The Age at Which Young Deaf Children Receive Cochlear Implants and Their Vocabulary and Speech-Production Growth: Is There an Added Value for Early Implantation?

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Objective: **The age at which a child receives a cochlear implant seems to be one of the more important predictors of his or her speech and language outcomes. However, understanding the association between age at implantation and child outcomes is complex because a child's age, length of device use, and age at implantation are highly related. In this study, we investigate whether there is an added value to earlier implantation or whether advantages observed in child outcomes are primarily attributable to longer device use at any given age.**

Design: **Using hierarchical linear modeling, we examined latent-growth curves for 100 children who had received their implants when they were between 1 and 10 yr of age, had used oral communication, and had used their devices for between 1 and 12 yr. Children were divided into four groups based on age at implantation: between 1 and 2.5 yr, between 2.6 and 3.5 yr, between 3.6 and 7 yr, and between 7.1 and 10 yr.**

Results: **Investigation of growth curves and rates of growth over time revealed an additional value for earlier implantation over and above advantages attributable to longer length of use at any given age. Children who had received their implants before the age of 2.5 yr had exhibited early bursts of growth in consonant-production accuracy and vocabulary and also had significantly stronger outcomes compared with age peers who had received their implants at later ages. The magnitude of the early burst diminished systematically with increasing age at implantation and was not observed for children who were older than 7 yr at implantation for consonant-production accuracy or for children who were over 3.5 yr old at implantation for vocabulary. The impact of age at implantation on children's growth curves differed for speech production and vocabulary.**

Conclusions: **There seems to be a substantial benefit for both speech and vocabulary outcomes when children receive their implant before the age of 2.5 yr. This benefit may combine a burst of growth after implantation with the impact of increased length of use at any given age. The added advantage (i.e., burst of growth) diminishes systematically with increasing age at implantation.**

(Ear & Hearing 2006;27;628–644)

Children with profound sensorineural hearing loss are at significant risk for serious speech and language delays that can impact their communication, academic, and social development (Allen, 1986; Holt, 1994; Karchmer, Milone, & Wolk, 1979). One treatment for profound hearing loss is the cochlear implant, which provides substantial, usable hearing for many children (NIH consensus conference, 1995). Use of a cochlear implant has been associated with stronger outcomes in speech perception (Tyler, Teagle, Kelsay, et al., 2001), speech production (Connor, Hieber, Arts, et al., 2000; Geers, 2002), language (Svirsky, 2001), and reading (Connor & Zwolan, 2004; Geers, 2002; Spencer, Tomblin, & Gantz, 1998) compared with children using conventional hearing aids. However, the variability in these results among children is high, and many factors seem to contribute to the successful use of cochlear implants. In particular, the age at which children receive a cochlear implant has been related to speech, language, and literacy outcomes (Connor, Hieber, Arts, et al., 2000; Connor & Zwolan, 2004; Lederberg & Spencer, 2005; Tomblin, Barker, Spencer, et al., 2005; Zwolan, Ashbaugh, Alarfaj, et al., 2004).

One challenge in estimating the impact of children's age at implantation on speech and language development is that the chronological age, length of cochlear implant use, and the age at which children receive the implant are all highly related. Indeed, at any given age, length of use, and age at implantation are perfectly correlated—children who receive implants at younger ages will have used the implant for a longer time compared with same-age peers. However, language theories of critical or sensitive periods (Lederberg & Spencer, 2005; Lenneberg, 1967; Newport, 1990) suggest that access to sound during the first few years of life may lead to accelerated growth and stronger outcomes over and

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above those associated with increasing lengths of device use. The purpose of this study was to use latent-growth modeling to tease apart the typically conflated effects of developmental maturation, length of implant use, and age at implantation on children's speech and vocabulary growth, and to explore any additional value (i.e., improvement in speech and language skills obtained over and above what can be explained by length of device use alone) early implantation may afford.

DEAF CHILDREN'S SPEECH AND LANGUAGE DEVELOPMENT, COCHLEAR IMPLANTS, AND AGE AT COCHLEAR IMPLANTATION

Children who are younger when they receive the implant generally achieve stronger skills after sustained implant use than do children who receive devices when they are older. Such implantation-age effects have been observed for speech perception (Manrique, Cervera-Paz, Huarte, et al., 2004; McConkey Robbins, Koch, Osberger, et al., 2004; Zwolan et al., 2004), speech production (Tye-Murray, Spencer, & Woodworth, 1995), vocabulary (Connor, Hieber, Arts, et al., 2000), grammar (Nikolopoulos, Dyar, Archbold, et al., 2004), and reading comprehension (Connor & Zwolan, 2004). Although these studies suggests a robust effect, other studies suggest that there is no advantage to early implantation (Geers, 2002, 2004). In this study, we focus on two outcomes—children's speech production and vocabulary—because both represent important indices of children's communicative competence and are related to long-term academic success for all children (Catts, Fey, Zhang, et al., 1999).

Tye-Murray et al. (1995) reported that children who were prelingually deaf and who had received a cochlear implant between 2 and 5 yr of age achieved greater rates of growth in phoneme accuracy and word intelligibility than did children who had received their implants between the ages of 5 and 8 yr and 8 to 15 yr. There were no significant differences in the performance of the children in the latter two groups. The authors also reported a significant positive correlation between speech-production and speech-perception performance. Connor et al. (2000) observed that children who were younger (i.e., < 5 yr) when they received their implants achieved higher scores and significantly greater rates of growth over time on consonant-production accuracy tasks than did children who were over 5 yr of age when they received their implants.

Stronger receptive and expressive vocabulary scores and stronger language development have also been associated with earlier implantation (Connor, Hieber, Arts, et al., 2000; Kirk, Miyamoto, Lento, et al., 2002; Manrique et al., 2004; Svirsky, Teoh, & Neuburger, 2004; Tomblin, Barker, Spencer, et al., 2005). In one study (Connor, Hieber, Arts, et al., 2000), children who received their implants before age 5 yr demonstrated vocabulary-growth rates that were significantly greater than those for children who were over 5 yr of age when they received the implant. Similarly, Svirsky et al. (2004) and Kirk et al. (2002) found that children who received an implant before their second or third birthday demonstrated stronger rates of acquisition than did children who received their device after their third birthday. Tomblin et al. (2005) observed greater overall rates of growth in expressive language for children who were younger when they received their implants, when age at implantation was considered as a continuous variable, rather than when groups of children were compared. This is notable because 24 of the 29 children followed over time had received their implants before reaching 30 mo of age. The remaining five children were between 31 and 40 mo of age. Thus, even when comparing children who were all relatively young when they received their device, younger age at implantation was associated with stronger language growth.

Conversely, Geers and colleagues (Geers, 2002, 2004; Geers, Brenner, Nicholas, et al., 2002; Geers, Nicholas, & Sedey, 2003) reported that children's age at implantation was an inconsistent predictor of speech and language outcomes. Because outcomes were examined at one point in time rather than over time in these studies, the effect of age, age at implantation, and length of implant use were likely confounded and may have contributed to their findings. Also, children's age at implantation ranged only from 2 to 5 yr, whereas the others studies had children with widely varying ages at implantation. For example, Sharma et al. (2002) included children as young as 24 mo and older than 7 yr at implantation.

Many researchers suggest that the impact of age at implantation is related to the developmental plasticity of the central auditory system (Sharma, 2002; Sharma, Dorman, & Spahr, 2002; Shephard, Hartmann, Heid, et al., 1997; Robinson, 1998; but also see Gordon, Papsin, & Harrison, 2003). They observe that neurological changes occur in the brain as a result of auditory deprivation, and that the "central auditory structures can undergo functional reorganization in response to sensory input via a cochlear implant" (Shephard, Hartmann, Heid, et al., 1997, p. 29). This has been additionally supported with electrophysiological recordings of evoked potentials (Ponton, Don, Eggermont, et al., 1996), event-related brain potentials (Neville, Mills, & Lawson, 1992) and cortical auditory-evoked potential studies

(Sharma, 2002; Sharma, Dorman, & Spahr, 2002; Sharma, Dorman, & Kral, 2005).

