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Epilogue: Factors Contributing to Long-Term Outcomes of Cochlear Implantation in Early Childhood

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INTRODUCTION

The articles in this volume of *Ear and Hearing* (volume citation) provide detailed descriptions of performance outcomes measured in 112 teenage users of the first versions of multi-channel cochlear implants (CI) available to children in North America. Each of the articles in the volume focuses attention on an in-depth evaluation of performances observed in early elementary school ages compared to performances observed as the children prepared to graduate from high school. In this epilogue report, we focus on how speech perception, speech production, language, and literacy performance in adolescence is influenced by a common set of predictor variables obtained during elementary school. Use of a common set of predictor variables across these important domains allows for an integrated picture regarding how these domains are influenced by important early variables associated with a child and that child's family. In addition, the analyses provide an integrated view of how early performance in elementary school influences later adolescent performance.

Performance across a variety of domains first was evaluated in a group of children using CIs when they were in elementary grades (CI-E) after an average of 5.5 years of device use. None of the CI-E children demonstrated significant amounts of pre-implant residual hearing as indicated by speech perception testing in their individual clinics. During the time the CI-E children were implanted, candidacy requirements stipulated a hearing aid trial period of at least 6 months with no evidence of open set speech perception before receiving a CI. Furthermore, participation in the study was restricted to children whose families spoke only English at home and children without additional educationally significant disabilities (although 3.5% of the CI-HS participants did subsequently obtain nonverbal performance intelligence quotients (PIQ) scores at or below 70). These students were evaluated again in high school (CI-HS) after an average of 13.3 years of device use (Geers, Brenner, & Tobey,

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2010). On average, these CI teenagers demonstrated increased participation in mainstream academic settings, a growing reliance on spoken communication, and movement towards age-appropriate language, academic and social skills. Almost half of the children were enrolled in simultaneous communication (SC) educational settings during their first five years of CI experience; however, most of the CI teenagers reported a decrease in use of sign communication and an increased use of oral communication (OC) over time. CI-HS students who benefitted the most from the use of sign to supplement speech tended to be those teenagers demonstrating the greatest delays in language development (Geers & Sedey, 2010). A subsample of 86 CI-HS students completed questionnaires regarding how strongly they identified with their age peers in hearing and Deaf communities. Responses indicated the CI-HS teenagers were fairly evenly divided between those adolescents with a strong identification with the hearing community, those teenagers with a strong identification with the Deaf community and those adolescents with mixed identification in both the Deaf and hearing communities (Moog, Geers, Gustus, & Brenner, 2010).

Performance of these students far exceeds expectations for children in previous generations with severe-profound sensorineural hearing losses (SNHL) who used conventional hearing aids before the advent of multi-channel CIs; however, several residual problems in some communication domains remain. Excellent open-set speech recognition scores observed in optimal listening conditions (average = 60% for words and 80% for sentences) deteriorated when the testing conditions were made more challenging by reducing the intensity of signals (average = 47% for words) or introducing competing noise (average = 52% for sentences) (Davidson, Geers, Blamey, & Tobey, 2010). The teenagers' speech was highly intelligible to naïve listeners when presented in quiet listening conditions (average = 84%), but intelligibility was considerably reduced when their speech was presented to listeners in a multispeaker babble speech background (average = 63%) (Tobey, Geers, Sundararajan, & Lane, 2010). During elementary grades, 56% of students scored within one standard deviation of hearing age-mates in verbal reasoning and 30% of the students scored within one standard deviation in language. Remarkably, this percentage increased to 83% and 68%, respectively, by the time these students were in high school. However, a significant gap between verbal intelligence quotient (VIQ) and PIQ remained for over half of the adolescent sample (Geers & Sedey, 2010). The majority of CI students kept pace with normal development of reading skills between elementary grades and high school, but nearly 20% of the sample exhibited minimal progress over the eight-year interval between the CI-E and CI-HS test sessions. About half of the CI-HS students achieved reading scores within the normal range for hearing high school students. However, written expression remained difficult for most of the CI-HS students, with only 38% of the adolescents scoring within a standard deviation of the normal hearing control group (Geers & Hayes, 2010).

