74	98	46
200311	2	24	117	66	90	4	25	91	66	68	100	66
200312	2	26	70	50	46	4	20	75	46	56	90	28
Average		33	119	50	63		30	100	48	62	81	52
St Dev		13	61	25	36		12	45	24	23	26	26
Min		13	27	0	0		14	29	0	0	0	0
Max		85	317	90	100		87	219	90	94	100	98

‘Tech’ is the Technology Rating Scale for the CI processor: 1 = MSP, 2 = Spectra, 3 = Esprit 22, 4 = Esprit 3G, and 5 = Freedom. ‘T’ and ‘C’ map levels are given in nanocoulombs (nC). Speech scores are percent-correct word scores. At Session 1, speech tests are the Lexical Neighborhood Test presented at 70 dB SPL (LNT70) and the BKB sentences presented in quiet (BKBQ). At Session 2, approximately 8 years later, two additional speech tests were employed, the Lexical Neighborhood Test presented at 50 dB SPL (LNT50) and the BKB sentences presented with a +10 dB signal-to-noise ratio (BKBN). Note: Subjects 96103 and 96105 did not complete the LNT70 test at Session 1.

Appendix



Appendix B.
The relation between arbitrary clinical units (SL = Stimulus Level for CI22M processors; ESL = ESPrit Stimulus Level for CI22M-ESPrit processors) to charge-per-phase in units of nanocoulombs (nC). The maximum allowable charge-per-phase is 700 nC for the CI22M processors, but only 230 nC for the CI22M-ESPrit processors. Note, also, that a single value of charge-per-phase corresponds to two different "stimulus level" values, depending on the model of external speech processor. For example, 75 nC corresponds to 138 SL, but to 191 ESL.

Appendix

Appendix C

Correlations amongst map characteristics and speech perception scores at Sessions 1 and at Session 2.

Session 1						
	Tech	**T**	**C**	**EDR**	**LNT-70**	**BKB-Q**
Tech	-	0.04	-0.01	-0.02	0.27	0.28
T		-	0.45**	0.25	0.25	0.23
C			-	0.98**	0.39**	0.49**
EDR				-	0.36*	0.47**
LNT-70					-	0.88**
BKB-Q						-

Session 2								
	Tech	T	C	EDR	LNT-70	BKB-Q	LNT-50	BKB-N
Tech	-	-0.05	-0.04	-0.03	0.20	0.19	0.38**	0.13
T		-	0.61**	0.39	0.16	0.08	0.04	0.16
C			-	0.97**	0.35*	0.29*	0.17	0.34*
EDR				-	0.35*	0.31*	0.18	0.34*
LNT-70					-	0.90**	0.73**	0.78**
BKB-Q						-	0.71**	0.77**
LNT-50							-	0.70**
BKB-N								-

Map characteristics are ‘Tech’ = ‘Technology Rating Scale,’ ‘T’ = ‘T Level,’ ‘C’ = ‘C Level,’ and ‘EDR’ = ‘Electrical Dynamic Range.’ At Session 1, speech tests are the Lexical Neighborhood Test presented at 70 dB SPL (LNT-70) and the BKB sentences presented in quiet (BKB-Q). At Session 2, speech tests are LNT-70 and BKB-Q, and the Lexical Neighborhood Test presented at 50 dB SPL (LNT-50) and the BKB sentences presented with a +10 dB signal-to-noise ratio (BKB-N).

* $p<.01$

** $p<.001$

Abbreviations

CI	Cochlear Implant
LNT	Lexical Neighborhood Test
BKB	Bamford-Kowal-Bench
nC	nanocoulomb
EDR	Electrical Dynamic Range
T levels	Threshold Levels
C levels	Comfort Levels
MSP	Mini Speech Processor
WSP	Wearable Speech Processor
IDR	Input Dyanmic Range