EARLY LANGUAGE DEVELOPMENT AND SENSITIVE PHASES

One reason researchers have been intrigued with the potential value of early implantation is that there may exist an early critical or sensitive phase for speech and language development. The existence of an early critical or sensitive phase for language development would suggest that delaying children's receipt of an implant might jeopardize their lifetime communication abilities by withholding critical auditory information when it is most useful developmentally. A sensitive phase occurring early in life is one of the most persistent yet controversial tenets of theories regarding child language development (Bailey, 2002; Bruer, 1999; Curtiss, 1977; Johnson & Newport, 1989; Lenneberg, 1967; Locke, 1997; Mayberry, 1993; Mayberry, Lock, & Kazmi, 2002; Newport, 1990, 1991; Oyama, 1976; Ruben, 1997; Sharma, Dorman, & Spahr, 2002).

Locke (1997) suggested that there may exist a series of overlapping and interrelated critical phases within an overall sensitive period. The lexicon developed during the first 2 to 3 yr of life may act to trigger or stimulate the development of the grammatical centers of the brain that are served primarily by the left hemisphere, which make possible phonology, morphology, and syntax. Inadequate lexical development during the first years of life may result in understimulation of the grammatical centers, which may result in long-term language-development delays (Locke, 1993, 1994). Others suggest that phonological, grammatical, and semantic subprocesses may have differing critical periods based on evidence from event-related brain potentials. For example, sensitive periods for phoneme discrimination seem to occur from before birth until 12 mo of age, whereas semantic organization occurs before 4 yr of age (Ruben, 1997; Neville, Mills, & Lawson, 1992). Thus, we might expect a child's age at implantation to affect consonant-production accuracy differently than it affects vocabulary development.

There is additional evidence that the first years of life may be especially important for vocabulary development for children with normal hearing. For example, children with normal hearing demonstrate more rapid vocabulary growth if their parents talk to them more during the first years of life (Hart & Risley, 1995; Huttenlocher, Haight, Bryk, et al., 1991). Moreover, the rate of vocabulary growth seems to remain virtually unchanged from kindergarten and beyond, regardless of the special services provided to the children (Hart & Risley, 1995). Follow-up studies with children in the Hart et al. (1995) study indicated that the amount and the ways parents talked to their babies were also related to later literacy-skill development. Further, children's language at age 3 yr, as measured by mean length of utterance in a language sample, accounted for a significant amount of variance in reading performance in fourth grade (Dickinson & Tabors, 2001). Children's vocabulary is an important predictor of future academic success (Storch & Whitehurst, 2002).

Thus, exposure to speech and language during the early years of life seems to have a lasting impact on children's auditory, speech, language, and literacy development. Moreover, children's speech and language skills are important predictors of later academic success (Scarborough, 2001). In this study, we examine whether receiving a cochlear implant during the first years of life results in improved speech and vocabulary growth over and above the advantage offered by having used an implant for a longer period of time than same-age peers who received an implant at an older age. We do this by examining longitudinal speech-production and language-growth curves as a function of children's age at implantation.

RESEARCH QUESTIONS

The following research questions were posed: How do growth curves (slope and acceleration) for speech skills, specifically, consonant-production accuracy, vary for children who receive their implants at different ages, ranging from 12 mo to 10 yr? How do growth curves (slope and acceleration) for vocabulary vary for children who receive their implants at different ages? Comparing patterns across outcomes (consonant-production accuracy and vocabulary), are the growth curves similar or different?

Observed positive effects of age at implantation may be a result of at least three potential growth curves (Fig. 1): (1) length-of-use effect—longer exposure to sound; the younger children are when they receive their implant, the longer they will have used their implant when they reach any given age, resulting in stronger outcomes compared with same-age peers who received their implant later; (2) early burst plus length-of-use effect—an immediate advantage after early implantation; outcomes are better because children experienced a burst of speech or vocabulary growth after early implantation in addition to a length-of-use effect; or (3) sustained growth-rate change plus length-of-use effect—greater long-term rates of growth; outcomes are better because skills are growing faster (i.e., an ongoing effect of early implantation and access to sound). The latter two growth patterns would indicate an additional ad-

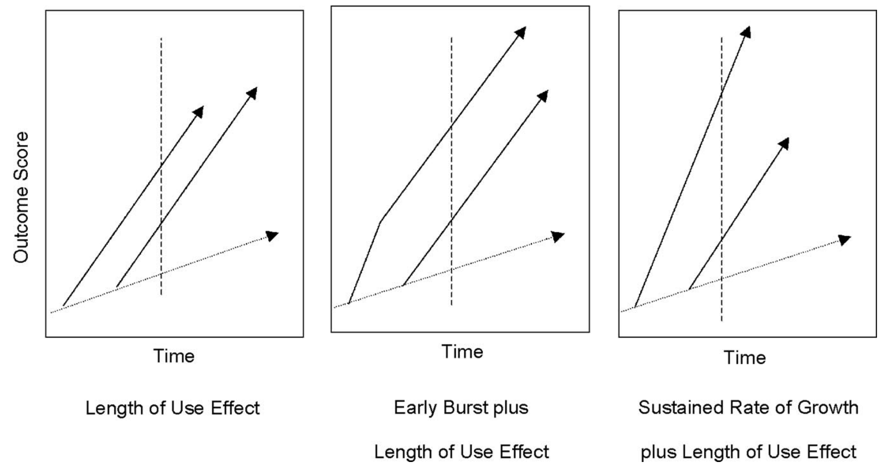

Figure 1. ***Left,*** **length-of-use effect.** ***Middle figure,*** **early burst plus a length-of-use effect.** ***Right figure,*** **sustained growth-rate change plus a length-of-use effect. The x-axis represents time and the y-axis represents the child's consonant-production accuracy (SPEECH) or vocabulary score. The solid arrows represent the predicted growth curves for children using cochlear implants. The dotted arrows represent the predicted growth curve for deaf children using conventional hearing aids. The solid arrows begin at the moment in time at which the child receives the cochlear implant. The vertical slashed line represents the specific moment in time at which the children's speech or vocabulary is measured. The difference in scores when the arrowed lines intersect the vertical dotted line represents the respective scores when children are the same age. In each example, the child who receives the implant at a younger age achieves a higher score than the child who receives the implant later. The ways in which the paths or trajectories differ is of particular interest in this study.**

vantage or value for earlier implantation, over and above that related to how long children used their implants at any given age. If rates of speech and vocabulary growth differ according to the age at which a child received his or her cochlear implant (i.e., the latter two examples; Fig. 1, middle and right), this would indicate that the effect of age at implantation is not solely related to length of implant use. If rates of spoken receptive vocabulary and speech-production growth do not differ according to the age at which children received their implants (Fig. 1, left), then children's superior performance would, most likely, be a function of longer exposure to usable auditory information. The trajectories for speech and language may differ. We hypothesize that an early burst is more likely for vocabulary growth than for speech production. A vocabulary burst has been observed for typically developing children with normal hearing sensitivity (Elman, Bates, Johnson, et al., 1999; Fenson, Dale, Reznick, et al., 1993).

Children with access to sign language have access to language, albeit visuospatial (Mayberry, Lock, & Kazmi, 2002; Meier, 1991; Petitto & Marentette, 1991). This presents a confounding influence on language development that we may not be able to control solely with statistics. Thus, all study participants were congenitally profoundly deaf children (unaided pure-tone threshold average ≥90 dBHL) whose parents chose to use an oral communication approach (i.e., no use of sign language) (Carney & Moeller, 1998), thus precluding children's access to language via sign language before implantation.

METHODS AND MATERIALS

Participants

Participants (N = 100) were children who received a cochlear implant between 1981 and 2004 at a major cochlear implant center. Children received their implants between the ages of 12 mo and 10 yr (mean = 61 mo) and had used their implants for up to 13 yr at the time of the study (mean = 4 yr). On average, four assessments were available for each child. Children used a variety of cochlear implant devices including those made by leading manufacturers. Details are provided in Table 1.