In addition to higher family socioeconomic status (SES) and PIQ, regression analyses examining predictors of speech, language and literacy reveal shorter durations of deafness prior to receiving a CI are associated with better long-term outcomes. Congenitally deaf children implanted at the youngest ages (2 years in this sample) are more likely to achieve age-appropriate language and reading skills in high school than those children implanted at later ages (4 to 5 years) (Geers & Sedey, 2010; Geers & Hayes, 2010). Children whose profound SNHL occurred shortly after birth (between 1 and 36 months) demonstrated higher long-term communication outcomes if they received a CI shortly after the onset of their hearing loss. In addition, better perception and speech intelligibility was observed in high school students whose early communication relied more on OC than on manual signs using SC. Speed and efficiency of verbal rehearsal, reflected in shorter duration of spoken sentences and longer forward digit spans, was associated with more accurate speech and language skills (Pisoni, Kronenberger, Roman, & Geers, 2010). Phonological processing skills, reflected in word attack, spelling and elision skills, also were associated with

teenagers achieving the highest literacy scores (Geers & Hayes, 2010). Children engaged in SC educational environments at early ages who continued to rely on manual signs to supplement their spoken communication demonstrated lower performance on many speech/language outcome measures relative to children who participated in OC academic environments for most of their education (Geers et al., 2010; Tobey et al., 2010).

In particular, we were interested in evaluating the influence of augmenting spoken communication with SC at the early CI-E test session and how this “sign enhancement” influenced later performance outcomes in adolescence. We also focused our attention on evaluating how “sign enhancement” is mediated by information capacity of immediate memory and speed of verbal rehearsal in working memory during the early elementary school ages. CI-E Sign Enhancement was estimated by comparing four language measures obtained in an OC language sample with similar values derived from an SC language sample in the same individuals (Geers et al., 2010). These measures of CI-E Sign Enhancement were based on the ratio of OC to SC measures of: a) words per utterance, b) different words per minute, c) Index of Productive Syntax (IPSyn) noun phrases, and d) IPSyn sentence structure. CI-E Verbal Rehearsal Speed was estimated by combining four measures incorporating average sentence durations from an imitation task and recall of digits (Pisoni et al., 2010). The measures were: a) the average duration of 7-syllable sentences, b) average duration of sentences varying in length between 3-, 5-, and 7-syllables, c) raw total correct scores for recall of forward digits from the Wechsler Intelligence Scale for Children - WISC (Wechsler, 1991) and d) the scaled score for forward and backward digit span on the WISC. Digit spans evaluate neuro-cognitive processes involved in storing, maintaining, and manipulating verbal information in immediate memory for short periods of time (Pisoni & Cleary, 2003). Sentence duration provides an index of how fast children recode and maintain verbal information in immediate memory for short periods of time (Pisoni & Cleary, 2003). Cognitive processing measured in these tasks is critical for the active working memory of other complex linguistic processes such as spoken word recognition, sentence comprehension and language production. Measures of immediate memory capacity and verbal rehearsal speed represent elementary information processing variables widely used in cognitive psychology and neuroscience (Pisoni et al., 2010).

Thus, this manuscript focuses attention on the “big picture” of long-term outcomes across a number of domains important to oral communication in adolescents using cochlear implants. The overall objectives of the study are to: a) examine how a common set of predictor variables associated with elementary school performance influence performance during adolescence, b) investigate how augmenting OC with SC is reflected in adolescent communication outcomes; and c) explore how measures of verbal rehearsal speed contribute to the variance in adolescent performance. Collectively, the analyses provide a penetrating evaluation of factors influencing communication performance in adolescent users of cochlear implants.

METHODS

Outcome and Predictor Variables

The epilogue study uses time-lag analyses incorporating seven common predictor variables associated with the elementary school test period. The elementary school-age variables included five individual characteristics found to be important contributors across the performance domains: gender, PIQ, family size, SES and duration of deafness (operationally defined as the time period between the age of implantation and the onset of deafness). Once these characteristics were accounted for, we evaluated how adolescent performance was influenced by composite predictor variables derived from elementary school-age performance. Table 1 summarizes the variables created through principal component

analyses and the principal component loadings. In addition, references to articles in this volume associated with each of the variables are given to aid a reader in accessing details of their construction.