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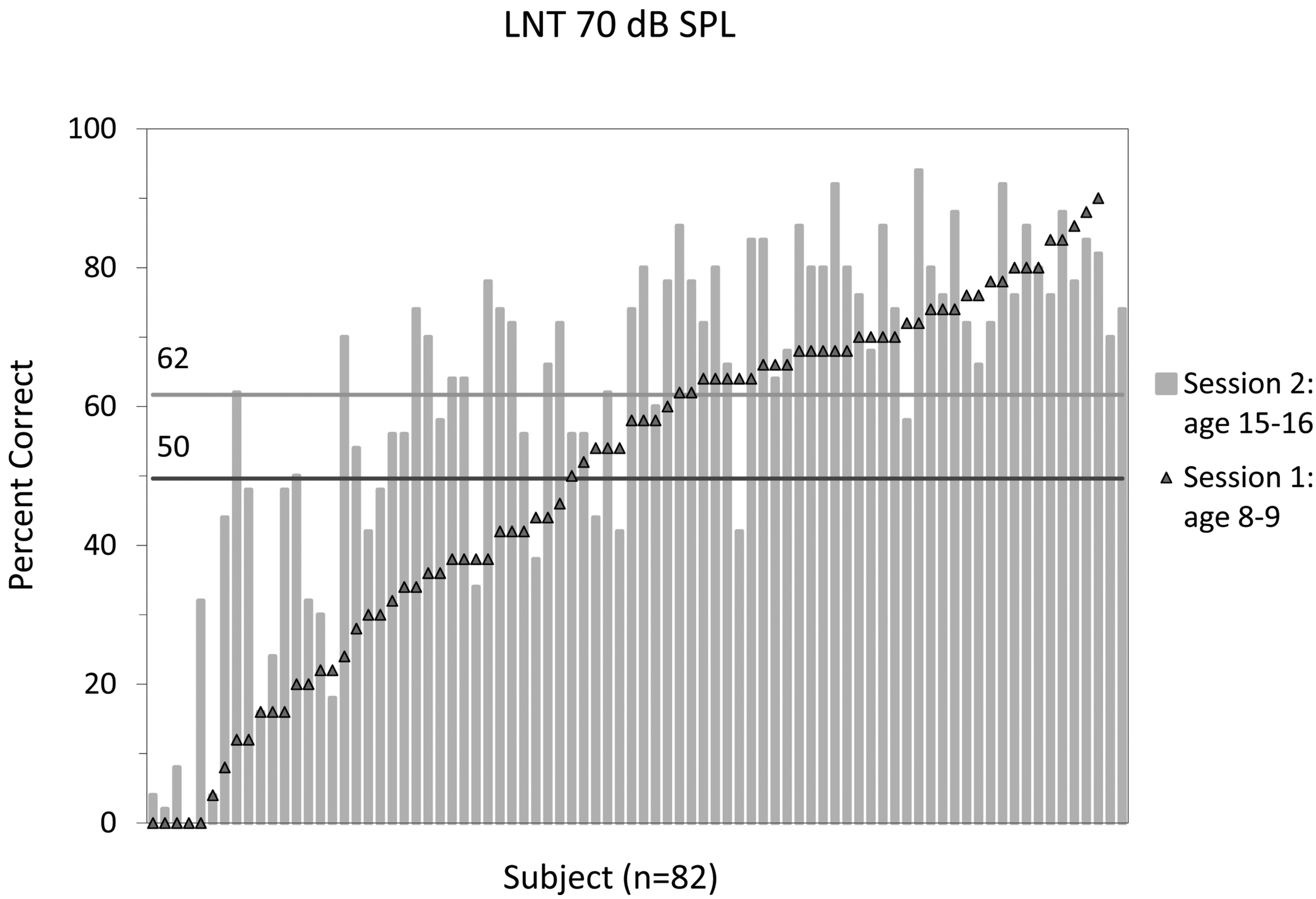

Figure 1.
Individual percent-correct scores for the LNT-70 test at sessions 1 and 2, rank ordered by session 1 scores from lowest to highest. Session 1 scores are represented by black triangles while session 2 scores are represented by grey columns. Group mean scores are shown by the horizontal lines, in black for session 1 and in grey for session 2.