Children were divided into four groups based on their age at implantation: group A1 (ages 1 to 2.5 yr, N = 21), group A2 (ages 2.6 to 3.5 yr, N = 15), group B (ages 3.6 to 7 yr, N = 20), and group C (ages 7.1 to 10 yr, N = 44). Age at implantation was determined using the date on which the cochlear implant device was activated (initial stimulation or hookup). The grouping strategy was developed based on previous research (Holt, Svirsky, Neuburger, et al., 2004; Sharma, Dorman, & Spahr, 2002; Sharma, Dorman, & Kral, 2005; Tomblin, Barker, Spencer, et al., 2005), taking into account recent trends for earlier implantation. Specifically, Sharma et al. (2002), using cortical auditory-evoked response waveforms for children who received cochlear implants at different ages,

TABLE 1. Descriptive information for children by age at implantation groups A1, A2, B, and C

Age at implantation (mo)	Group A1 12–30	Group A2 31–42	Group B 43–84	Group C 85–120
Number of children in group	21	15	20	44
Mean age at implantation (mo)	21	36	50	90
Mean year of birth	1999	1995	1994	1990
Mean preoperative aided speech-detection thresholds (dB HL)	50	51	47	48
Mean propensity score (predicted age at implantation in months)	31	42	54	76
Device				
% Cochlear Corp Mini-22	18	57	47	58
% Nucleus-24M and RCS	41	36	44	32
% other (Clarion and MedEl)	41	7	9	10

demonstrated distinctive patterns for three implantation-age ranges, which correspond to our groups A, B, and C. They demonstrated that children who received their implants before age 3.5 yr obtained P1 latencies comparable with those of children with normal hearing sensitivity after about 6 mo of implant use. The P1 response is generated by auditory thalamic and cortical sources, reflects synaptic propagation through peripheral and central auditory pathways, and is sensitive to age (Sharma, Dorman, & Spahr, 2002). Results were mixed for children implanted between ages 3.5 and 7 yr. No child in the study who had received the implant after age 7 yr demonstrated typical central auditory system activity even after 4 yr of implant use.

We split group A into groups A1 and A2 because of emerging evidence that children who receive implants as young as 12 mo of age achieve stronger language growth than do children who are only a year or two older (Svirsky, Teoh, & Neuburger, 2004; Tomblin, Barker, Spencer, et al., 2005). The division at 2.5 yr was based on language research (Bates, 1999; Elman, Bates, Johnson, et al., 1999; Locke, 1997), which reveals that children with normal hearing may experience rapid vocabulary growth around their second birthday. Additionally, examination of the growth curves in Tomblin et al. (2005) suggested that there may have been qualitative differences in growth curves for children under 28 mo at implantation compared with children who were over 32 mo at activation. Other grouping options based on these findings would suggest dividing groups at 21 mo. However, we lacked sufficient numbers of children who had received their implants between 12 and 21 mo to consider this grouping (only four children would have been in this group).

Only children who used a strictly oral communication approach (i.e., used spoken language with or without lip reading and did not use sign language) were included in the study. All children were congenitally deaf with causes including familial/genetic (n = 15) and prenatal complications (n = 3); cause of deafness for the majority of children was unknown (n = 82). No children with histories of meningitis or Mondini malformation were included. Additionally, any children with disabilities in addition to profound deafness were excluded from the sample. In this way, we intended to minimize potentially confounding, unmeasurable variables.

Description of Variables

Children were assessed on a battery of speech and language measures as part of clinical follow-up before and after cochlear implantation. The preferred schedule included a preimplantation speech and language assessment in the 6 mo before surgery. Children were then followed after implantation semiannually for the first 2 yr, with annual speech and language assessments thereafter. This schedule was not followed for some children because of missed appointments, scheduling conflicts, or educational or therapy needs. Additionally, not all assessments were given during each visit (e.g., if the child was too young or too fatigued to complete the assessment battery). Nevertheless, the two measures used in this study were given at most of the visits.

Vocabulary

Spoken receptive vocabulary skills were assessed using the Peabody Picture Vocabulary Test 3 (PPVT-3, Dunn & Dunn, 1997). This test was administered by speech-language pathologists using spoken English (no sign language) in a quiet room. Before the availability of the PPVT-3, the PPVT-R (Dunn & Dunn, 1981) was administered. All PPVT-R raw scores were converted to PPVT-3 raw scores using the table provided in the PPVT-3 examiner's manual. PPVT scores were available for 100 children, with approximately four observations per child (390 in all).

Consonant-Production Accuracy

Consonant-production accuracy (SPEECH) was assessed by computing the percentage of consonant phonemes children produced correctly in response to

TABLE 2. Consonant-production accuracy (SPEECH) intercepts, slopes, and acceleration for age at implantation groups with time centered at 24 months after receipt of cochlear implant

Fixed effects	Coefficient	Standard error	*t* ratio (df)
For intercept π_0			
Intercept β_{00}	68.95	3.85	17.91 (74)***
Group A1 β_{01}	−32.00	9.38	−3.41***
Group A2 β_{02}	−29.59	7.80	−3.79***
Group B β_{03}	−18.95	7.24	−2.62**
Propensity score β_{04}	−0.08	0.19	−0.46
For time (months) after implantation centered at 24 months π_1			
Slope β_{10}	0.60	0.07	9.08 (74)***
Group A1 β_{11}	1.23	0.46	4.67***
Group A2 β_{12}	0.59	0.20	2.91**
Group B β_{13}	0.75	0.17	4.40***
Propensity score β_{14}	−0.001	0.002	−0.59
For quadratic trend (acceleration) centered at 24 months after implantation π_2			
Mean acceleration β_{20}	0.001	0.002	0.25 (330)
Group A1 β_{21}	−0.02	0.007	−2.37*
Group A2 β_{22}	−0.003	0.006	−0.59
Group B β_{23}	−0.01	0.003	−2.46**
Propensity score β_{24}	0.00003	0.0001	−0.62
For preoperative status using hearing aids π_3			
Intercept β_{30}	−12.77	5.35	−2.38 (330)*
Group A1 β_{31}	35.54	13.35	2.66**
Group A2 β_{32}	16.9	7.87	2.15**
Group B β_{33}	15.57	7.87	1.98*
Random effects	**Standard deviation**	**Variance**	X^2 **(df)**
Intercept r_{0i}	15.48	239.58	297.18 (70)***
Time r_{1i}	0.08	0.007	108.58 (70)**
Level 1 e_{it}	16.64	277.04	

*** $p < 0.001$; ** $p \le 0.01$; * $p < 0.05$. *Note: Deviance = 3009. Age Implanted Group A1 <2.6 years, A2 2.6–3.5 yr, Group B 3.6–7.0 years, Group C (the fixed reference group), 7.1–10 yr. Model explains 54% of the variance in children's scores.*

picture stimuli from one of two standardized articulation tests, the Arizona Articulation Proficiency Scale (Fudala, 1974) or the Goldman–Fristoe Test of Articulation (Goldman & Fristoe, 1969). This method has been used successfully to describe children's speech and is described more completely in Connor et al. (2000). Children's responses were transcribed by a speech–language pathologist and entered into the PROPH+ software, Computerized Profiling (Long & Fey, 1993). In this software, the number of consonant phonemes produced correctly was divided by the total number of possible phonemes to compute the percentage of consonants produced correctly (Shriberg, Austin, Lewis, et al., 1997; Shriberg & Kwiatkowski, 1988). We diverged from the protocol of Shriberg and colleagues in calculating percentage consonants correct from language samples of connected speech rather than picture stimuli. With this exception, we have replicated their procedures as closely as possible because they have demonstrated reliability and are related to perceptions of speech intelligibility. The SPEECH value was used in the statistical models. Connor et al. (2000) provide a more complete description of this metric. Overall, higher SPEECH scores are associated with better speech intelligibility for children with normal hearing (Shriberg & Kwiatkowski, 1988) and for children with cochlear implants (Connor, Hieber, Arts, et al., 2000). SPEECH scores were available for 79 children, with an average of more than four observations per child (347 in all). Group membership was as follows: group A1 = 12, group A2 = 11, group B = 16, and group C = 40. Children lacking SPEECH scores were represented in each of the four groups, and although descriptive statistics revealed a slightly higher propensity score (67.3 versus 63.4), no other systematic differences between children with and without SPEECH scores were observed on any of the other variables included in the models.