As described above, the CI-E Sign Enhancement variable was based on ratio measures acquired during language sampling and the Verbal Rehearsal Speed variable was constructed from sentence durations and digit recall performance. The CI-E Speech Perception variable was based on total correct scores from the Lexical Neighborhood Test (LNT) (Kirk, Pisoni, & Osberger, 1995), Bamford Kowal Bench Sentences (BKB) (Bamford & Wilson, 1979), Early Speech Perception Test (ESP) (Moog & Geers, 1990) and Word Intelligibility by Picture Identification (WIPI) (Ross & Lerman, 1971). The CI-E Speech Production variable was composed of the total number of high and low context key words identified on the McGarr sentences (McGarr, 1983), the total number of correct consonants produced on the McGarr sentences and parent responses regarding how well listeners understood their child in elementary school (Tobey et al., 2010). The CI-E Language variable was constructed from performance on the WISC Similarities subtest, the number of different words per minute and number of words per utterance, and IPSyn total scores produced in a language sample (Geers & Sedey, 2010). The CI-E Reading score was based on quotients from the Woodcock Reading Mastery Test (WRMT), Word Attack subtest (Woodcock, 1987) and the Peabody Individual Achievement Test (PIAT) (Dunn & Markwardt, 1989) reading recognition and comprehension standard scores (Geers & Hayes, 2010).

Four variables were constructed to reflect performance outcomes at the CI-HS session. These variables were CI-HS Speech Perception, CI-HS Speech Production, CI-HS Language and CI-HS Literacy. The CI-HS Speech Perception variable was constructed from the LNT scores for signals presented at 70 and 50 dB SPL, BKB sentences in quiet and BKB sentences presented at +10dB signal-to-noise ratio. The CI-HS Speech Production variable contained five measures taken from McGarr sentences including total number of words identified in high and low context sentences in quiet, in multispeaker babble background noise, and total correct consonants (Tobey et al., 2010). The CI-HS Language variable was composed of the best standard score achieved of the Peabody Picture Vocabulary Test (PPVT) (Dunn & Markwardt, 1989) in the OC or SC condition, the WISC VIQ, the Clinical Evaluation of Language Fundamentals (CELF) (Semel-Mintz, Wiig, & Secord, 2003) Language Content Index, and Expressive One-Word Picture Vocabulary Test (EOWPVT) (Gardner, 2000) standard score. The CI-HS Literacy variable was composed of the proportion of words spelled correctly, the PIAT standard score and standard scores from the Test of Reading Comprehension (TORC) (Brown, Hammill, & Wiederholt, 1995).

Table 2 summarizes the correlations between the overall principal component scores, eigen values, the variance accounted for by each component, and the estimated principal component reliabilities. Eigen values all exceed 2.5, indicating that the PC score contains much more information than any single item from the original set. The percentage of variance that these new linear combinations accounted for ranged from 68.9% for sign enhancement to 83% for CI-E speech production. Reliability of the principal component scores ranged from .85 for sign enhancement to .94 for language at CI-HS. The interrelations suggest the outcomes are related and also demonstrate important degrees of independence suggesting their separate consideration. The correlation matrix in Table 2 permits examination of relations among the outcome variables (Perception, Production, Language and Literacy) at the CI-E and CI-HS test sessions. Some of the highest correlations occurred between outcome measures collected at the CI-E session and similar measures collected at CI-HS (values ranging from .75 to .83) suggesting that the relative standing of individuals on these outcomes is highly stable over time. The best performers in

elementary grades continue to exhibit the best outcomes in high school, and early difficulties tend to persist throughout the elementary and high school years. The most highly-related outcome areas were language and reading/literacy (values ranging from .74 to .88). These skills appear closely linked and CI children who demonstrate the best vocabulary and syntax skills in elementary grades go on to achieve the highest literacy performance in high school. Speech perception and speech production skills are also highly correlated with one another ($r = .69$ to $.87$), suggesting that the most direct result of improved auditory input from a CI is the child's ability to produce intelligible speech. The lowest correlations are observed between reading/literacy and speech perception ($r = .30$ to $.54$) or speech production (values ranging from .31 to .58). While these skills are related (i.e. all correlations are significant at $p < .01$ or better), other factors intervene to moderate these relationships.

RESULTS

The multiple regression analyses proceeded in three stages. First, we examined the influence of 1) duration of deafness and 2) sign enhancement ratio on verbal rehearsal speed. Second, we examined the influence of 1) duration of deafness, 2) sign enhancement ratio and 3) verbal rehearsal speed on early outcomes (speech perception, speech production, reading, and language). Third, we examined the influence of 1) duration of deafness, 2) sign enhancement ratio, 3) verbal rehearsal speed, and 4) early outcome (CI-E) on later outcomes (CI-HS). In all three stages of our analysis, the influences of gender, family size, SES, and PIQ were controlled by entering them on an initial step. Thus, the possible influences of developmental delay or low SES was removed before other relationships were examined. In all subsequent analyses, this collection of variables accounted for substantial proportions of variance in the outcomes (ranging from 13% to 22%). Collectively, the results of the three stages of analyses allow inferences about pathways of influence from early to later measures.

