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Research Article

Consonant Acquisition in Young Cochlear Implant Recipients and Their Typically Developing Peers

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Purpose: Consonant acquisition was examined in 13 young cochlear implant (CI) recipients and 11 typically developing (TD) children.
Method: A longitudinal research design was implemented to determine the rate and nature of consonant acquisition during the first 2 years of robust hearing experience. Twenty-minute adult–child (typically a parent) interactions were video and audio recorded at 3-month intervals following implantation until 24 months of robust hearing experience was achieved. TD children were similarly recorded between 6 and 24 months of age. Consonants that were produced twice within a 50-utterance sample were considered "established" within a child's consonant inventory.
Results: Although the groups showed similar trajectories, the CI group produced larger consonant inventories than the TD group at each interval except for 21 and 24 months. A majority of children with CIs also showed more rapid acquisition of consonants and more diverse consonant inventories than TD children.
Conclusions: These results suggest that early auditory deprivation does not significantly affect consonant acquisition for most CI recipients. Tracking early consonant development appears to be a useful way to assess the effectiveness of cochlear implantation in young recipients.

Cochlear implantation is rapidly becoming the technology of choice for young children with severe-to-profound hearing loss. With the lowering of the FDA-recommended age for implantation to 1 year in 2000, many children are receiving cochlear implants (CIs) at increasingly young ages. Because young CI recipients begin to hear within an age range when spoken language skills are typically acquired, it is important to monitor the early development of speech and language in order to demonstrate the efficacy of this new technology. Research conducted thus far has shown largely favorable outcomes for speech and language in young CI recipients (e.g., Connor, Craig, Raudenbush, Heavner, & Zwolan, 2006; Nicholas & Geers, 2007).

Little is known, however, about the early phases of consonant acquisition in young CI recipients (defined in the present study as less than 3 years of age at the time of implantation). Consonant development contributes greatly to the attainment of intelligible speech, a significant area of deficit for children with profound hearing loss (e.g., Hudgins & Numbers, 1942; see Osberger, 1992, for a review). The pace of consonant acquisition also appears to be a predictor of later spoken language abilities. A recent reanalysis of data from 60 children with CIs implanted before or close to 3 years of age by Geers, Nicholas, Tobey, and Davidson (2016) showed that children with CIs who had persistent language impairments at 10.5 years of age had low consonant diversity in their preschool years. Moeller et al. (2007b) reached similar conclusions when they found that consonant accuracy at 24 months in children with hearing loss affected later vocabulary outcomes at 30 months of age and articulation scores at 36 months of age. These findings suggest that examination of early consonant acquisition may be especially useful in identifying children at risk for later speech and language difficulties.

In the present study, we attempted to increase knowledge in this area by longitudinally examining early consonant inventories of young CI recipients within spontaneous speech samples and comparing these with inventories obtained from typically developing (TD) peers with comparable robust hearing experience. Robust hearing has been previously defined as "the amount of time that a child has had

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auditory access to speech at conversational intensity levels" (Ertmer & Inniger, 2009, p. 1581).

Consonant Development in Young CI Recipients

Early studies of consonant inventories, consonant accuracy, and speech intelligibility in children with relatively older ages at implantation show significant increases following implantation but less than typical levels of performance in these areas (e.g., Chin & Pisoni, 2000; Kirk, Diefendorf, Riley, & Osberger, 1995; Miyamoto, Kirk, Robbins, Todd, & Riley, 1996; Tobey, Pancamo, Staller, Brimacombe, & Beiter, 1991). More recent studies have shown that relatively young CI recipients at the time of implantation also increased consonant inventories, consonant accuracy, and intelligibility following implantation but continued to lag behind TD children, especially when matched for chronological age (e.g., Connor et al., 2006; Dettman et al., 2016; Ertmer, Kloiber, Jung, Kirleis, & Bradford, 2012; Flipsen, 2011; Spencer & Guo, 2013; Tobey, Geers, Brenner, Altuna, & Gabbert, 2003; Tomblin, Peng, Spencer, & Lu, 2008; Tye-Murray, Spencer, & Woodworth, 1995). With one exception (Tobey et al., 2003), these studies also showed that the younger the age at implantation, the more favorable the outcome for consonant production. Tobey et al. (2003) found that age at implantation did not contribute to eventual outcomes. Overall, these studies of CI recipients, implanted at various ages, paint a guardedly optimistic picture of consonant development.

The studies discussed thus far have focused on consonant accuracy, speech intelligibility, or consonant inventories within meaningful words and sentences. This type of analysis is referred to as *relational* analysis (Stoel-Gammon & Dunn, 1985) and allows for the child's productions to be compared with adult targets. However, young CI recipients may not be producing an abundance of words and sentences during the first 1–2 years of CI experience. Relational analysis, therefore, cannot provide insights into the initial phases of consonant development and tendencies in children's spontaneous productions. An independent analysis, on the other hand, allows an examination of the emergence of consonants in children's spontaneous speech without reference to adult targets and thereby allows us to assess children's early consonant development (Stoel-Gammon & Dunn, 1985).

Five studies have applied an independent analysis to young CI recipients' spontaneous vocalizations to date. Serry and Blamey (1999) and Blamey, Barry, and Jacq (2001) tracked nine children with CIs, only two of whom were implanted before 3 years of age, for 6 years following implantation. They collected speech samples from these children at regular intervals and used what they termed a *targetless* criterion of two productions of a consonant to count the consonant in a child's inventory. The criterion for group acquisition of a consonant was the first time point at which 50% of the children reached this targetless criterion individually. Serry and Blamey found that 92% of all consonants reached the group criterion by the end of 4 years following implantation. Blamey et al. found that the remaining two consonants, [ɵ, ʒ], reached the group criterion by 6 years following implantation. Serry and Blamey noted that the order of consonant acquisition was similar to that reported in the typical literature except that it was slower. Also, although children with CIs made steady gains in the first 4 years following implantation, growth slowed somewhat in the fifth to sixth year following implantation.

Bouchard, Le Normand, and Cohen (2007) followed 22 French-speaking children for 18 months after implantation, seven of whom had been implanted before 3 years of age. They collected 20-min free play samples from these children at 6, 12, and 18 months postimplantation. They used similar criteria as Blamey and colleagues (Blamey et al., 2001; Serry & Blamey, 1999) except that they termed targetless consonants as *emergent* consonants. Stops, labial, and alveolar consonants were found to be the most frequent types of consonants produced across all intervals. Glides, velars, and palatal consonants, on the other hand, were absent or infrequently produced even at the 18-month interval. These results mostly resemble those noted in the literature for TD children except that glides are noted as occurring in the speech of TD 18-month-olds often rather than infrequently (Stoel-Gammon, 1985).