Data Analysis

Hierarchical linear modeling (HLM) (Raudenbush & Bryk, 2002) was used to model SPEECH and vocabulary latent-growth curves for each of the four groups of children. HLM was selected for these analyses because it (1) is robust to unequal group size; (2) can accommodate missing data; (3) can model longitudinal data collected across uneven

TABLE 3. Consonant-production accuracy (SPEECH) slope (percentage points per year) by length of use for each group

Length of use (mo)	Group A1 12–30	Group A2 31–42	Group B 43–84	Group C 85–120
Slope at 12 mo	21.6	16.7	18.7	7.0
	A1 > A2			
	$\chi^2(2) = 17.6$**			
	A1 > B	A2 < B		
	$\chi^2(2) = 27.0$**	$\chi^2(2) = 17.6$**		
	A1 > C	A2 > C	B > C	
	$t(74) = 3.9$***	$t(74) = 2.07$*	$t(74) = 3.9$***	
Slope at 24 mo	22.0	14.4	18.0	7.2
	A1 > A2			
	$\chi^2(2) = 27.5$***			
	A1 > B	A2 < B		
	$\chi^2(2) = 38.42$***	$\chi^2(2) = 26.3$***		
	A1 > C	A2 > C	B > C	
Slope at 36 mo	17.2	14.4	13.8	7.3
	A1 = A2			
	$\chi^2(2) = 4.3$			
	A1 = B	A2 = B		
	$t(74) = 1.7$~	$t(74) = -0.2$		
	A1 > C	A2 > C	B > C	
	$\chi^2(2) = 53.7$***	$\chi^2(2) = 38.2$***	$t(74) = -5.0$***	

*** p < 0.01; * p < 0.05; ~p ≤ 0.10. See Table 2 for t values for comparisons with group C. Chi-square results were obtained using the hypothesis-testing feature of HLM. For 36 mo, group C was the fixed reference group. By 48 mo of use, fitted rates of growth were not significantly different among groups A1, A2, and B, but fitted rates of growth were significantly greater for these groups than for group C.*

intervals; (4) permits modeling of latent-growth curves, enabling examination of the shapes of the growth curves; (5) enables examination of the child characteristics that contribute to both outcomes and latent-growth curves; and (6) enables comparison of these growth curves across the four implantation-age groups. Latent-growth curves (i.e., imputed from the data rather than observed) are a function of both the linear and quadratic terms, with time represented as length of use in months. An exemplar model and more information about the model are provided in the Appendix.

In this study, age at implantation is used as a naturally and randomly occurring independent (or treatment) variable (Cook & Campbell, 1979). This assumes that the decision to implant at a certain age was made without selection bias, which may not be true (e.g., children with less usable hearing may be systematically implanted at a younger age). Thus, propensity scores (Rosenbaum & Rubin, 1983; Rubin, 1997) were used to control for possible selection bias. Propensity for age at implantation was computed using regression with age at implantation as the dependent or outcome variable and all measured variables that might affect age at implantation as the independent or predictor variables. From this regression model, the predicted age at implantation for each child model was computed using SPSS software and used as the propensity score. Adjusting for the propensity score equates the groups compared on all of the covariates that were used to predict propensity. The following variables were included as independent variables in the regression model: year of birth, low versus middle socioeconomic status (LSES = 1; MSES = 0), preimplant hearing sensitivity measures (unaided binaural pure-tone thresholds, dB HL), cause of deafness (unknown = 0, familial = 1), type of cochlear implant device (a series of dummy coded variables), and gender (girl = 1; boy = 0).

Only year of birth and type of device significantly predicted age at implantation (year-of-birth coefficient = −6.61, $p < 0.001$; Cochlear Corp. Mini-22 coefficient = −26.47, $p < 0.001$; Nucleus 24M coefficient = 14.88, $p < 0.007$). Children who were younger when they received their implants were more likely to have been born more recently ($r = -0.71$, $p < 0.001$) than children who were older at implantation. This was most likely the result of United States Food and Drug Administration restrictions on age at implantation. Not until the year 2000 were cochlear implants approved for children younger than 2 yr of age. Children who were younger at implantation were also more likely to use newer and more technologically advanced cochlear implant devices (24M $r = -0.27$, $p < 0.001$, Mini-22 $r = 0.20$, $p = 0.006$) than children who were older when they received their implants. Propensity scores were included in all models to control for variables related to age at implantation. Thus, any variable used to compute propensity score is controlled for in these analyses.

Growth curves for children using hearing aids were estimated using children's preimplant scores using a strategy similar to that used by Svirsky et al. (2000). By computing preoperative outcome as a function of age at evaluation, we can predict how children might have performed over time had they not received cochlear implants. Preoperative vocabulary data were available for 98 of the children and were distributed across the groups as follows: 23% from group A1, 14% from group A2, 18% from group B, and 45% from group C, which is in proportion to the group sizes overall. Sixty-eight children contributed preoperative SPEECH scores, with similar group distribution.

RESULTS

Consonant-Production Accuracy

Overall, the final model explained 54% of the variability in SPEECH compared with the unconditional model (no covariates at either level 1 or 2). Children in groups A1, A2, and B, who were younger than 7 yr of age at implantation, had SPEECH scores that grew faster, on average, than those of the children in group C who were over 7 yr of age at implantation (Tables 2 and 3, Figs. 2 and 3). As can be seen in Figure 2, rates of growth for groups A1, A2, and B were significantly greater than group C even after 4 yr of implant use, indicating a sustained change in growth rate for children implanted before their seventh birthday.

There were also differences among groups A1, A2, and B. Because of the significant quadratic trend in the model, children's rates of growth varied systematically with length of time after implantation. To compare these differences over time, length of use and the quadratic trend (length of use squared) were centered at 12, 24, 36, and 48 mo, and differences in SPEECH slopes were compared for the groups using the hypothesis-testing feature of HLM (Table 3 and Fig. 2). Rates of SPEECH growth were significantly greater for group A1 compared with groups A2 and B for the first 2 yr of implant use. After 3 yr of use, groups A1, A2, and B demonstrated highly similar rates of growth. Interestingly, group A2 began with rates of growth that were less than those of groups A1 and B, but they caught up to both groups after 3 yr of implant use. Figure 2 suggests that group A2 demonstrated linear growth, whereas group B demonstrated deceleration in rate of growth over time. Children in groups A1 seemed to demonstrate an early burst of SPEECH growth that lasted about 2

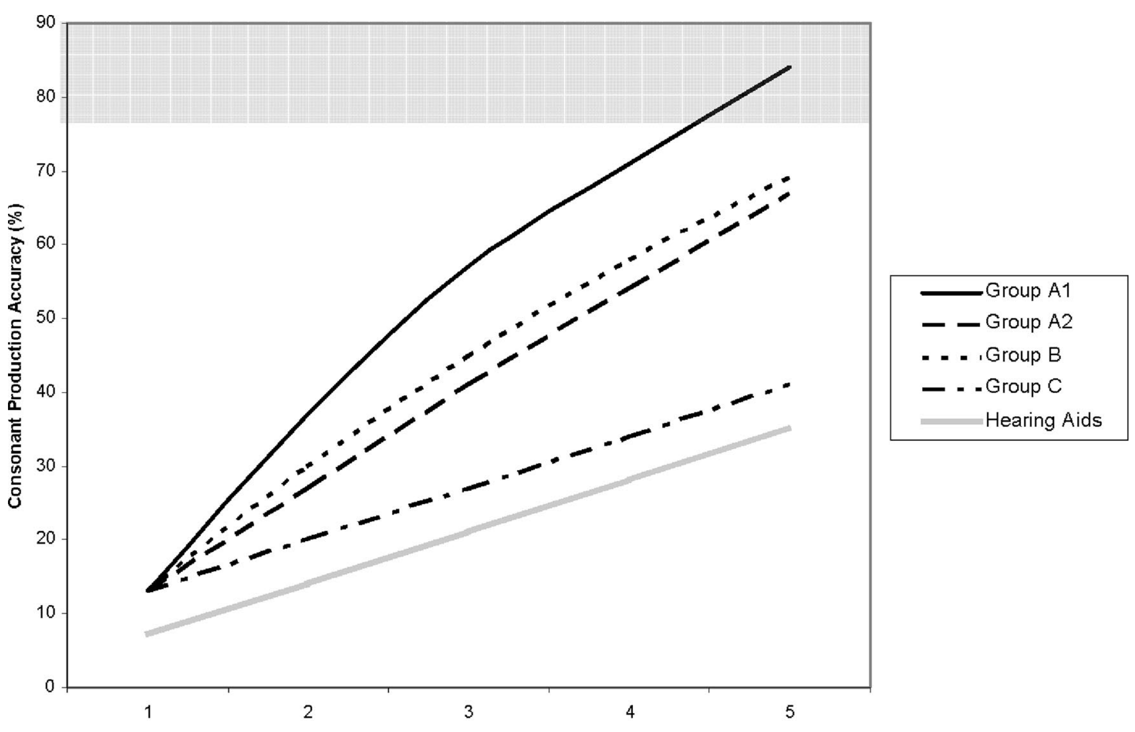

Figure 2. Fitted consonant-production accuracy (SPEECH) growth curves considering only rate of growth and acceleration, but not the intercept. Scores after 12 mo of use were transformed so that all groups started with an initial score equal to that of group A1. Group A1 received implants before age 2.5 yr; group A2 received implants between 2.6 and 3.5 yr of age; group B received implants between 3.6 and 7.0 yr; group C received implants between 7.1 and 10 yr of age. The rate of growth for hearing aid users is the predicted slope based on children's preoperative scores using hearing aids.