Table 3 contains the results for the analysis of CI-E verbal rehearsal speed and shows that the CI-E sign enhancement ratio is an independent, significant and substantial predictor. CI-E sign enhancement ratios below 1.0 indicate better performance on language outcome measures in the SC as compared to the OC interviews; thus, high values indicate reliance on speech without sign enhancement. High principal component scores on the CI-E verbal rehearsal speed composite variable indicate poorer verbal rehearsal skills (i.e., shorter digit spans and longer sentence durations). Thus, the negative impact of CI-E Sign Enhancement ratio on verbal rehearsal speed establishes that children whose language did not improve in an SC compared to an OC interview exhibited better verbal rehearsal skills.

Tables 4, 5, 6, and 7 present the analyses of the early outcomes for speech perception, speech production, language and reading. These regression models duplicate the predictors in Table 3, but now add CI-E verbal rehearsal speed as a predictor. What is particularly striking in these Tables is that CI-E verbal rehearsal speed is an independent and powerful predictor of each early performance outcome, accounting for between 13% and 30% of the variance in early outcomes above and beyond that accounted for by gender, family size, SES, PIQ, duration of deafness, and the CI-E sign enhancement ratio. Interestingly, the CI-E sign enhancement ratio also influences speech perception, speech production, and language significantly and independently of verbal rehearsal speed. However, it is not a significant predictor of literacy skills. The effect of sign enhancement on these early outcomes is both direct and indirect, with part of the influence acting through the impact on verbal rehearsal speed and part of the influence acting independently of verbal rehearsal speed.

Tables 8, 9, 10, and 11 present the last set of multiple regression analyses, examining later outcomes associated with the CI-HS test session for speech perception, speech production,

language and literacy. These regression models build upon the predictor sets used in the previous set of analyses, but add the early CI-E outcome associated with the performance domain as a predictor to each later outcome. Here, too, there is a striking similarity across the four analyses. In each instance, the early CI-E outcome forms a significant and independent predictor, above and beyond the other predictors by accounting for an additional 10% to 33% of the variance in later outcome. Other predictors also exert independent influences on different outcome domains (e.g., CI-E sign enhancement for CI-HS speech production; CI-E verbal rehearsal speed for CI-HS Literacy) but these predictors account for far less variance in the CI-HS outcomes than do the early CI-E outcomes.

Taken together, the analyses reported in Tables 3 through 11 indicate that CI-E sign enhancement strongly influences verbal rehearsal speed which, in turn, strongly influences all early elementary school outcomes which, in turn, strongly influence later high school outcomes. Although there was evidence for a direct influence of communication mode used by the child on speech perception and speech intelligibility outcomes (i.e., OC communicators scored higher), early communication mode did not predict language or literacy skills in the later adolescent years.

DISCUSSION

These analyses support the hypothesis that verbal rehearsal speed and information processing capacity are basic/core mediators of verbal development in children with hearing loss. Continued reliance on sign to supplement spoken communication influences the underlying core information processing speed and verbal rehearsal of items in working memory. The more CI students' spoken language is augmented by sign, the slower their verbal rehearsal speed. Verbal rehearsal speed constitutes one of the largest sources of variance underlying all of the speech and language outcomes in the battery. The verbal rehearsal measure used in these analyses reflects the availability of verbal storage capacity required for performing the digit span task and the rapid encoding and immediate response demands required for sentence repetition, reflecting individual differences in representational efficiency of the information processing system underlying speech perception and speech production.

The role of early communication mode in the development of representational efficiency warrants continued exploration in future research on children with hearing impairment. A finding that early emphasis on speech and spoken language processing facilitates the development of verbal rehearsal skills in CI users would be anticipated from findings with typically-developing children (Conway, Pisoni, & Kronenberger, 2009). Experience and activities with auditory input develop a broad set of domain-general sequential processing capacities including rote phonological memory strategies. Efficiency, speed, and fluency of verbal coding and processing, reflected in the sentence duration measures, likely influence language outcomes by enhancing the volume and "throughput" of phonological information rapidly encoded, processed and stored in immediate memory. These processes, in turn, allow a child to perceive, rehearse, and retrieve larger chunks of verbal information per unit of time. As in normal-hearing typically-developing children, verbal rehearsal speed also underlies the development of auditory-verbal processing skills in children who are learning and developing spoken language through the degraded acoustic-phonetic input provided by their CI from early childhood on (Pisoni & Cleary, 2003).