Salas-Provance, Spencer, Nicholas, and Tobey (2014) also used a similar targetless criterion as Blamey and colleagues (Blamey et al., 2001; Serry & Blamey, 1999) to examine the consonant inventories of five young CI recipients, implanted between 19 and 36 months of age, with age-matched TD peers at 3.5 years of age. The CI recipients' implant experience ranged from 7 to 24 months at the time they were assessed. Unlike Blamey and colleagues (Blamey et al., 2001; Serry & Blamey, 1999), however, Salas-Provance et al. used a more stringent criterion for group acquisition of consonants. They considered a consonant to be acquired only if 80% of the children in the group produced it. Despite young CI recipients having varying amounts of robust hearing experience from 7 to 24 months, their consonant inventories were similar to that of age-matched TD peers and included stops, nasals, glides, fricatives, and affricates.

Schauwers, Gillis, and Govaerts (2008) used a different approach to examining consonant inventories in 10 very young CI recipients learning Dutch, who were implanted between 6 and 18 months of age. They matched children with CIs to TD peers on the basis of neither age nor robust hearing experience but instead matched them on their acquisition of speech and language milestones. Sampling started when children began canonical babbling (approximately 1–4 months after implant activation for children with CIs) and ended sampling when the children were producing 10 different words (approximately 17–26 months of age). Both groups produced labials, alveolars, and palatals in terms of place of articulation and produced mainly stops and glides in terms of manner of articulation throughout the study. The TD children produced more liquids than children with CIs; however, the overall frequency of liquids was very low, and so any conclusions regarding liquids were necessarily tentative. These results confirmed that children with CIs often have similar consonant inventories as TD children in the early phases of speech and language development.

Warner-Czyz, Davis, and MacNeilage (2010) used a similar approach to Schauwers et al. (2008) when they matched four children with CIs, implanted between 1 and 2 years of age, to TD peers on the basis of age of onset of meaningful word use. They collected data on these children each month for 6 months. They found that the labial consonant–central vowel pairing for CV syllables (C = consonant, V = vowel) was most common in both groups of children during the 6-month period, again reiterating the conclusion that young CI recipients are not disadvantaged when compared with their TD counterparts.

Two other studies of young CI recipients (Moore & Bass-Ringdahl, 2002; Moreno-Torres & Moruno-López, 2014) examined consonant production in young children with CIs as well but used imitative tasks. Although imitation is a useful and efficient way to assess children's speech sound production, imitative tasks might not be representative of the child's everyday speech. Use of spontaneous speech samples and independent analyses allow us to examine consonants as they emerge naturally.

Taken together, these five studies show that young CI recipients make impressive gains in their independent consonant inventories. Often, the recipients' consonant inventories resemble their TD peers regardless of whether they are matched for age, robust hearing experience, or vocal or language milestones. Although Blamey and colleagues (Blamey et al., 2001; Serry & Blamey, 1999) and Bouchard et al. (2007) showed some limitations in young CI recipients' consonant inventories when compared with their TD peers, these two investigations had a wider age range of implantation than other studies. They included children older than 3 years of age at the time of implantation in their sample, whereas other studies restricted the age of implantation to at or below 3 years of age. Thus, it is difficult to ascertain the effects of age of implantation upon outcomes. The communication modalities in these two studies also varied from the others. Participants used a combination of habilitation techniques, for example, oral, total communication, in these two studies, whereas in the other studies, participants were enrolled in auditory–oral programs alone. The differences among these studies might have led to the different outcomes obtained.

Young CI recipients also appear to have more favorable outcomes for consonant production than that reported in the recent literature for young children fitted with hearing aids. Moeller et al. (2007a) and Wiggin, Sedey, Awad, Bogle, and Yoshinaga-Itano (2013) conducted an independent analysis of consonantal production and noted that, although children fitted with hearing aids showed a similar pattern as TD children in their consonant development, they were delayed in their development of certain sounds. For example, fricative and affricate development were affected in some children (Moeller et al., 2007a). In addition, later developing consonants in the typical literature (e.g., ʧ, ʤ) were particularly late to emerge in children fitted with hearing aids (Wiggin et al., 2013). Such delays in the acquisition of specific sounds have not consistently been reported in the literature on children with CIs.

Methodological Rationales and Research Questions

The main aims of the present study were to determine (a) if the consonant inventories of young CI recipients increased at a rate that was comparable to younger, TD children who had comparable amounts of robust hearing experience; (b) to compare customary use and mastery trends (defined in next paragraph) for specific consonants (Sander, 1972) between the two groups; and (c) to examine differences between manner (i.e., how a consonant is produced) and place of articulation (i.e., where a consonant is produced) between the two groups. To accomplish these overarching objectives, we longitudinally examined consonant production in the spontaneous vocalizations of 13 CI recipients implanted before 3 years of age. All the children in the present study were enrolled in auditory–oral intervention programs. Thus, confounding effects of varying ages of implantation and different communication modalities were minimized. Because participants were followed at regular 3-month intervals following activation up to 2 years, the present study also provided more frequent sampling of children's consonant inventories than prior studies. Results were, therefore, expected to provide new information regarding children's consonant inventory sizes and the order of acquisition of consonants at different ages. A control group of TD children, who were matched for the duration of robust hearing experience, was also included. For example, children with 6 months of robust hearing following CI activation were matched with infants who were 6 months old because both groups had auditory access to speech at conversational intensity levels for the same amount of time. Matching for duration of robust hearing experience has been recommended as an alternative to matching for age as children with CIs are deprived of significant auditory input prior to implantation (Spencer & Guo, 2013). The inclusion of a TD control group allowed us to make direct comparisons of consonant inventories between the two groups rather than relying on the extant literature on typical development as has previously been done (e.g., Serry & Blamey, 1999). Of course, we recognize that matching for robust hearing experience necessarily means that children with CIs will be chronologically older and, therefore, more developmentally mature than their TD peers.

We examined children's spontaneous productions using an independent analysis. As Salas-Provance et al. (2014) stated, examination of spontaneous consonant use allows us a window into children's naturally emergent speech sound repertoires much earlier than accuracy analyses may permit. Similar to Serry and Blamey (1999), we examined consonants occurring in prelinguistic vocalizations as well as in intelligible words. In addition to consonant inventory growth, we examined trends in both customary usage (i.e., the ages at which a consonant was produced two or more times within a session by at least 50% of the children) and mastery usage (i.e., the ages at which a consonant was produced two or more times within a session by at least 90% of the children). Customary and mastery definitions were derived from the literature on speech sound acquisition in TD children (Sander, 1972). Sander (1972) argued that using a range to depict speech sound acquisition allows for showing the median age or average performance at which a consonant is used as well as illustrating the wide age range that complete normality may sometimes take. As is frequently done in the TD literature, we also descriptively examined the development of consonant manner and consonant place of articulation in the two groups using customary criteria. Individual differences in the rate and nature of consonant acquisition were descriptively examined as well.