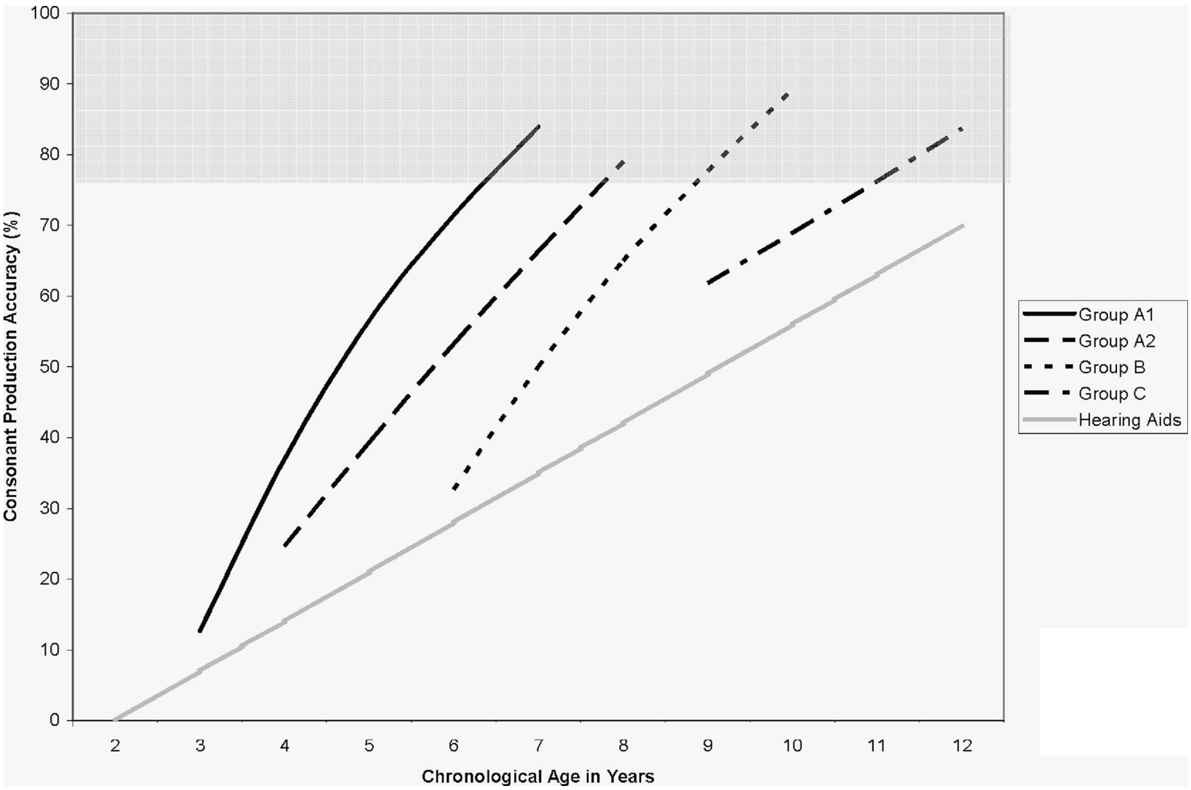

Figure 3. Fitted consonant-production accuracy (SPEECH) growth curves for age at implantation groups including intercept, rate of growth, and acceleration simultaneously. The growth curve for hearing aid users is the predicted score based on children's preoperative scores when they were using hearing aids. The shaded area represents speech that would be generally intelligible (McGarr, 1983). Group A1 received implants before age 2.5 yr; group A2 received implants between 2.6 and 3.5 yr of age; group B received implants between 3.6 and 7.0 yr; and group C received implants between 7.1 and 10 yr of age. Age at implantation plus length of use equals chronological age.

yr before slowing to rates similar to those of children in groups A2 and B.

In Figure 3, we include the model's intercept and examined the impact of age at implantation on growth curves with children's chronological age on the x-axis. This reveals the effect of longer implant use at any given age combined with, for group A1, a burst of SPEECH growth after implantation (group B also demonstrates a small burst, but it occurs after age 6). A child in group A1 at age 6 yr would be expected to achieve a SPEECH score of about 75 compared with a 6-yr-old child in group A2, with a predicted score of about 55, and a child in group B, with a predicted score of about 35. Although the fitted growth rate for group B is greater than for group A2, at the same age, children in group A2 still achieve higher scores because they have been using their implants for a full 2 yr longer.

All groups demonstrated stronger SPEECH scores than those predicted for hearing aid users. Groups A1, A2, and B demonstrated greater rates of growth than did hearing aid users, but group C did not. The fitted growth curve for group C was almost parallel to the predicted hearing aid curve.

Vocabulary

The final model predicted 58% of the variability in children's vocabulary scores compared with the unconditional model. Overall, the earlier in life a child received an implant, the greater his or her rate of vocabulary growth was after implantation. By 4 yr after implantation, rates of growth were the same regardless of when children had received their implants (i.e., no significant difference in rate of growth among groups; see Tables 4 and 5 and Fig. 4). This rate was about twice that observed for the predicted rate of growth using hearing aids and was highly similar to the rate of growth reported for children with normal hearing who comprised the PPVT test standardization sample (Fig. 4).

Again, because of the significant quadratic trend in the model, rates of growth for children in each group varied systematically with the length of time after implantation (Tables 4 and 5, Fig. 4). Overall, children in group A1 demonstrated significantly greater rates of vocabulary growth for the first 3 yr after implantation compared with children in all other groups. After 4 yr of implant use, rates of

TABLE 4. Vocabulary (PPVT) score intercepts, slopes, and acceleration for age at implantation groups with time centered at 24 mo after receipt of cochlear implant

Fixed effects	Coefficient	SE	*t* ratio (degrees of freedom)
For intercept π_0			
Intercept β_{00}	62.77	4.28	14.64 (95)***
Group A1 β_{01}	−28.49	7.67	−3.71***
Group A2 β_{02}	−26.50	6.36	−3.04***
Group B β_{03}	−31.68	5.96	−5.32***
Propensity score β_{04}	0.30	0.15	1.99*
For time (mo) after implantation centered at 24 mo π_{11}			
Slope β_{10}	0.88	0.09	9.32 (95)***
Group A1 β_{11}	0.62	0.18	3.39***
Group A2 β_{12}	0.36	0.16	2.24*
Group B β_{13}	0.20	0.14	1.41
Propensity score β_{14}	−0.0002	0.002	−0.14
For quadratic trend (acceleration) centered at 24 mo after implantation π_2			
Mean acceleration β_{20}	−0.001	0.001	−0.87 (371)
Group A1 β_{21}	−0.007	0.003	−1.93*
Group A2 β_{22}	−0.008	0.004	−2.07*
Group B β_{23}	−0.001	0.001	−1.27
Propensity score β_{24}	−0.00004	0.00003	−1.38
For preoperative status using hearing aids π_3			
Intercept β_{30}	−1.00	3.22	0.76 (371)
Group A1 β_{31}	37.65	11.69	3.22**
Group A2 β_{32}	14.42	5.98	2.41*
Group B β_{33}	9.57	5.13	1.86~
Random effects	SD	Variance	χ^2 (degrees of freedom)
Intercept r_{0i}	20.65	426.73	1140.95 (78)***
Time r_{1i}	0.23	0.05	268.45 (78)***
Level 1 e_{it}	8.47	71.72	

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ~$p < 0.1$. Deviance = 3133. Age of implanted group A1 <2.6 yr, A2 = 2.6–3.5 yr, group B = 3.6–7.0 yr, and group C (the fixed reference group) = 7.1–10 yr. The model explains 58% of the variance in child scores.

growth for children in group A1 were similar to those of children in the other groups. Fitted rates of growth for group A2 were greater than those for groups B and C at 1 yr after implantation but were highly similar after that. There were no significant differences in rates of growth for groups B and C.