The current CI-HS sample is not representative of the entire population of children receiving CIs in the United States and Canada in the early 1990s. First, this study was restricted to children whose families spoke only English at home. Second, children with additional significant disabilities were not selected to participate at age 8–9. Additionally, the mean

parental education and income level was higher than the average for the general American population. Finally, the 112 students recruited from the original sample of 181 students outperformed the 72 students who did not return for follow-up on some outcome measures at CI-E (Geers et al., 2010). It is possible, therefore, that although the current sample exhibits the expected distribution of average and below-average PIQ scores, along with similar socioeconomic characteristics to those children who did not return for follow-up testing, the CI-HS participants may be advantaged in some respects. On the other hand, the CI-HS students in the current study did not have some of the benefits of more recently implanted children such as more advanced implant technology, auditory input from a CI before 2 years of age and/or significant amounts of pre-implant residual hearing due to the technology that was available and the selection criteria in place when this sample was implanted. As the current population of CI children with these advantages reaches adolescence, even more of them may exhibit age-appropriate outcome scores.

The design of this study does not allow us to determine causality among variables but rather to explore the influence of variables on communication outcomes in young adolescents. The results support the hypothesis that verbal rehearsal speed and information processing capacity during the elementary years are strongly related to later speech, language, and literacy outcomes in children with hearing loss. Children whose spoken language skills in elementary school were not on par with their sign language ability typically demonstrated slower verbal rehearsal speed. It is possible that the relation between verbal rehearsal speed and reliance on sign language is bi-directional. Continued reliance on sign may impact the development of verbal rehearsal speed. On the other hand, students who have slower processing speeds may have more difficulty perceiving and producing spoken language and so need to use sign in order to maximize their language abilities. Slower processing speed and/or continued reliance on sign language may be the result of undocumented disabilities in addition to deafness. Although parents and teachers reported that the participants in this study did *not* have any additional disabilities, the only objective index we have to support these reports is the WISC PIQ score. Performance IQ was controlled in each analysis before the impact of verbal rehearsal speed and sign enhancement was examined. Therefore, although we cannot rule out the possible influence of additional disabilities on the observed relationships, statistically controlling for PIQ serves to minimize this explanation.

CONCLUSIONS

The important conclusions derived from analyzing results from this nationwide sample of adolescents with profound SNHL who used a CI since their preschool years are as follows:

1. Speech perception, speech intelligibility, language, literacy and psychosocial adjustment far exceeded that reported for similar groups prior to the advent of CI technology.
2. Group mean scores for language, reading and social adjustment were generally within a standard deviation of normative samples of typically-developing age mates with normal hearing.
3. Performance of children in early elementary grades (age 8–9) was highly predictive of their relative standing in high school.
4. Variability in performance across a wide range of outcomes used to assess speech/language benefit following cochlear implantation was largely accounted for by a small set of core underlying neurocognitive information processing measures associated with verbal rehearsal speed.

5. Children who in the early elementary grades relied on spoken language (as indicated by receiving no benefit from manual signs) exhibited better verbal rehearsal skills and higher levels of speech perception, speech intelligibility, language and literacy in high school.

This article summarizes important relations between early sample characteristics and speech, language and reading outcomes in 112 adolescent cochlear implant users. Regression analyses examined how communication mode in early elementary grades influenced skills exhibited in high school and how this influence was mediated by information capacity of immediate memory and speed of verbal rehearsal. Use of an oral mode of communication positively influenced verbal rehearsal speed, which was a strong predictor of all early outcomes, which in turn strongly influenced later outcomes. These analyses suggest early communication mode exerts a powerful influence on early outcomes that persist into later years.

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Table 1

Variables used to construct principal component variables associated with elementary (CI-E) and high school (CI-HS) performance. Principal component loadings for each value are also depicted.