On the basis of these rationales, three specific research questions were addressed in the present study:

1. Does the size of consonant inventories vary with amount of robust hearing experience and group membership (CI vs. TD)?
2. What trends in the customary and mastery use of consonants were observed across the intervals for young CI recipients and their TD peers?
3. What trends in the development of place and manner of articulation features were observed across the intervals in the two groups?

Method

Participants

A total of 13 children (eight girls and five boys) with CIs participated in the present study. These children were selected from a broader database of young CI recipients described in Ertmer and Jung (2012a, 2012b). The two inclusion criteria were (a) children who provided 2 years of longitudinal speech samples by completing study participation until 24 months postactivation and (b) children who did not have additional disabilities besides hearing loss. Each child in the present study had bilateral severe-to-profound hearing losses. All children were implanted before their third birthday (mean age at implantation = 19.65 months, *SD* = 8.94). Children were enrolled in auditory–oral early intervention programs. Families of all children spoke English only at home. Seven children had unilateral and six had bilateral implants. Of the bilaterally implanted children, one was implanted simultaneously with his first CI, and the other five children were sequentially implanted during the course of the study. Additional audiological and demographic information is presented in Table 1.

Speech samples were collected at regular 3-month intervals following activation until the children had accumulated 24 months of robust hearing experience with their CIs (i.e., at 3, 6, 9, 12, 15, 18, 21, and 24 months postactivation), but timing of initial entry into the study varied. Three of the 13 children with CIs started participating in the study prior to implantation. Of these three children, only one child showed one established consonant prior to implantation. Seven additional children became available within 1 month following activation. The session in which a majority of children (*n* = 12) contributed speech samples was 3 months postactivation. Therefore, the development of consonant production between 3 months and 24 months postactivation are presented in this study. By the end of the study (after 24 months of CI use following activation), children in the CI group ranged in age from 33 to 60 months (see Table 1).

The TD group was composed of seven boys and four girls (total *n* = 11). They entered the study at 6 months of age and continued study participation every 3 months until they became 24 months old. All these children had passed a newborn hearing screening. Parents reported that they had no concerns regarding their children's physical, social, and cognitive development. The TD children served as controls on the basis of the duration of robust hearing experience at each data collection interval. Further information for the TD group can be found in Ertmer and Jung (2012b).

Recording Procedures

Twenty-minute adult–child interactions were audio and video recorded using Sony mini-DVD camcorders (Model number DCR-DVD405). This camcorder was coupled with a Bluetooth wireless microphone system. Children wore a specially designed vest that positioned a wireless microphone so that their speech could be recorded clearly with a consistent mouth-to-microphone distance of approximately 4 in. All children and adults were provided with a standard set of toys, including dolls, toy foods, toy animals, cars, books, and puzzles. The adults were instructed to play as they usually did with the child at home.

CI children's recordings were made at their schools except for one participant. The majority of recordings for this participant were made at her home with the exception of the 24-month session, which was recorded at her preschool. A total of 109 sessions were collected from CI children during the time period between preimplantation and 24 months postactivation. Adults familiar to the child participated in every session. Parents participated in 83% of CI children's recordings (*n* = 91). When parents were not available, children's early interventionists substituted in that role (17% of sessions). Four sessions from three children with CIs were missed between 3 and 24 months postactivation, the time period of focus in the present study, due to a family emergency, extremely bad weather conditions, or failure in delivery of the recorded DVD from the child' school to the lab.

All the TD children interacted with their parents. Their recordings were made at the Speech Development Lab at Purdue University. Recall that they entered this study when they were 6 months old. Therefore, a total of seven sessions was recorded for each TD child at 6, 9, 12, 15, 18,

Table 1. Individual demographic and audiological information for children in the CI group.

Child	Gender	Age at first CI activation in months (Age at second CI activation)	Study entry point, session; months postactivation	Age at completing study, months	Device (processing strategy)	Pre-CI pure- or warble-tone thresholds, unaided better ear dB HL	Mean CI-aided thresholds (SF or better ear) last available audiogram (months postactivation)
Unilateral							
JOIR	M	12	Pre[a]	36	Freedom (ACE)	106	29.0 (19)
DAST	M	21	Pre[a]	45	Freedom (ACE)	76; NR[b] ≥ 4k	26.0 (23)
OLHE	F	25	Early[c]	49	Freedom (ACE)	80	26.0 (24)
ETKO	M	26	Pre[a]	50	Freedom (ACE)	90; NR[b] ≥ 4k	22.0 (18)
ABHO	F	27	3 months	51	PSP (HiRes-P[d])	89	23.0 (22)
AAWI	F	36	3 months	60	Freedom (ACE)	NR[b]	22.5 (24)
JORO	F	36	Early[c]	60	Freedom (ACE)	96; NR[b] ≥ 2k	18.0 (23)
Bilateral							
OWJO	M	9 (22)	Early[c]	33	Freedom (ACE)	NR[b]	16.7 (25)
CAST	F	13 (19)	3 months	37	Freedom (ACE)	NR[b] for ABR	25.0 (18)
MAJE	M	13 (13)	6 months	37	Freedom (ACE)	NR[b]	21.7 (20)
GIAI	F	13 (27)	Early[c]	37	Freedom (ACE)	100	20.0 (23)
MAMA	F	18 (20)	3 months	42	Freedom (ACE)	100	25.0 (21)
JAWE	F	19 (38)	Early[c]	43	PSP and Harmony (HiRes-P)[d]	87.5	39.0 (24)
M		20.62 (23.17)		44.62			24.15
SD		8.92 (8.57)		8.92			5.61

Note. CI = cochlear implant; SF = sound field; ACE = advanced combination encoder; NR = no reponse; PSP = Platinum Series sound processor; ABR = auditory brainstem response test; M = male; F = female.

[a]Preimplantation session. [b]No response to pure- or warble-tones. [c]Early session within 1 month of activation. [d]HiResolution-Paired.

21, and 24 months of age. No child missed a session (total sessions = 77).

Data Analysis

In a previous study, Ertmer and Jung (2012b) identified utterances produced by the children within the recorded sessions. For the present study, the first 50 consecutive utterances, or all available utterances when a child produced fewer than 50 utterances, were included. Because this was an independent phonetic analysis, all utterances, both meaningful (e.g., words) and nonmeaningful (e.g., babble), were included (Serry & Blamey, 1999). Three graduate research assistants used the International Phonetic Alphabet to transcribe utterances that contained adult-like vowels and/or consonants.

When a consonant was produced at least twice by a child during a session, that consonant was considered as being established in that child's consonant inventory (see Blamey et al., 2001; Bouchard et al., 2007). The consonant inventory for a child for each session included any consonants that were considered as established in previous sessions along with any new consonants identified as being established in that particular session. For example, if a child established [b] at his or her 6-month session and subsequently established [d] at his or her 9-month session, the consonant inventory for that child would include [b] at 6 months and [b, d] at 9 months of robust hearing experience, respectively. For the few times that children missed their sessions, the missing sessions were conservatively treated as having no consonants to add to that child's consonant inventory.