In Figure 5, we add the intercept and examine the combined effect of length of use and the early burst of growth (groups A1 and A2). Again, consider children who are 6 yr of age; a child in group A1 at age 6 yr would be expected to achieve a vocabulary score of 68, which is a standard score of 90 (mean = 100, SD = 15). This falls within low- normal limits for a child with normal hearing (note the standard error of adjoining measurement bars in Fig. 5 for normal hearing and group A1). A child in group A2 would be predicted to score 50 at 6 yr of age, which is a standard score of 79, more than one standard deviation below the mean for children with normal hearing. A child in group B at age 6 yr would be predicted to achieve a score of about 20 and a standard score of 48.

Our hypotheses were largely supported. For both SPEECH and vocabulary, children in group A1 demonstrated an early burst of growth during the first 2 yr for SPEECH and during the first 3 yr of implant use for vocabulary. For vocabulary, group A2 also demonstrated a short burst that lasted about 1 yr and that was of lesser magnitude than group A1's burst.

The impact of age at implantation on SPEECH and vocabulary growth differed. SPEECH growth was significantly greater for children who had received implants before their seventh birthday compared with children who had received their implants between 7 and 10 yr of age. There was a sustained growth-rate change plus length-of-use effect (Fig. 1, right). For SPEECH, we also observed an early burst plus length-of-use effect for children under 2.5 yr of age at implantation (Fig. 1, middle).

In contrast, vocabulary-growth rate was highly similar for all four groups after 4 yr of implant use. For vocabulary, we observed an early burst plus a length-of-use effect (Fig. 1, middle) for children in groups A1 and A2 (a miniburst) and a length-of-use effect for all other groups (Fig. 1, left).

TABLE 5. Vocabulary (PPVT) score slope (points per year) by length of use for each group

Length of use (mo)	Group A1 12–30	Group A2 31–42	Group B 43–84	Group C 85–120
Slope at 12 mo	20.2	17.3	13.5	10.7
	A1 > A2	A2 > B		
	$\chi^2(2) = 12.95^{**}$	$\chi^2(2) = 6.96^{*}$		
	A1 > B	A2 > C	B = C	
	$\chi^2(2) = 11.48^{**}$	$t(95) = 2.50^{*}$	$t(95) = 1.51$	
	A1 > C			
	$t(95) = 3.34^{**}$			
Slope at 24 mo	18.0	14.8	13.0	10.5
	A1 > A2	A2 = B	B = C	
	$\chi^2(2) = 11.75^{**}$	$\chi^2(2) = 5.24\sim$		
	A1 > B	A2 = C		
	$\chi^2(2) = 11.46^{**}$			
	A1 > C			
Slope at 36 mo	16.0	12.5	12.4	10.4
	A1 > A2	A2 = B	B = C	
	$\chi^2(2) = 8.12^{*}$	$\chi^2(2) = 1.83$	$t(95) = 1.22$	
	A1 > B	A2 = C		
	$\chi^2(2) = 7.75^{*}$	$t(95) = 1.21$		
	A1 > C			
	$t(95) = 2.78^{*}$			

*** $p < 0.01$; * $p \leq 0.05$; $\sim p < 0.10$. Rates of growth at 48 mo after implantation were not significantly different among groups. See Table 4 for t values for comparisons at 24 mo with group C. Chi-square results were obtained using the hypothesis-testing feature of HLM (version 6).*

DISCUSSION

The purpose of this study was to examine whether there was any added benefit to earlier cochlear implantation over and above the advantage provided by longer implant use for children compared with same-age peers. Children were divided into four groups based on the age at which they had received a cochlear implant (group A1 = 1 to 2.5 yr, group A2 = 2.6 to 3.5 yr, group B = 3.6 to 7 yr, and group C = 7.1 to 10 yr). Overall, children who were younger when they received implants demonstrated stronger outcomes at any given age than their same age peers who were older when they received the implant. This advantage seemed to be related primarily to longer experience using the implant (i.e., a length-of-use effect; Fig. 1, left). However, there was an additional value to very early implantation, which appeared to result in a burst of growth immediately after implantation (Fig. 1, middle). The pattern of results differed, however, for consonant-production accuracy (SPEECH) and vocabulary outcomes. Regardless of the age at which children received their implants, their vocabulary and SPEECH scores were greater, on average, compared with children using hearing aids at any given age.

For speech-production accuracy, the growth curves for speech production (i.e., SPEECH) were not parallel. Indeed, rates of growth never really increased after implantation for children over 7 yr of age at implantation (group C) compared with predicted rates of SPEECH growth with hearing aids, although their scores were generally higher than predicted levels for children of the same age using hearing aids. Children in groups A1, A2, and B demonstrated greater rates of growth even after 4 yr of implant use compared with group C (Fig. 1, right). Additionally, group A1 demonstrated an additional burst of SPEECH growth during the first 2 yr of implant use (Fig. 1, middle) before growth stabilized to rates similar to those of groups A2 and B.

Extrapolating out, the different trajectories represent important differences in children's outcomes, with children in groups A1, A2, and B potentially achieving high levels of consonant production, accuracy, and speech intelligibility. However, these are fitted results, and although extrapolation indicates strong outcomes, no child who was younger than 2.5 yr at implantation had used his or her implant for more than 4 yr. It may be that as children get older, their growth trajectories will change. Replication of these results is needed with greater numbers of children who are 2.5 yr of age or younger at implantation and who have used their implants for 5 yr or longer.

Regarding vocabulary, children who gained access to sound via a cochlear implant before age 2.5 yr (group A1) generally demonstrated receptive vocabulary-growth curves that approximated those observed for children with normal hearing sensitivity. The combination of burst and length-of-use effect (Fig. 1, middle) brought the fitted vocabulary-growth curve for children in group A1 to within normal limits for children with normal hearing sensitivity (Dunn & Dunn, 1997) (Fig. 5). This was not the case for children