Measure	Loading	Measure	Loading
<i>^b</i> <u>CI-E Verbal Rehearsal Speed</u>		<i>^a</i> <u>CI-E Sign Enhancement</u>	
Average Duration of McGarr Sentences	.89	Words per Utterance Ratio OC:SC	.81
Duration of 7-syllable McGarr Sentences	.90	Different Words per Minute Ratio OC:SC	.86
Digit Span Raw Score: Forward Span	-.81	IPSyn Noun Phrases Ratio OC:SC	.81
Digit Span Scaled Score	-.82	IPSyn Sentence Structure Ratio OC:SC	.84
<i>^c</i> <u>CI-E Speech Perception</u>		<i>^c</i> <u>CI-HS Speech Perception</u>	
LNT Percent Correct at 70 dB SPL	.926	LNT Percent Correct at 70 dB SPL	.944
Average ESP Spondees & Monosyllables	.873	LNT Percent Correct at 50 dB SPL	.861
BKB Sentences in Quiet	.935	BKB Sentences in Quiet	.939
WIPI	.853	BKB Sentences in Noise (+10 dB SNR)	.894
<i>^d</i> <u>CI-E Speech Production</u>		<i>^d</i> <u>CI-HS Speech Production</u>	
High Context Keywords Understood	.955	High Context Keywords in Noise	.858
Low Context Keywords Understood	.942	Low Context Keywords in Noise	.876
Transcribed Consonant Production	.903	High Context Keywords Understood	.943
Use of Speech Questionnaire	.838	Low Context Keywords Understood	.953
		Transcribed Consonant Production	.822
<i>^e</i> <u>CI-E Language</u>		<i>^e</i> <u>CI-HS Language</u>	
WISC similarities	.827	Best PPVT Scaled Score	.936
Different Words per Minute	.924	EOWPVT Scaled Score	.930
Words Per Utterance	.894	CELF Language Content Index	.902
IPSyn Total Score	.883	WISC Verbal IQ	.924
TACL	.835		
<i>^f</i> <u>CI-E Reading</u>		<i>^f</i> <u>CI-HS Literacy</u>	
Woodcock Word Attack Quotient	.872	Proportion of Words Spelled Correctly	.845
PIAT Reading Recognition Quotient	.934	PIAT Reading Standard Score	.919
PIAT Reading Comprehension Quotient	.850	TORC Reading Quotient	.904

^a Geers, Brenner & Tobey;

^b Pisoni, Kronenberger, Roman & Geers;

^c Davidson, Geers, Blamey, Tobey & Brenner;

^d Tobey, Geers, Sundarajan & Lane;

^e Geers & Sedey;

^f Geers & Hayes

The interrelations between elementary school (CI-E) and high school (CI-HS) variables, Eigen values, proportion of variance contributed and reliability are also indicated for the variables.

Table 2

	1	2	3	4	5	6	7	8	9	10
1 Sign Enhancement	1									
2 Verbal Rehearsal Speed	-.369	1								
3 Speech Perception CI-E	.568	-.634	1							
4 Speech Perception CI-HS	.469	-.498	.834	1						
5 Speech Production CI-E	.676	-.654	.865	.688	1					
6 Speech Production CI-HS	.663	-.529	.708	.692	.773	1				
7 Language CI-E	.439	-.748	.706	.522	.760	.545	1			
8 Language CI-HS	.191	-.584	.486	.392	.510	.287	.754	1		
9 Reading CI-E	.278	-.633	.538	.408	.581	.388	.749	.746	1	
10 Literacy CI-HS	.175	-.628	.442	.299	.510	.306	.740	.876	.803	1
Eigen value	2.757	2.937	3.223	3.313	3.318	3.979	3.815	3.409	2.356	3.195
Proportion of Variance	0.689	0.734	0.806	0.828	0.830	0.796	0.763	0.852	0.785	0.799
Reliability	0.850	0.879	0.920	0.931	0.932	0.936	0.922	0.942	0.863	0.916

r ≥ .1861, p < .05

Table 3

Multiple regression results for CLE Verbal Rehearsal Speed.

Predictor	Step 1			Step 2		
	β	t	p	β	t	p
Gender	-0.13	-1.41	0.16	-0.14	-1.57	0.12
Performance IQ	-0.18	-1.98	0.05	-0.19	-2.23	0.03
Family Size	0.17	1.83	0.07	0.08	0.94	0.35
SES	-0.28	-2.95	0.003	-0.18	-1.95	0.05
Duration of Deafness				0.10	1.15	0.25
Sign Enhancement Ratio				-0.31	-3.46	0.001
Explained Variance				0.16		0.09
Total Explained Variance				0.16		0.25

Table 4

Multiple regression results for CLE Speech Perception.