The session at which a consonant was first established was considered to be the point at which the consonant entered their inventory. Applying the Sander (1972) classification system, the criterion for customary group use of a consonant was the first session when at least half the participants (seven out of 13 for CI, six out of 11 for TD) had individually established a consonant. The first session when 90% of the participants (12 out of 13 for CI, 10 out of 11 for TD) had individually established a consonant was considered the criterion for mastery group use of a consonant.

Transcriber Agreement

Agreement or nonagreement between transcribers was determined for a randomly selected sample of 11% (n = 1,012) of all utterances (n = 9,003). Two sets of transcriptions were compared for each utterance. An agreement occurred when (a) both the original and the second transcriber identified the same consonant(s) within an utterance and (b) the two transcribers were not able to identify any consonants from an utterance (e.g., if the child produced only a vowel or the utterance contained only precanonical/nonsegmental features). In addition, when one transcriber identified a consonant(s) but the other identified a different consonant(s) or no consonant at all, it was considered as a disagreement. This analysis yielded a Cohen's kappa value of .70 for consonant agreement. According to Viera and Garrett (2005), a value between .60 and .80 is considered to be substantial agreement. Intratranscriber agreement was examined by having the original research assistant retranscribe 12% of randomly selected utterances (n = 1,119). A Cohen's kappa value of .68 for this analysis also indicated substantial agreement between the two sets of transcriptions.

Statistical Analysis

A two-way repeated-measures analysis of variance was conducted to evaluate the effects of hearing status (CI vs. TD) and length of robust hearing experience (in months) on consonant inventories. The between-subjects factor was Group with two levels (children with CIs and TD peers), and the within-subject factor was Hearing Experience with six levels (9, 12, 15, 18, 21, and 24 months). The 3-month interval could not be included because TD children entered the study at only 6 months of age. Also, preliminary testing of homogeneity of variance and normality showed violations of these assumptions in the 6-month TD group. Although all 11 TD children entered the study when they were 6 months old, only one child established some consonants at the 6-month session causing violation of homogeneity and normality at that age. Thus, only data from six intervals (i.e., 9-, 12-, 15-, 18-, 21-, and 24-month sessions) were included in the present analyses. The number of established consonants at each session served as the dependent variable in the statistical analysis.

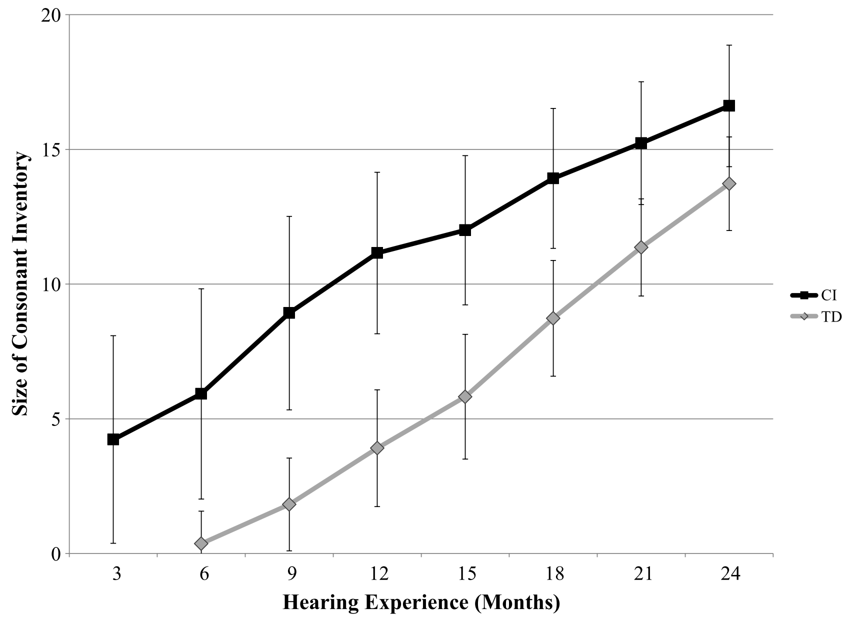
Additional descriptive analyses were used to compare the development of consonants in the two groups. These included (a) the time course for customary (at least 50% of children established a consonant) and mastery (at least 90% of children established a consonant) use for each consonant, (b) the time course for customary use of manner of articulation for established consonants, and (c) the time course for customary use of place of articulation for established consonants. These analyses were completed for both groups of children. Individual differences were also descriptively examined.

Results

Consonant Inventory Size

Figure 1 shows the mean consonant inventory sizes at each session for the two groups of children (CI, TD) at 3, 6, 9, 12, 15, 18, 21, and 24 months of robust hearing experience. Recall that TD children were recorded starting at 6 months of age. As is evident from Figure 1 and expected, the consonant inventory sizes at each session steadily increased from the first to the last recording sessions for both groups of children. The number of established consonants for the CI group across sessions was, however, consistently greater than that for the TD group. By the 21-month interval, TD and CI groups had overlapping numbers of established

Figure 1. Mean (and *SD*) of size of established consonant inventories as a function of group (cochlear implant [CI], typically developing [TD]) and months of robust hearing experience. Note that data collection began at 6 months of age for TD children.



consonants. The size of the error bars in Figure 1 also show that children in the CI group were more variable in their establishment of consonants than those in the TD group. For example, consonant inventory sizes ranged from zero to 14 at the 6-month interval for the CI group (M = 5.92, SD = 3.9), whereas, except for one TD child whose consonant inventory size was four, other TD children had no established consonants in their inventories at 6 months (M = 0.36, SD = 1.2). At the 24-month interval, consonant inventory sizes ranged from 13 to 21 in young CI recipients at 24 months of implant use (M = 16.62, SD = 2.26), whereas in TD children consonant inventories ranged from 12 to 17 consonants (M = 13.73, SD = 1.74).

Results from statistical analysis showed that the main effects of Group, $F(1, 22) = 47.34$, $p < .01$, $\eta_p^2 = .68$, and Hearing Experience, $F(5, 18) = 60.39$, $p < .01$, $\eta_p^2 = .94$, were significant. Children with CIs had more established consonants in their inventories (M = 12.99, SE = 0.534) than their TD peers with similar amounts of robust hearing experience (M = 7.56, SE = 0.58). The group inventory sizes also significantly differed from each other at every interval. The interaction effect of Group × Hearing Experience was not significant. In sum, young CI recipients had more established consonants than TD children when matched for amount of robust hearing experience.

Customary and Mastery Use of Established Consonants

Figure 2 shows the range of ages at which customary and mastery use for various consonants was attained by the two groups. Only 17 consonants are represented in Figure 2 because the remaining six consonants, [ŋ, v, ɵ, ð, z, ʒ], did not achieve customary use by either group before the end of the study. Please note that [h] was not analyzed in the present study.