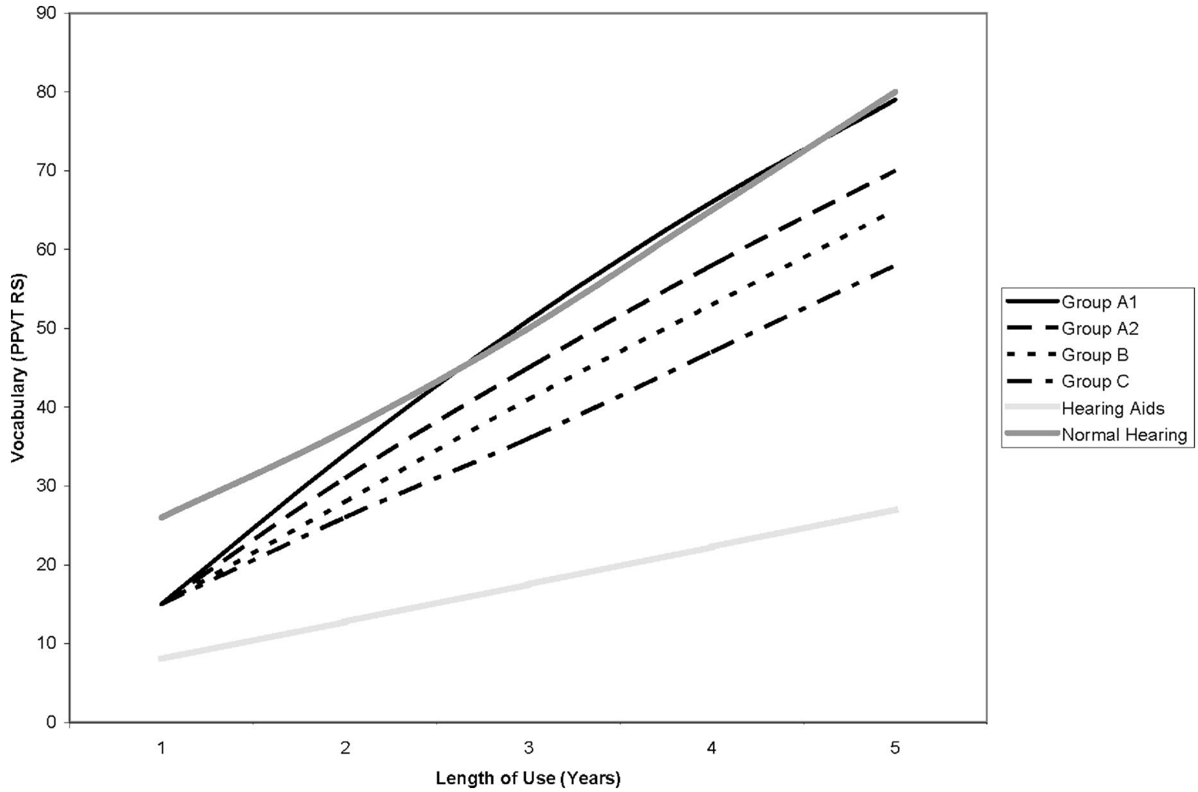

Figure 4. Fitted vocabulary-score growth curves considering only rate of growth and acceleration but not the intercept. Scores after 12 mo of use were transformed so that all groups started with an initial score equal to that of group A1. Group A1 received implants before age 2.5 yr; group A2 received implants between 2.6 and 3.5 yr of age; group B received implants between 3.6 and 7.0 yr; group C received implants between 7.1 and 10 yr of age. The rate of growth for hearing aid users is the predicted slope based on children's preoperative scores using hearing aids. The growth curve for children with normal hearing is based on the test standardization norms, with the initial score representing an age equivalent of 2 yr.

who had received implants after 2.5 yr; vocabulary outcomes for groups A2, B, and C were substantially less than those observed for children with normal hearing sensitivity. The rates of growth for the four groups were surprisingly similar after 3 to 4 yr of implant use and were similar to rates of vocabulary growth for children with normal hearing sensitivity.

Early implantation seems to offer children substantial advantages. First, there is a length-of-use effect of having earlier access to sound and spoken language on vocabulary and speech-production accuracy, which should not be underestimated (Fig. 1, left). Indeed, there seem to be changes in the cortical auditory system based on length of use alone (Gordon, Papsin, & Harrison, 2005). Secondly, children who receive their implants before age 2.5 yr seem to experience faster rates of vocabulary and consonant-production accuracy growth immediately after implantation (an early burst; see Fig. 1, middle). Thirdly, for consonant-production accuracy, there is evidence of lasting rate of growth change after implantation for children under 7 yr of age at implantation (growth rates for groups A1, A2, and B > group C; Fig. 1, right). Our results for consonant-production accuracy closely resemble patterns observed at the cortical level described by Sharma et al. (2005). Children who received their implants after age 7 yr demonstrated substantially different patterns of speech development compared with children who were younger than 7 yr of age.

Overall, our results do not rule out an early sensitive phase for speech and vocabulary development, and our results imply both early and ongoing plasticity in the central auditory system and the systems of the brain subserving speech and language development. These results suggest a high degree of plasticity, especially before age 2.5 yr, in the neurological systems subserving vocabulary development, particularly those associated with central auditory pathways. The window seems to be even wider for speech-production accuracy. These results also support theories that purport an early sensitive phase (Locke, 1997; Newport, 1990), chronotopic constraints on the plasticity of the developing neural system (Bates, 1999), potentially different sensitive phases for different speech and language processes (Neville, Mills, & Lawson, 1992), and the importance of early exposure to a formal

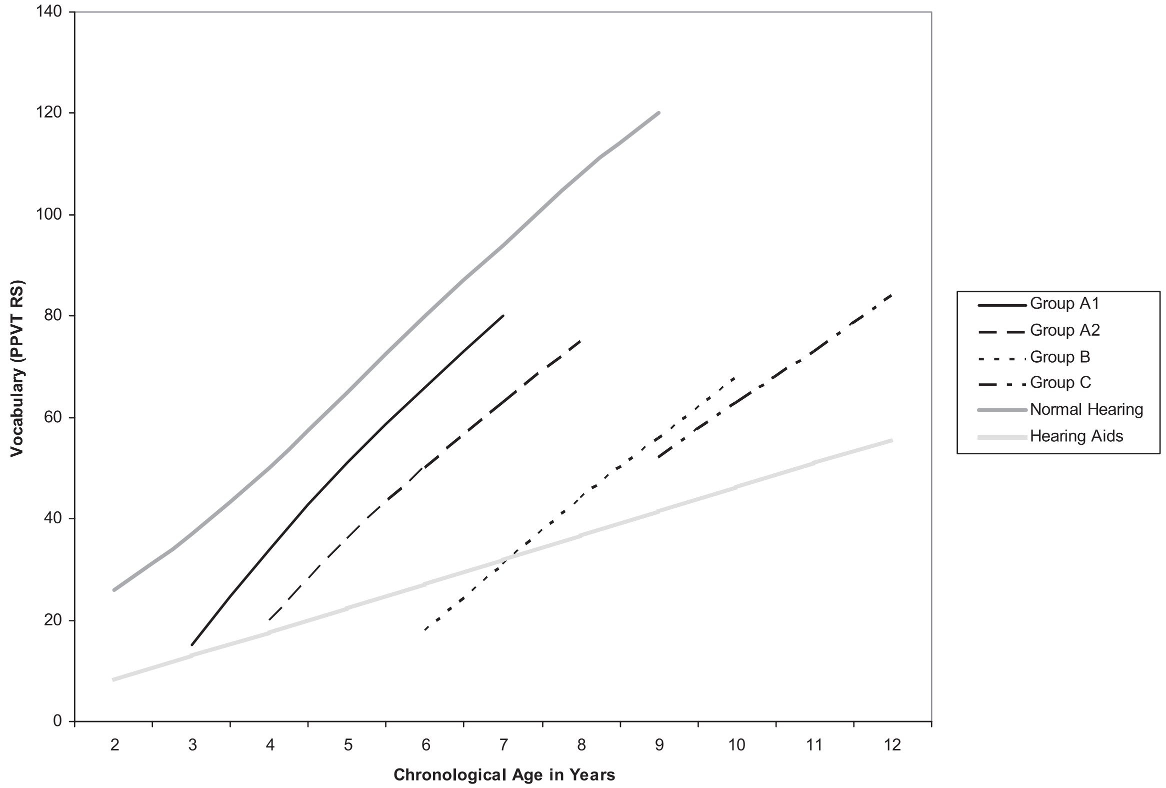

Figure 5. Fitted vocabulary-growth curves, including intercept, rate of growth, and acceleration, for implantation-age groups, children with hearing aids (cross-sectional), and a normally hearing PPVT test standardization sample. The latter are raw scores corresponding to published age-equivalent scores. The standard error of measurement for PPVT-3 raw scores ranged from 4.7 to 5.4. Group A1 received implants before age 2.5 yr; group A2 received implants between 2.6 and 3.5 yr of age; group B received implants between 3.6 and 7.0 yr; group C received implants between 7.1 and 10 yr of age. Age at implantation plus length of use equals chronological age.

system of language for optimal long-term development of language ability (Locke, 1997; Mayberry, 1993; Mayberry, Lock, & Kazmi, 2002).

However, our results provide no support for an abrupt cessation of the sensitive period for either vocabulary or speech production; rather, our findings indicate a diminution of the effect after 2.5 to 3.5 yr of age. For example, children in group A2, who gained access to spoken language between 2.5 and 3.5 yr, did not demonstrate as strong a vocabulary burst as was observed for children who gained access to language before age 2.5 (group A1). However, children in group A2 did demonstrate statistically more rapid growth in vocabulary immediately after access to spoken language compared with groups B and C, who were over 3.5 yr of age at implantation. Additionally, the results for speech production reveal greater growth for children who were between 3.5 and 7 yr old when they received the implant compared with children who were 7 to 10 yr old. These results are quite similar to the results of research examining cortical auditory-evoked response waveforms for children who received cochlear implants at different ages (Sharma, Dorman, & Spahr, 2002; Sharma, Dorman, & Krahl, 2005) and imply a synergy between brain and speech/language development.

