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Research Article

Alveolar and Postalveolar Voiceless Fricative and Affricate Productions of Spanish–English Bilingual Children With Cochlear Implants

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Purpose: This study investigates the production of voiceless alveolar and postalveolar fricatives and affricates by bilingual and monolingual children with hearing loss who use cochlear implants (CIs) and their peers with normal hearing (NH).
Method: Fifty-four children participated in our study, including 12 Spanish–English bilingual CI users (*M* = 6;0 [years;months]), 12 monolingual English-speaking children with CIs (*M* = 6;1), 20 bilingual children with NH (*M* = 6;5), and 10 monolingual English-speaking children with NH (*M* = 5;10). Picture elicitation targeting /s/, /tʃ/, and /ʃ/ was administered. Repeated-measures analyses of variance comparing group means for frication duration, rise time, and centroid frequency were conducted for the effects of CI use and bilingualism.
Results: All groups distinguished the target sounds in the 3 acoustic parameters examined. Regarding frication duration and rise time, the Spanish productions of bilingual children with CIs differed from their bilingual peers with NH. English frication duration patterns for bilingual versus monolingual CI users also differed. Centroid frequency was a stronger place cue for children with NH than for children with CIs.
Conclusion: Patterns of fricative and affricate production display effects of bilingualism and diminished signal, yielding unique patterns for bilingual and monolingual CI users.

Cochlear implants (CIs) offer access to sound for individuals who have severe-to-profound sensorineural hearing loss (HL) that, in turn, promotes the acquisition of spoken language (Kant, Patadia, Govale, & Rangasayee, 2012). Existing research provides strong evidence for the benefits of CI use on spoken language outcomes in individuals with HL, but the degree of success for speech production and perception with respect to each individual has been linked to a variety of factors, including age of implantation, duration of implant use, duration and intensity of therapy, characteristics of the hearing device, the rehabilitation program, and the recipient's motivation and family support (Connor, Craig, Raudenbush, Heavner, & Zwolan, 2000; Dowell et al., 2002; Gordon, Daya, Harrison, & Papsin, 2000; Peng, Weiss, Cheung, & Lin, 2008; Sarant, Blamey, Dowell, Clark, & Gibson, 2001; Tobey, Geers, Brenner, Altuna, & Gabbert, 2003).

Among the sounds that are challenging to acquire for young children who use CIs tend to be fricatives and affricates, a finding that has been consistent not only across studies focusing on English-speaking children (e.g., Ingram, McCartney, & Bunta, 2001; Serry & Blamey, 1999), but also children acquiring other languages, such as Croatian (Liker, Mildner, & Šindija, 2007; Mildner & Liker, 2008) or Mandarin (Peng et al., 2008). To be more specific, Blamey, Barry, and Jacq (2001) found that monolingual English-speaking CI users display some inconsistencies in production and may not fully acquire and differentiate /t/, /s/, /z/, and /tʃ/ even 6 years postimplantation. Among the factors that may contribute to the relatively late acquisition of these segments, Blamey et al. (2001) identify articulatory variability involving the production of alveolar and postalveolar obstruents as well as perceptual issues, albeit the authors claim that perceptual similarity may not be the predominant factor leading to the lack of differentiation of these sounds. However, they do note that the most common substitution pattern involving the phoneme /s/ is [ʃ] in that 24% of all the

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errors involving the realization of /s/ are [ʃ] for /s/ substitutions. Considering that temporal fine structure and spectral cues are not as readily available via the implant as envelope cues and temporal information in general (cf. Loizou, 2006; Moon & Hong, 2014; Rubinstein, 2004; Shannon, Fu, Galvin, & Friesen, 2004), CI users' access to contrasts that require relatively good spectral resolution (such as the /s/ versus /ʃ/ contrast) may be more limited than children with normal hearing (NH). Caldwell and Nittrouer (2013) point out that children with CIs "are perfectly capable of forming well-defined phonological categories, as long as they have access to signal properties upon which those categories are based" (p. 24). For example, stop differentiation on the basis of voice onset time is a difference CI users acquire whether they are monolingual English-speaking children (Caldwell & Nittrouer, 2013) or bilingual Spanish and English speakers (Bunta, Goodin-Mayeda, Procter, & Hernandez, 2016). However, when a phonemic contrast is dependent more on spectral cues than temporal or envelope cues, children with CIs may find acquiring the feature challenging.