As is evident from Figure 2, children in the CI group customarily produced more consonants than TD children at earlier months of robust hearing experience. In a similar manner, they mastered more consonants at earlier months than TD children. Overall, 10 consonants were mastered by the CI group and nine by the TD group when the study ended. It was remarkable that both groups of children mastered eight of the same consonants by the end of the study, namely [b, t, d, k, ɡ, m, n, w]. The consonants [p, j], however, were mastered only by children with CIs, and [s] was mastered only by TD children by the end of the study. The consonant [l] was used by at least 50% of the children in both groups during the study but was not mastered by either group. The consonants [f, ʃ, ʧ, ʤ, r] showed customary use only by children with CIs; TD children did not achieve customary use of these consonants by the end of the study. Children in the CI group, however, appeared to take a longer time to move from customary to mastery use of consonants than TD children. On average, children with CIs took approximately 8 months (M = 8.40, SD = 3.69) to move from customary to mastery use across all the 10 consonants they had mastered by the end of the study, but TD children took only approximately 5 months (M = 5.56, SD = 2.19) across the nine consonants they had mastered.

In terms of order of acquisition of specific consonants, the CI group customarily used and mastered highly visible and voiced consonants [b, m] first, followed by [d, w], and then several voiceless or nonvisible consonants, including

Figure 2. Customary and mastery use of specific consonants as a function of group (cochlear implant [CI], typically developing [TD]) and month of robust hearing experience. Note that data collection began at 6 months of age for TD children. The left edge of each horizontal bar represents customary use (50% of group), and the right edge represents mastery use (90% of group). If the bar ends without a point, this means that the phoneme was not mastered by the 24-month interval. In this case, the number next to the bar shows the percentage of children within the group that had established that consonant by the 24-month interval. Numbers in parentheses represent the percentage for TD children. *Consonants that at least one group of children had not mastered by the end of the study.

[p, t, k, n, g, j] in the 2 years of implant use. TD children followed a similar pattern of acquisition in that eight of the same consonants as noted for the CI group were customarily used and mastered in the first 2 years. TD children, however, did not show a marked tendency to use voiced and more visible consonants before voiceless and less visible consonants began to emerge. The less visible velar [g] was, in fact, one of the first consonants to emerge in TD children's productions.

Table 2 shows the number and type of consonants that were not established even after 24 months of robust hearing experience by each child in the CI and TD groups. As is evident, children with CIs resembled each other in the consonants that they did not establish, namely [ŋ, v, ɵ, ð, z, ʒ] by the end of the study. There were, however, a few exceptions. For example, ETKO was the only child in the CI group who did not establish [k, g]. In a similar manner, AAWI and MAJE were the only children who did not establish [f, s]. These two children also had the least amount of consonants mastered by the end of the study, 14 and 13, respectively, when compared with their CI peers, who had established 15 or more consonants. Similar variability was seen in the TD group (see Table 2). Although most TD children resembled each other in the consonants that they did not establish by the end of the study, for example, [ŋ, f, v, ɵ, ð, z, ʒ, ʧ, ʤ], there were a couple of exceptions. COKU was the only TD child who did not establish [k], and FACO was the only TD child who did not establish [s].

Table 2. The number and identity of nonestablished consonants at the end of the study (24-month interval) for individual children in the cochlear implant (CI) and typically developing (TD) groups.

Child	Nonestablished consonants (at 24 months)	Number of nonestablished consonants
CI		
ABHO	ʒ, ʤ	2
DAST	v, ð, ʒ	3
JOIR	θ, ð, z, ʒ	4
JORO	ŋ, v, ð, ʃ, ʒ, ʧ	6
MAMA	v, θ, ð, z, ʒ, r	6
CAST	ŋ, v, θ, ð, ʒ, ʧ, ʤ	7
ETKO	k, g, ŋ, θ, ð, z, ʤ	7
GIAI	v, θ, ð, z, ʒ, ʧ, ʤ	7
OLHE	ŋ, θ, ð, z, ʒ, r, l	7
OWJO	ŋ, v, θ, ð, ʒ, r, l	7
JAWE	ŋ, v, θ, z, ʃ, ʒ, r, l	8
AAWI	ŋ, f, v, θ, ð, s, z, ʒ, ʧ	9
MAJE	ŋ, f, v, θ, ð, s, z, ʒ, ʧ, l	10
TD		
LIRO	ŋ, f, v, θ, ð, ʒ	6
OLHA	p, ŋ, ð, ʃ, ʒ, ʤ, l	7
PARI	ŋ, θ, ð, z, ʒ, ʤ, r, l	8
HOWA	θ, ð, z, ʃ, ʒ, ʧ, ʤ, r, l	9
ISIL	ŋ, f, v, θ, ð, z, ʧ, ʤ, j	9
SYNE	ŋ, f, v, ð, θ, ʃ, ʒ, ʤ, r	9
FACO	ŋ, f, θ, ð, s, ʃ, ʒ, ʧ, ʤ, r	10
COKU	k, ŋ, v, θ, ð, z, ʒ, ʧ, ʤ, j, r	11
SASN	p, ŋ, f, v, θ, ð, ʒ, ʧ, ʤ, j, r	11
TRTO	ŋ, f, v, θ, ð, z, ʃ, ʒ, ʧ, ʤ, r	11
WIAB	p, ŋ, v, θ, ð, z, ʃ, ʒ, ʧ, ʤ, l	11

Analysis of Consonant Manner of Articulation

Figures 3 and 4 display the percentage of consonants within each manner of articulation category customarily used by children with CIs and TD peers, respectively. For example, only one consonant, [b], in the stop category was used by 50% or more of children with CIs at 3 months of robust hearing experience. This means that only 17% of the six possible English stop consonants, [p, b, t, d, k, g], were produced by at least 50% of children with CIs at 3 months of robust hearing experience (see Figure 3). We chose to display customary as opposed to mastery use for manner and place of articulation in order to allow us to compare our findings with other studies with young CI recipients that have only shown customary usage (e.g., Serry & Blamey, 1999).