Nevertheless, these results do not rule out the possibility that there is no sensitive phase. Access to sound and spoken language at earlier ages may, for example, enhance mother–child interactions, which accumulating evidence reveals to be critical for child language development (Hart & Risley, 1995; Huttenlocher, Vasilyeva, Cymerman, et al., 2002; Lederberg & Spencer, 2005; NICHD-ECCRN, 2004). Access to sound may provide children with additional social and cognitive connections to the world around them that enhance speech and language development. Additionally, the earliest age at which any of the children received an implant was 12 mo, and so the long-term impact of even earlier implantation cannot be evaluated with these data. Implantation for children aged 7 to 12 mo seems to be safe, with babbling emerging shortly after hookup (Colletti, Marco Carner, Miorelli, et al., 2005). Emerging research does suggest, however, that children who receive implants between 6 and 12 mo of age demonstrate speech and language outcomes that are highly similar to those of children who are between 12 and 24 mo of age (Holt, Svirsky, Neuburger, et al., 2004).

Although our groupings were based on previous research findings for children with cochlear implants (Sharma, Dorman, & Spahr, 2002; Svirsky, Teoh, & Neuburger, 2004; Tomblin, Barker, Spencer, et al., 2005) and children with normal hearing sensitivity (Locke, 1997), configuring our groups differently may have changed the results. For example, if we had split group A at 21 mo rather than at 2.5 yr, we may have found different results. More research following children who are younger at implantation for longer periods of time will be revealing.

Implications

The findings of this study have direct clinical implications for deaf children. Continuing efforts for early identification and treatment are critical because of the relation of early implantation with speech production and spoken vocabulary growth and the resulting implications for speech and language development. Universal newborn hearing screening and new United States Food and Drug Administration guidelines permitting children younger than 18 mo to receive implants offer new opportunities as well as challenges. Ongoing research to monitor the language development of children younger than 30 mo when they receive implants will be important for guiding professionals' and parents' decisions regarding cochlear implantation.

These results, as they pertain to understanding the development of speech and language and the importance of early language experiences, may have broader implications. Our findings agree with studies examining the vocabulary growth of children with normal hearing sensitivity: early language opportunities seem to affect the trajectory of vocabulary growth, which may have implications for children's overall language development (Hart & Risley, 1995; Huttenlocher, Haight, Bryk, et al., 1991; Huttenlocher, Vasilyeva, Cymerman, et al., 2002; Locke, 1997). This suggests that programs and policies ensuring children's access to rich linguistic environments early in life (e.g., by offering parenting education and high-quality early childcare and preschool opportunities), access to cochlear implants and other appropriate types of hearing aids, and continuing to expand newborn and ongoing hearing screenings may enhance children's speech and language development (Hart & Risley, 1995; Huttenlocher, Haight, Bryk, et al., 1991; Huttenlocher, Vasilyeva, Cymerman, et al., 2002; Locke, 1997) and later success in school (Connor & Zwolan, 2004; Dickinson & Tabors, 2001; Neuman & Dickinson, 2001). Finally, by examining the complex synergy between early brain development and the linguistic environments in which children develop speech and language, we can develop stronger and more useful theories of language development.

ACKNOWLEDGMENTS

The authors would like to thank John Locke, City University of New York, for feedback on earlier versions of this paper, and Fred Morrison and Annemarie Hindman, University of Michigan, and Amy Lederberg, Georgia State University, for comments on more recent versions. We would also like to thank Steve Telian and members of the UM Cochlear Implant Center and the children and parents who participated in this study. Without them, this study would not have been possible. We would also like to thank the Spencer Foundation, who funded part of this study.

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Received July 7, 2005; accepted June 26, 2006.

APPENDIX

Hierarchical Linear Modeling (HLM) for Examining Latent-Growth Curves

Group A1 includes children who were 2.5 yr or younger at implantation; group A2, 2.6 to 3.5 yr; group B, 3.6 to 7.0 yr; and group C, 7.1 to 10 yr. A variable for group C, the fixed reference group, is not entered into the equation, and so β_{00} represents the fitted mean outcome for group C. The fitted mean outcome for the other groups is computed by adding their coefficient (i.e., β_{01}, β_{02}, or β_{03}) to the intercept coefficient (β_{00}) and adding the propensity score controls for all variables associated with age at implantation (i.e., year of birth, device, etc.). Variability of the quadratic trend was tested and did not vary significantly at level 2; therefore, it was fixed (no r_{2i} in the model). This means that we modeled differences in the latent-growth curve between individual children but not within repeated measures for each child.

Level 1:

$$Y_{it} = \pi_{0i} + \pi_{1i}T_{it} + \pi_{2i}T_{it}^2 + \pi_{3i}(\text{preimplantation status}_{it}) + e_{it} \quad (1)$$

Level 2:

$$\pi_{0i} = \beta_{00} + \beta_{01}(\text{group A1}_i) + \beta_{02}(\text{group A2}_i) + \beta_{03}(\text{group B}_i) + \beta_{04}(\text{propensity age implantation}_i) + r_{0i}$$

$$+ \beta_{12}(\text{group A2}_i) + \beta_{13}(\text{group B}_i) + \beta_{14}(\text{propensity age implantation}_i) + r_{1i}$$

$$\pi_{2i} = \beta_{20} + \beta_{21}(\text{group A1}_i) + \beta_{22}(\text{group A2}_i) + \beta_{23}(\text{group B}_i) + \beta_{24}(\text{propensity age implantation}_i)$$

$$\pi_{3i} = \beta_{30} + \beta_{31}(\text{group A1}_i) + \beta_{32}(\text{group A2}_i) + \beta_{33}(\text{group B}_1)$$

Y_{it}, the consonant-production accuracy percent (SPEECH) or vocabulary score for child i at time t, is a function of the grand mean for the group (β_{00}), the mean rate of growth (β_{10}, the linear term), and acceleration (β_{20}, the quadratic term), controlling for preimplantation scores using hearing aids (β_{30}), plus the child-specific effects on intercept π_{0i}, slope π_{1i}, and quadratic trend π_{2i} of being in group A1, A2, or B (group C is the fixed reference group), plus the child-specific age at implantation propensity score effects, β_{04}, β_{14}, and β_{24}. T is the length of time in months after implantation for child i at time t. The coefficients β_{11}, β_{12}, and β_{13} indicate the effect of age of the implantation group on the rate of consonant-production accuracy or receptive vocabulary growth for groups A1, A2, and B, respectively, compared with children in group C (Tables 2 and 4).

With HLM latent-growth curve modeling, level 1 defines the trajectory of growth over time, and level 2 defines the deflections from this trajectory that are attributable to child characteristics. Growth curves are considered latent because they are not observed but are imputed using data from all of the children. When T is centered at different intervals (i.e., length of use = 12, 24, or 36 mo), the fitted intercept and rate of growth can be determined for each respective interval. For example, if we center T at 24 mo (length of use = 24), the intercept β_{00} represents the fitted mean outcome at that moment in time, at 24 mo of cochlear implant use, and β_{10} represents the slope at 24 mo (Tables 2 and 4). The model can be used to compute fitted scores at, for example, 36 mo by multiplying both the linear (β_{10}) and quadratic (β_{20}) terms by 12 mo and adding these values to the intercept β_{00}. Using the data in Table 4, $\beta_{00} = 62.77$ is the fitted mean vocabulary score for children in group C at 24 mo after implantation. To compute the fitted mean for 36 mo, the linear-term coefficient is multiplied by 12 ($0.88 \times 12 = 10.56$), the quadratic term is multiplied by 12 ($-0.0003 \times 12 = -0.012$), and they are summed ($11.26 - 0.004$) and then added to β_{00} ($62.37 + 11.25 = 74.03$). Because the quadratic-term coefficient is essentially 0, group C demonstrates virtually linear growth. However, the quadratic term is significantly less than 0 for groups A1 and A2, suggesting more rapid growth initially, with slower growth over time (Table 5, Fig. 5).

Comparison of groups A1, A2, and B in Tables 3 and 5 was accomplished using HLM multivariate-hypothesis tests (HLM version 6.0) and running models with T and T^2 centered at 12, 24, 36, and 48 mo. Residuals (e, r) were assumed normally distributed with a mean of zero.

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