Nittrouer, Studdert-Kennedy, and McGowan (1989) note that spectral frequency information is a critical acoustic dimension for fricative and affricate perception, especially differentiating the place for alveolar versus postalveolar obstruents. Even though CIs are known to provide a greater amount of spectral information in the high frequencies relative to low frequencies (due to the typical placement of electrodes more toward the basal end of the basilar membrane), the spectral resolution needed to differentiate place of articulation (such as in the case of alveolar vs. postalveolar fricatives) is still a challenge for CI users (cf. Loizou, 2006; Moon & Hong, 2014; Rubinstein, 2004). As a result, children with CIs are commonly reported to produce neutralized or less contrasted fricatives (Liker et al., 2007; Mildner & Liker, 2008; Peng et al., 2008; Todd, Edwards, & Litovsky, 2011), sometimes even yielding atypical error patterns. For instance, although children with NH commonly substitute [s] for /ʃ/ during the course of fricative acquisition, the reversed pattern was found in pediatric CI users (Blamey et al., 2001). Furthermore, in comparison with children with NH, the affricates produced by children with CIs acquiring Croatian are longer and are frequently substituted by other fricatives and stops (Liker et al., 2007; Mildner & Liker, 2008).

The acquisition of fricatives and affricates by children with CIs is further complicated when they are learning two spoken languages that have vastly different fricative and affricate systems (such as Spanish and English)—an issue with virtually no published acoustic or phonological data. Existing studies on bilingual phonological acquisition in typically developing Spanish- and English-speaking bilingual children indicate that fricatives and affricates are usually among the middle or late acquired sounds (cf. Fabiano-Smith & Goldstein, 2010a). In fact, Linares (1981) found that Spanish–English bilingual children acquired /tʃ/ later than their monolingual Spanish-speaking peers. In addition, Fabiano-Smith and Goldstein (2010a, 2010b) found lower segmental accuracy rates in the productions of Spanish–English bilingual children than their monolingual Spanish-speaking peers for /x, s, β, ð, γ/ as well as compared with their monolingual English-speaking peers with respect to /tʃ, ʃ, ð, s, z, θ/. Thus, data on the speech patterns of bilingual children with NH indicate that fricatives and affricates may pose special challenges for bilingual CI users.

Investigating how bilingual CI users produce their alveolar and postalveolar fricatives and affricates offers a window into how these children acquire contrasts that may be challenging and whether or not those contrasts can be represented differentially in distinct phonological systems unique to each language. To date (and to our knowledge), no studies have been published on the fricative production patterns—acoustic or otherwise—of Spanish–English bilingual children with CIs as compared with their bilingual peers with NH and their monolingual English-speaking peers with CIs. The need to better understand the phonological skills of bilingual children with HL is only made more urgent by both the growing number of individuals who speak a language other than English at home in the United States (cf. U.S. Census Bureau, 2015) and the fact that Hispanic individuals display a higher prevalence of HL than what is attested in the general population of the United States (Mehra, Eavey, & Keamy, 2009).

The current study addresses the important question of how the use of CI affects bilingual language acquisition. We specifically focus on speech production and whether or not these children are able to acquire separate phonological systems of alveolar and postalveolar fricatives and affricates. We investigate the acoustics of voiceless fricatives (alveolar and postalveolar) and affricates produced by Spanish–English bilingual children with CIs, their bilingual Spanish- and English-speaking peers with NH, their monolingual English-speaking peers with CIs, and their monolingual English-speaking peers with NH. The findings of our study have clear implications for speech-language pathologists, audiologists, and educators serving bilingual and monolingual children with HL who use CIs. Our results also provide unique insights into how phonological skills are shaped by both bilingualism in spoken languages and the diminished auditory signal provided by the CI, thus informing theoretical approaches to bilingual phonological acquisition. To be more specific, our study focuses on how HL and bilingualism interact in children who received CIs. It is important to note that throughout this article, we refer to bilingualism in the context of two spoken languages, and our bilingual participants were acquiring Spanish and English simultaneously upon implant activation.

Fricatives and Affricates in English and Spanish

We chose to investigate the productions of voiceless alveolar and postalveolar fricatives (English /s/ and /ʃ/ and Spanish /s/) and affricates (English and Spanish /tʃ/) because (a) these segments allow us to consider cross-linguistic interaction, (b) they provide insights into language separation, and (c) they represent sounds that are known to cause challenges for CI users. With respect to fricatives and affricates, English has a richer inventory of nine fricatives

(/h, f, v, s, z, ʃ, θ, ð, ʒ/) and two affricates (/tʃ, dʒ/; Roach, 1998) than Mexican Spanish, which only has three fricatives (/f, x, s/) and one affricate /tʃ/ (Hammond, 2001). Other fricatives ([β, ð, γ]) also occur allophonically in complementary distribution with voiced stops and may even be treated as phonemes (cf. Fabiano-Smith & Goldstein, 2010a, 2010b), but even if these sounds were treated as part of the Mexican Spanish inventory, the American English system of fricatives and affricates would still be more complex and varied. Thus, for Spanish–English bilingual children who use CIs, a distinction between /s/ and /ʃ/ needs to be maintained in their English, which may be problematic due to diminished auditory input provided by the implanted device, and this issue may be exacerbated by the fact that Spanish only has /s/ as a phoneme and lacks the alveolar–postalveolar contrast. Moreover, when examining the error patterns involving /s/ for monolingual English-speaking children with CIs, [ʃ] for /s/ substitutions are found (Blamey et al., 2001; Chin & Pisoni, 2000)—a pattern not commonly attested in monolingual English-speaking children with NH. Adding to the complexity of substitution patterns involving alveolar and postalveolar fricatives, bilingual children with CIs display more substitutions using [tʃ] for /ʃ/, indicating the unique ways that the listening device interacts with bilingualism (Bunta, Harrison, & Douglas, 2012). These issues require an in-depth investigation relying on acoustic data that are provided in the present study.