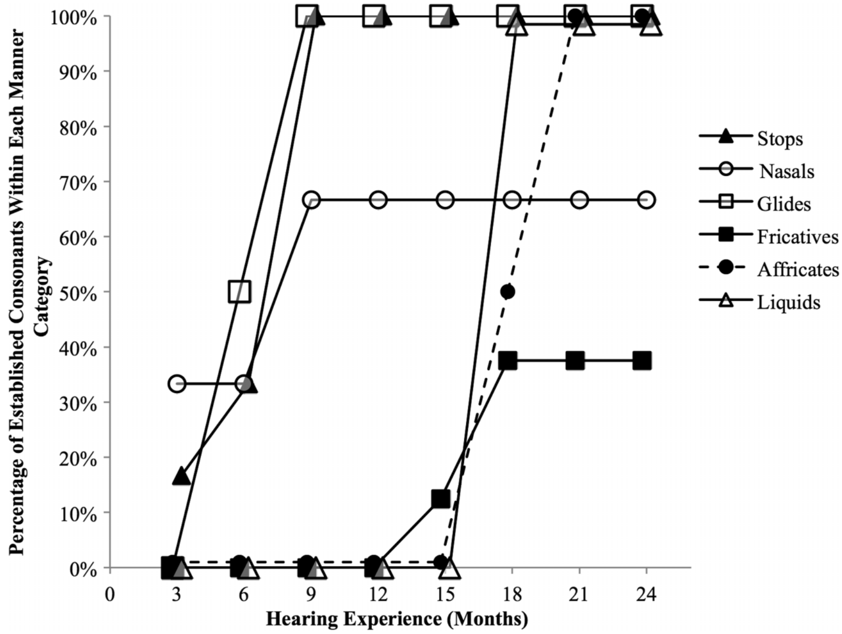
As seen in Figure 3, children with CIs customarily used 100% of all stops and glides by 9 months of robust hearing experience. Although two nasals, [m, n], reached customary use fairly rapidly by 9 months, the remaining nasal, [ŋ], had not reached this level of use even at the end of the study. Both English affricates, [ʧ, ʤ], were customarily used by 21 months, and both liquids, [l, r], were customarily used by 18 months of CI experience following activation. Fricatives were the least frequently used manner by children with CIs; only approximately 40% were customarily used by children with CIs by the end of the study.

Similar to children with CIs, TD children (see Figure 4) used 100% of all stop consonants and glides but at the relatively later ages of 18 and 21 months of age, respectively. In a similar manner, two out of three nasals, [m, n], were customarily used by TD children by 18 months of age but later than the CI group's use of these two nasals by 9 months; the third nasal, [ŋ], was not customarily used even at 24 months of age—a pattern also observed in the CI group. Liquids, affricates, and fricatives showed a different pattern of customary use for TD children than children with CIs. Only one liquid, [l], was customarily used by TD children by 24 months of age; [r] did not achieve customary use. Affricates were not customarily used by TD children at any age during the course of the study. Only approximately 10% of all English fricatives (as opposed to 40% for children with CIs) were customarily used by TD children at 24 months of age.

Analysis of Place of Articulation

Figures 5 and 6 display the percentage of consonants within each place of articulation category customarily used by children with CIs and TD peers, respectively. As seen in Figure 5, 100% of all consonants within the labial place category, [p, b, m, w], were customarily used by children with CIs by 9 months of robust hearing experience. Approximately 85% of all English alveolar consonants and 80% of all palatal consonants were customarily used by 18 and 21 months, respectively. Two out of three velars, [k, g], were customarily used by 9 months of robust hearing

Figure 3. The percentage of consonants established within each manner of articulation category by at least half the children with cochlear implants across months of robust hearing experience. Please note that points are offset horizontally for visual clarity.



experience; the third velar, [ŋ], was not customarily used until the end of the study. One out of two labiodentals, [f], was used by 18 months. As may be expected, neither of the two interdentals, [ɵ, ð], were customarily used by children with CIs until the end of the study.

TD children showed similar, although later, customary use of labials, velars, and interdentals as children with CIs (see Figure 6). They used 100% of all labial consonants and two out of three velars by 18 months of age. Similar to children with CIs, interdentals were not customarily

Figure 4. The percentage of consonants established within each manner of articulation category by at least half of typically developing children across months of robust hearing experience. Please note that points are offset horizontally for visual clarity.

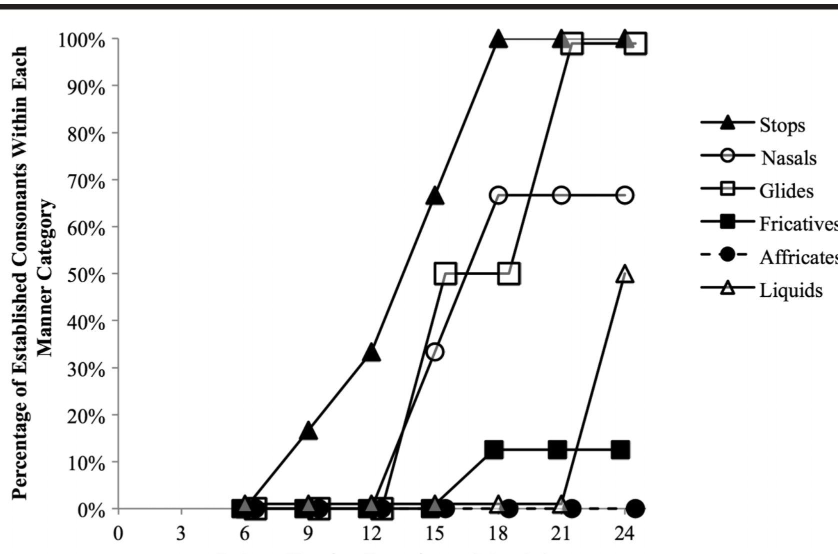
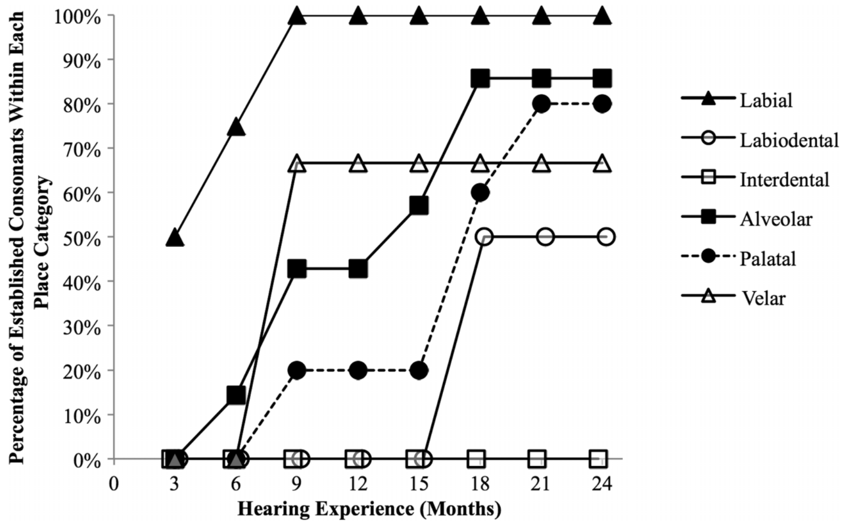


Figure 5. The percentage of consonants established within each place of articulation category by at least half the children with cochlear implants across months of robust hearing experience. Please note that points are offset horizontally for visual clarity.