Predictor	Step 1				Step 2				Step 3			
	β	t	p	R ²	β	t	p	R ²	β	t	p	R ²
Gender	-0.04	-0.48	0.63		-0.00	-0.42	0.68		-0.04	-1.50	0.14	
Performance IQ	0.15	1.75	0.08		0.18	2.40	0.02		0.09	1.657	0.18	
Family Size	-0.42	-4.78	< .001		-0.30	-3.88	< .001		-0.26	-3.94	< .001	
SES	0.24	2.74	0.01		0.09	1.17	0.23		0.007	0.01	0.92	
Duration of Deafness					-0.06	-0.70	0.41		-0.00	-0.13	0.87	
Sign Enhancement Ratio					0.50	6.47	< .001		0.33	5.14	< .001	
Verbal Rehearsal Speed									-0.47	-6.55	< .001	
Explained Variance				0.23				0.22				0.16
Total Explained Variance				0.23				0.45				0.61

Table 5

Multiple regression results for CIE Speech Production.

Predictor	Step 1			Step 2			Step 3		
	β	t	p	R^2	β	t	p	R^2	p
Gender	0.10	1.17	0.24		0.11	1.75	0.08	0.06	0.30
Performance IQ	0.13	1.47	0.14		0.16	2.40	0.02	0.08	0.17
Family Size	-0.38	-4.30	<.001		-0.23	-3.29	0.001	-0.19	-3.29 0.001
SES	0.27	3.04	0.002		0.09	1.21	0.23	0.009	0.15 0.88
Duration of Deafness					-0.10	-1.53	0.13	-0.06	-1.05 0.29
Sign Enhancement					0.62	9.0	<.001	0.49	7.96 <.001
Verbal Rehearsal Speed								-0.42	-6.59 <.001
Explained Variance				0.22				0.35	0.13
Total Explained Variance				0.22				0.56	0.69

Table 6

Multiple regression results for CIE Language.

Predictor	Step 1				Step 2				Step 3			
	β	t	p	R ²	β	t	p	R ²	β	t	p	R ²
Gender	0.11	1.25	0.21		0.12	1.47	0.14		0.03	0.55	0.58	
Performance IQ	0.11	1.19	0.23		0.12	1.47	0.14		-0.003	-0.04	0.97	
Family Size	-0.28	-3.11	0.002		-0.18	-2.08	0.04		-0.12	-1.93	0.05	
SES	0.30	3.27	0.001		0.19	2.14	0.03		0.07	1.05	0.29	
Duration of Deafness					-0.15	-1.85	0.06		-0.09	-1.42	0.16	
Sign Enhancement Ratio					0.36	4.21	< .001		0.16	2.39	0.02	
Verbal Rehearsal Speed									-0.64	-8.94	< .001	
Explained Variance				0.17				0.14				0.31
Total Explained Variance				0.17				0.31				0.62

Table 7

Multiple regression results for CLE Reading.

Predictor	Step 1			Step 2			Step 3		
	β	t	p	R^2	β	t	p	R^2	p
Gender	0.06	0.67	0.51		0.07	0.78	0.44		0.93
Performance IQ	0.14	1.55	0.12		0.15	1.65	0.10		0.62
Family Size	-0.13	-1.44	0.15		-0.06	-0.67	0.51		0.85
SES	0.30	3.18	0.001		0.23	2.45	0.01		0.11
Duration of Deafness					-0.18	-1.98	0.05		0.11
Sign Enhancement Ratio					0.21	2.27	0.02		0.66
Verbal Rehearsal Speed					-0.56	-6.46	<.001		
Explained Variance				0.13			0.07		0.23
Total Explained Variance				0.13			0.20		0.43

Table 8

Multiple regression results for CI-HS Speech Perception as a function of CI-E Speech Perception.

Predictor	Step 1				Step 2				Step 3				Step 4			
	β	t	p	R ²	β	t	p	R ²	β	t	p	R ²	β	t	p	R ²
Gender	-0.10	-1.12	0.26		-0.09	-1.13	0.26		-0.15	-1.85	0.06		-0.06	-1.09	0.28	
Performance IQ	0.08	0.89	0.37		0.11	1.25	0.21		0.03	0.40	0.69		-0.05	-0.86	0.39	
Family Size	-0.27	-2.98	0.003		-0.19	-2.11	0.04		-0.15	-1.88	0.06		0.08	1.34	0.16	
SES	0.25	2.61	0.01		0.12	1.35	0.18		0.05	0.62	0.54		0.05	0.80	0.43	
Duration of Deafness					0.01	0.09	0.93		0.04	0.57	0.57		0.05	1.01	0.32	
Sign Enhancement Ratio					0.41	4.67	< .001		0.29	3.40	0.001		-0.03	-0.47	0.64	
Verbal Rehearsal Speed									-0.38	-4.21	< .001		0.05	0.71	0.48	
Speech Perception CI-E													0.92	10.85	< .001	
Explained Variance				0.13				0.15				0.11				0.33
Total Explained Variance				0.13				0.28				0.39				0.71

Table 9
Multiple regression results for CI-HS Speech Production as a function of CLE Speech Production.