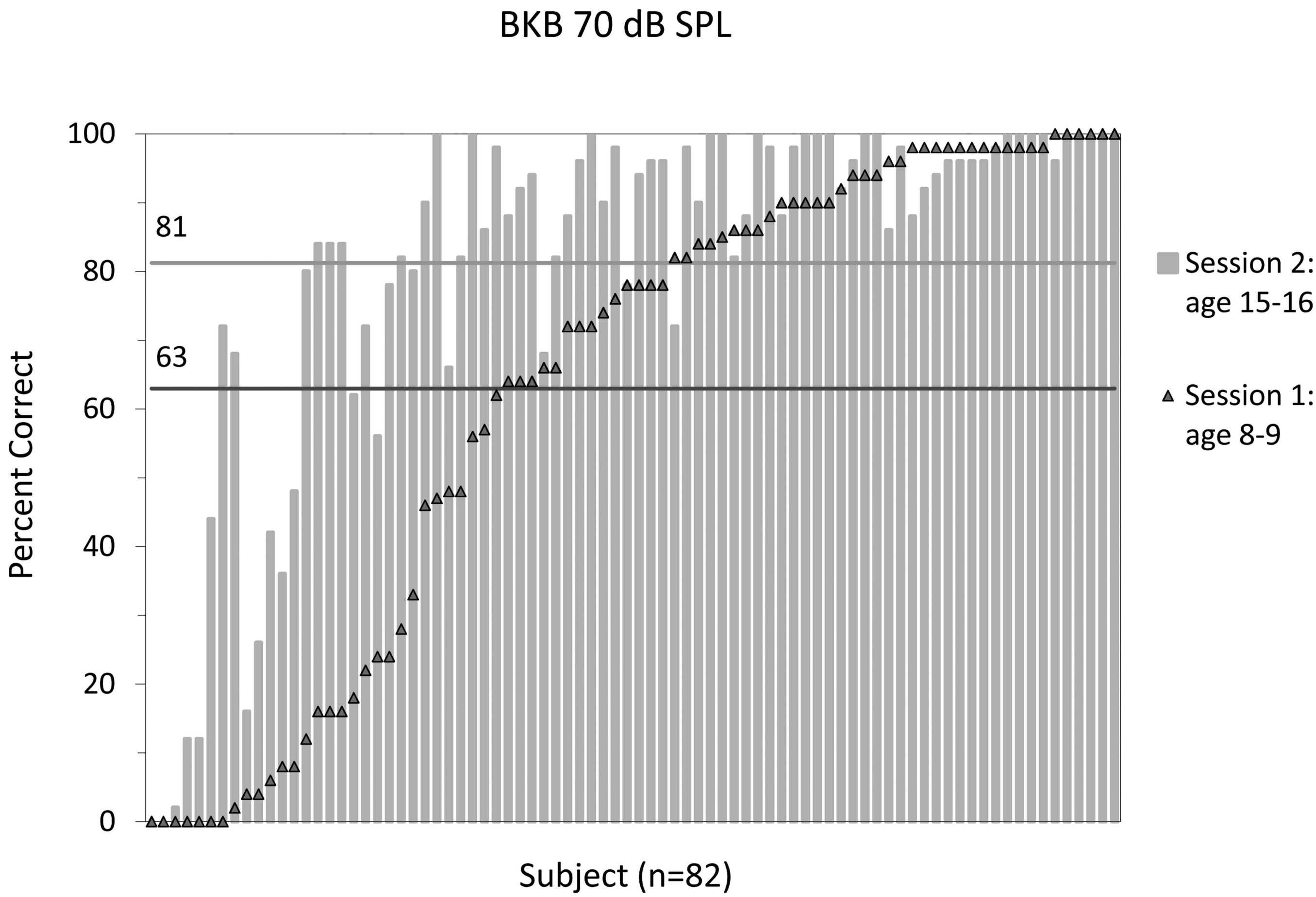

Figure 2.
Individual percent-correct scores for the BKB-Q test at sessions 1 and 2, rank ordered by session 1 scores from lowest to highest. Session 1 scores are represented by black triangles while session 2 scores are represented by grey columns. Group mean scores are shown by the horizontal lines, in black for session 1 and in grey for session 2.

Table 1

Number of participants at Sessions 1 and 2 with each of five external CI speech processors. The 'Technology Rating Scale' ranks CI speech processors from oldest ('1') to newest ('5').

CI Speech Processor		Number of Subjects	
Name	**Technology Rating Scale**	**Session 1**	**Session 2**
MSP	1	8	-
Spectra	2	74	9
ESPrit 22	3		22
ESPrit 3G	4		46
Freedom	5		5

Table 2

Mean T and C Levels, and Electrical Dynamic Range (EDR), in nanocoulombs (nC), at Sessions 1 and 2. Mean values represent an average across all participants, and across all active electrodes for each participant.

Map Characteristic (nC)	Session 1	Session 2
T Level	33	30
C Level	119	100
EDR	87	70