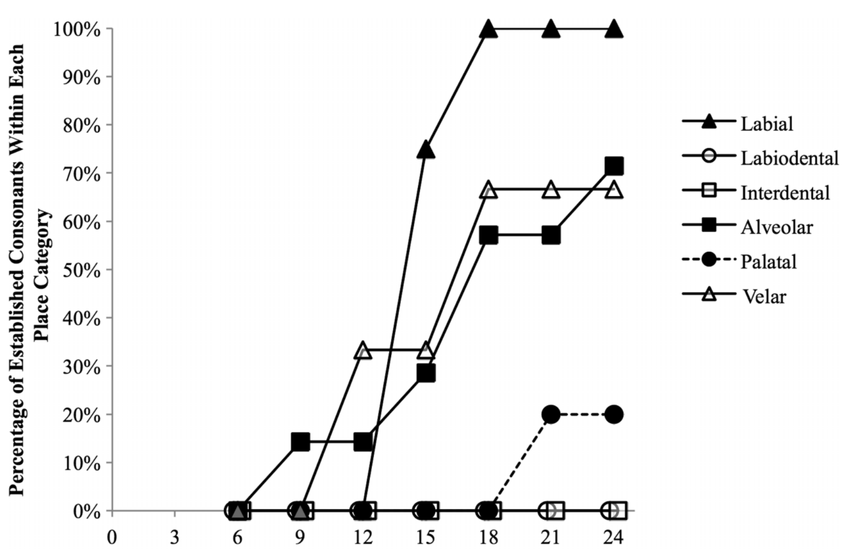
used by the end of the study. Alveolar, palatal, and labiodental consonants showed a different pattern of customary use for TD children than children with CIs. Approximately 70% of all alveolar consonants (as opposed to 85% of alveolar consonants for children with CIs) were customarily used by TD children by 24 months of age. Only one palatal, [j], or 20% of all palatal consonants, was customarily used by TD children, starting at 18 months of age (as opposed to 80% of palatals for children with CIs). Neither of the two labiodentals, [f, v], was customarily used by TD children at any age during the course of the study unlike the CI group who used [f] by 18 months.

Discussion

Growth in Consonant Inventories

Overall, both groups showed substantial growth in their spontaneous consonant inventories over the 2-year span of the study, establishing, on average, 14–15 consonants by

Figure 6. The percentage of consonants established within each place of articulation category by at least half of typically developing children across months of robust hearing experience. Please note that points are offset horizontally for visual clarity.



the end of the study (see Figure 1). In addition, neither group showed a plateau in their establishment of consonants toward the end of the study, suggesting the remaining eight to nine consonants could reasonably be expected to emerge over time. Highly similar growth trajectories were also noted across the intervals, suggesting that both groups were expanding their consonant inventories in a nearly linear manner without plateaus. For the months 6, 9, 12, 15, and 18, the children in the CI group had larger consonant inventories than those in the TD group. At 21 and 24 months, the two groups showed comparable inventory sizes. Overall, the CI group had statistically significant larger consonant inventories than TD children. These findings suggest that young CI recipients are able to overcome the effects of early auditory deprivation with regard to early consonant development. These results also add to a growing body of evidence showing that young CI recipients make substantial gains in their speech sound production abilities and that these gains parallel those of children who are TD (e.g., Ertmer, Jung, & Kloiber, 2013; Salas-Provance et al., 2014).

Although young CI recipients had larger consonant inventories than TD children, their performance was more variable (see Figure 1). This variability among CI recipients suggests that individual children progress at different rates in their consonant development following implantation. Some children appeared to make rapid gains immediately following implantation, whereas other children made slower but steady gains. Individual and continued monitoring of a child's progress following implantation is, therefore, critical in order to ensure the child is obtaining the maximum benefits of implantation and habilitation. It should also be noted that because the preimplantation performance of many CI recipients was not known, it is possible that some consonants may have been established in these children's inventories prior to implantation.

Achievement of Customary and Mastery Use

As Figure 2 shows, young CI recipients reached customary and mastery use for many consonants with fewer months of robust hearing experience than their TD peers. Young CI recipients also had more diverse consonant inventories than their TD peers. These findings are congruent with previous research that found more rapid than typical attainment of prelinguistic vocal developmental milestones, such as canonical babbling (Ertmer & Jung, 2012b). The present findings extend these findings by demonstrating that consonant development is also expeditious in young CI recipients.

Relatively early emergence of some consonants in some young CI recipients has also been noted by Spencer and Guo (2013). In fact, we observed many of the same consonants that Spencer and Guo reported as being acquired earlier by children with CIs than their TD peers, for example, [f, ʃ, ʧ]. They attributed the relatively rapid acquisition of these consonants to improved speech-processing strategies of CIs, greater visibility of some consonant sounds, greater maturity of children with CIs, and frequent targeting of consonants during intervention. These potential explanations seem reasonable for the findings of the present study as well—that is, it appears that modern CIs are capable of representing the frequency, intensity, and timing information of adult-like speech models; that young CI recipients are primed by their cognitive, social, and motoric maturity to recognize the different signals that CIs provide; and that speech intervention can be beneficial in increasing awareness of consonant diversity and the articulatory gestures needed to produce a variety of speech sounds. The relatively rapid increases in consonant inventories observed in the present study are especially encouraging because they suggest that many young CI recipients will catch up to age peers given consistent CI use and ongoing support from interventionists and parents. This speculation cannot be directly evaluated, as a control group matched for age was not included in the present study. We are, however, encouraged by Salas-Provance et al.'s (2014) findings that young CI recipients matched their chronological age-matched peers on their targetless (independent) consonant inventories.

Although the CI group appeared to have an advantage in the rate at which consonants were established during the study, both groups showed remarkably similar patterns for the types of consonants acquired. Of the 11 consonants that achieved mastery use by the end of the study, eight were the same for the two groups. These eight consonants included [b, t, d, k, g, m, n, w] and resembled those reported in the typical literature on speech sound acquisition as being among the first sounds to be acquired (Stoel-Gammon, 1985). In a similar manner, an additional six consonants, [ŋ, v, ɵ, ð, z, ʒ], were not produced by half the children in either group. Most of these sounds have been reported to be later acquired in the typical literature as well (e.g., Sander, 1972; Smit, Hand, Freilinger, Bernthal, & Bird, 1990).

There were differences, however, in consonant acquisition between the CI group and TD children. A close look at Figure 2 reveals that, across all consonants mastered by both groups of children by the end of the study, young CI recipients took an average of 3 months longer than their TD counterparts to move from customary to mastery use. This protracted period of development was especially striking for the less visible consonants, [k, g]. It took young CI recipients 15 months to move from customary to mastery use for these two consonants, whereas TD children took only 6 months. It should be noted, however, that, except for [s, g], the CI group obtained mastery use of all consonants before or at the same intervals as the TD group. Thus, even though there was an extended period of development, the CI group did not lag behind their TD peers with comparable hearing experience for most consonants. It also appears from Figure 2 that the CI group established many voiced consonants before establishing voiceless consonants (e.g., [d] was mastered before [t]), whereas the TD group did not always favor the acquisition of voiced consonants (e.g., [t] and [d] were mastered simultaneously). These findings suggest that perceptual and/or electrical signal limitations may, in fact, still play a role for young CI recipients.