Predictor	Step 1				Step 2				Step 3				Step 4			
	β	t	p	R ²	β	t	p	R ²	β	t	p	R ²	β	t	p	R ²
Gender	0.145	1.589	0.112		0.157	2.218	0.027	0.027	0.117	1.740	0.082	0.082	0.084	1.396	0.163	
Performance IQ	0.063	0.685	0.494		0.099	1.380	0.167		0.041	0.599	0.549		-0.003	-0.053	0.958	
Family Size	-0.226	-2.451	0.014		-0.082	-1.109	0.268		-0.058	-0.824	0.410		0.050	0.764	0.445	
SES	0.246	2.603	0.009		0.054	0.703	0.482		0.000	0.003	0.997		-0.005	-0.078	0.938	
Duration of Deafness					-0.028	-0.391	0.696		0.001	0.022	0.982		0.035	0.581	0.561	
Sign Enhancement Ratio					0.636	8.478	< .001		0.544	7.335	< .001		0.268	3.199	0.001	
Verbal Rehearsal Speed									-0.295	-3.860	< .001		-0.058	-0.715	0.475	
Speech Production CLE													0.566	5.334	< .001	
Explained Variance				0.13				0.36				0.07				0.10
Total Explained Variance				0.13				0.49				0.55				0.65

Table 10
Multiple regression results for CI-HS Language as a function of CLE Language. Language CI-HS

Predictor	Step 1				Step 2				Step 3				Step 4			
	β	t	p	R ²	β	t	p	R ²	β	t	p	R ²	β	t	p	R ²
Gender	-0.097	-1.111	0.266		-0.089	-1.047	0.295		-0.159	-2.150	0.032		-0.187	-3.369	0.001	
Performance IQ	0.237	2.671	0.008		0.234	2.710	0.007		0.133	1.754	0.079		0.136	2.389	0.017	
Family Size	-0.088	-0.995	0.320		-0.030	-0.332	0.740		0.013	0.172	0.863		0.111	1.891	0.059	
SES	0.325	3.580	<.001		0.287	3.114	0.002		0.192	2.366	0.018		0.136	2.231	0.026	
Duration of Deafness					-0.231	-2.707	0.007		-0.179	-2.420	0.016		-0.109	-1.949	0.051	
Sign Enhancement Ratio					0.116	1.297	0.194		-0.043	-0.529	0.597		-0.172	-2.735	0.006	
Verbal Rehearsal Speed									-0.518	-6.096	<.001		-0.012	-0.139	0.889	
Language CLE													0.791	9.005	<.001	
Explained Variance				0.19				0.06				0.20				0.24
Total Explained Variance				0.19				0.25				0.46				0.70

Table 11

Multiple regression results for CI-HS Reading as a function of CI-E Reading.

Predictor	Step 1				Step 2				Step 3				Step 4			
	β	t	p	R ²	β	t	p	R ²	β	t	p	R ²	β	t	p	R ²
Gender	0.125	1.404	0.160		0.131	1.506	0.132		0.055	0.742	0.458		0.060	1.072	0.284	
Performance IQ	0.212	2.354	0.019		0.210	2.365	0.018		0.100	1.301	0.193		0.075	1.302	0.193	
Family Size	-0.148	-1.647	0.100		-0.099	-1.080	0.280		-0.052	-0.667	0.505		-0.042	-0.725	0.468	
SES	0.270	2.934	0.003		0.238	2.521	0.012		0.135	1.647	0.100		0.049	0.793	0.428	
Duration of Deafness					-0.194	-2.216	0.027		-0.138	-1.858	0.063		-0.060	-1.060	0.289	
Sign Enhancement Ratio					0.100	1.088	0.276		-0.075	-0.921	0.357		-0.100	-1.624	0.104	
Verbal Rehearsal Speed									-0.565	-6.622	<.001		-0.199	-2.615	0.009	
Reading CI-E													0.656	9.010	<.001	
Explained Variance				0.165				0.045				0.238				0.244
Total Explained Variance				0.165				0.211				0.449				0.693