Table 2 also showed some individual differences in the CI group in the establishment of consonants. This suggests that individual monitoring and/or habilitation would be needed to ensure that all CI recipients continue to show diversity in their consonant inventories. Because TD children showed similar variability in the nature of their consonant inventories, these individual differences within the CI group did not constitute any particular source of concern.

Establishment of Customary Manner and Place of Articulation

Figures 3 through 6 show that at least half the children in the CI group achieved customary use of several manners and places of articulation more rapidly than their TD counterparts. To be specific, with respect to manner of articulation, young CI recipients customarily used all stops and glides and two-thirds of nasals by 9 months of robust hearing experience; all affricates and liquids were used by a majority of the CI group in the second year of implant use (see Figure 3). On the other hand, a majority of TD children used all stops and glides only in the second year of robust hearing experience. Furthermore, TD children did not customarily use affricates and liquids even after 24 months of robust hearing experience; only one liquid, [l], was customarily used by the end of the study (see Figure 4). The CI group also showed greater customary use of fricatives by 24 months of robust hearing experience than TD controls.

With regards to place of articulation, we see a similar picture. At least half the children in the CI group used all labial consonants and most velar consonants in the first year of implant use. In the second year of implant use, the CI group customarily used many alveolar and palatal consonants. They also used one of the two labiodental consonants in the second year of robust hearing (see Figure 5). On the other hand, TD children showed customary use of all labial consonants and most velar consonants only in the second year of robust hearing. In addition, TD children attained customary use of few alveolar and palatal consonants in the second year of robust hearing. TD children also did not show customary use of any labiodentals (see Figure 6).

These results accord well with the typical literature on speech sound acquisition. TD children acquire stops, most nasals, and glides before they acquire fricatives, affricates, and liquids (Smit et al., 1990; Stoel-Gammon, 1985), and this pattern was seen in both groups in the present study. In a similar manner, with regards to place of articulation, both CI and TD groups showed early customary use of labials, some alveolars, and some velars: a pattern similar to that noted in typical acquisition (Sander, 1972; Stoel-Gammon, 1985). At least half of young CI recipients also showed evidence of use of several other manner and place categories, for example, liquids, affricates, fricatives, labiodentals, and palatals, within the 2-year observation period of the present study, which is in advance of that noted in the typical literature (e.g., Sander, 1972).

These findings also accord well with the existing literature on young CI recipients. For example, stops and labials are frequently mentioned as being among the first sounds acquired by this population (e.g., Salas-Provance et al., 2014). Our study reached similar conclusions. Differences between our findings and the existing literature on CI recipients are difficult to interpret given methodological differences. For example, glides were noted as being infrequently produced even after 18 months of CI use by Bouchard et al. (2007), whereas in our study, glides were mastered within 9 months following implant activation. Fifteen out of the 22 children with CI studied by Bouchard et al. were, however, implanted after the age of 3 years, whereas in the present study all 13 children with CI were implanted by 3 years of age. The effects of age of implantation on consonant production, therefore, cannot be ruled out in the Bouchard et al. investigation.

In general, the present findings reiterate our previous conclusion that young CI recipients are remarkably successful in overcoming the effects of early auditory deprivation. We fully expect that CI recipients, as a group, would continue to establish the remaining manners and places of articulation with similar amounts of robust hearing experience as their TD counterparts.

Research Limitations and Future Directions

There are several caveats to the present study that temper our conclusions regarding the substantial growth of consonant inventories seen in our young CI recipients. First, it is important to reiterate that, because we matched the two groups on their duration of robust hearing experience rather than age, the children with CI were necessarily older and developmentally more mature than their TD peers. Their speech sound production may, therefore, have been more advanced than their developmentally immature TD peers due to their chronological advantage. Second, it is important to remember that children in the CI group had hearing loss as their only diagnosis; no secondary disabilities were noted. They also had received intensive communication intervention from a young age. As such, they had near optimal (but also relatively common) programming to develop spoken language skills. Children who have other disabilities in addition to hearing loss and those who do not receive comparable intervention might not show as much progress in consonant development. Indeed, Tobey et al. (2003) reported less favorable outcomes for consonantal accuracy in children with CIs and secondary intellectual disabilities when compared with children with CIs alone. Children enrolled in other types of intervention programs (e.g., oral vs. sign and speech vs. American Sign Language) fitted with older generation implants and with less involved families also may not experience similar gains during the first years of CI use. As Tobey et al. (1991) noted, there is a complex relationship between the implant, maturational factors, and habilitation, which is difficult to tease apart. It is also possible that consonant production in meaningful words might not progress as rapidly as the increases in phonetic inventories observed for the young CI recipients in the present study. Indeed, Serry and Blamey (1999) and Blamey et al. (2001) noted that meaningful consonant production lagged behind that seen for total production, including nonmeaningful productions. They found that [t, s, z], although produced spontaneously in vocalizations, were not produced accurately in meaningful words. Ertmer et al. (2012) compared consonant accuracy in words between the same CI users who participated in the present study and their TD gender- and chronological age-matched peers. They noted significant delays in consonant accuracy for the CI users after 2 years of device experience, relative to the TD peers. Although this finding could be anticipated due to the greater amounts of robust hearing experience of the TD controls, it confirms that the ability to produce consonants in nonmeaningful utterances does not immediately transfer to word productions—at least for some consonants.

Another caveat is that a control group matched for chronological age was not included in the present study. Therefore, it is unknown if the gains seen in the inventories of these young CI recipients matched those of their chronological age peers. Also, there were more girls than boys in the CI group, whereas there were more boys than girls in the TD group. We were unable to control for this gender difference in our data analysis given small sample sizes. Future investigations with larger sample sizes should control for this variable that is known to affect speech sound production (Smit et al., 1990).

It is clear that many future studies are needed to address unresolved issues for young children with CIs. Among these are investigations of consonant variability within and across young CI users, speech sound development in children who have secondary disabilities, the impact of gender and various communication modalities on speech sound development, the effectiveness of various types of intervention on speech sound development, and the identification of early observable factors that can predict the eventual attainment of readily intelligible speech.

Conclusions

In conclusion, young CI recipients made substantial increases in their consonant inventories during the first 2 years of robust hearing. On average, they established 15 of the 23 consonants studied during this period. A majority of children with CIs also showed faster acquisition and greater variety in the place and manner of articulation of consonants than their TD counterparts matched for duration of robust hearing. The relatively rapid advancements of the CI group appear to be due to their advanced maturity and intervention experiences, which enable them to closely approximate their consonant productions with the adult-like speech models they experience in the ambient environment and during intervention. Overall, the results from the present study show that the combination of communication intervention and CI experience are efficacious for early speech production development.

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