In addition, despite the fact that both /s/ and /tʃ/ exist as phonemes in American English and in Mexican Spanish, language-specific differences exist in how these phonemes are realized, including the distribution of the allophones and the phonotactics involving these segments in each language. Differences in allophonic variation and phonotactics across the two target languages pose further challenges for bilingual children in general and Spanish–English bilingual children with CIs, in particular. For example, the Spanish /s/ in word-initial position is more likely to be affricated than its English analog (Widdison, 1997). The place of articulation for /s/ may also differ somewhat in Spanish as compared with English (cf. Hammond, 2001). Furthermore, acoustic studies have found the Spanish /tʃ/ to be shorter than its English counterpart in onset position (Maddieson, 1980; Stockwell & Bowen, 1970). Regarding the postalveolar voiceless fricative, /ʃ/ is a phoneme in American English, but it does not have phonemic status in most dialects of Spanish although an allophonic variant of the postalveolar fricative does occur in areas of northern Mexico and Andalucía (Spain) as well as parts of Panama and Chile (Hualde, Olarrea, & Escobar, 2007).

Taken together, the divergent patterns in Spanish versus English fricatives and affricates and the diminished signal provided by the CI allow us to investigate how bilingualism and the limited auditory signal provided by the device interact to produce unique speech patterns in bilingual children with HL who use CIs. The complexity of the problem prompts the question as to whether or not bilingual children acquiring Spanish and English who use CIs are able to establish separate phonological systems and whether or not the production patterns of these segments would differ across the two spoken languages. To date, research is limited on either topic, and to our knowledge, no published studies exist that focus on fricative and affricate productions of bilingual CI users.

The present study aims to provide an acoustic characterization of the English /s/, /tʃ/, and /ʃ/ and the Spanish /s/ and /tʃ/ produced by Spanish- and English-speaking bilingual children with CIs in comparison to their bilingual peers with NH, monolingual English-speaking CI users, and monolingual English-speaking peers with NH. The acoustic parameters selected to describe children's fricative and affricate productions include frication duration, rise time of the fricative portion of the segment, and centroid frequency of the frication noise. Duration and rise time provide a means to distinguish affricates from fricatives and to gauge the degree of frication quantitatively. Affricates are typically characterized by shorter duration and rise time than fricatives (Dorman, Raphael, & Isenberg, 1980; Howell & Rosen, 1983; Kluender & Walsh, 1992). Centroid frequency denotes the mean spectral frequency of frication noise and is the key parameter distinguishing /s/ from /ʃ/ (Forrest, Weismer, Milenkovic, & Dougall, 1988; Jongman, Wayland, & Wong, 2000; Li, 2012). Because centroid frequency is inversely related with the front cavity enclosed by the tongue tip and the teeth during the production of sibilant fricatives, /s/ usually has a higher centroid frequency value than /ʃ/ (Jongman et al., 2000; Shadle, 1991).

Research Questions and Hypotheses

Our study was guided by the following questions and predictions:

1. How does the use of CIs affect the temporal and spectral cues in the production of alveolar and postalveolar fricatives and affricates? We predict that bilingual and monolingual children with NH will use spectral cues more reliably than their monolingual and bilingual peers with HL who use CIs.
2. Do bilingual versus monolingual CI users display different production patterns with respect to their voiceless alveolar and postalveolar fricatives and affricates in English? We expect that monolingual English-speaking children with CIs will display more marked differentiation of their /s/, /ʃ/, and /tʃ/ than their peers who are bilingual and use CIs. However, we also expect that bilingual children with CIs will differentiate these segments, albeit not as markedly as their monolingual peers.
3. Do bilingual children with CIs and with NH maintain different production patterns when it comes to fricatives and affricates in each language? We expect that children with both CI and NH will differentiate fricative and affricate manner, and we also predict that bilingual children with NH will display more differentiation for place of articulation due to better access to spectral cues. In addition, we predict that

bilingual children with NH will be better at separating the two languages than those with CIs because children with NH have access to enriched acoustic signals.

Method

Participants

The present study was approved by the institutional review board of the University of Houston. Participants were recruited from the greater Houston, Texas, metropolitan area. Children with CIs were recruited via contacts through the Center for Hearing and Speech in Houston, and their peers with NH were recruited via community contacts and flyers distributed in the same geographical area. A total of 54 children participated in the present study, including 12 Spanish- and English-speaking bilingual children with CIs (mean chronological age = 6;0 [years;months], *SD* = 15.7 months; mean duration of implantation = 4;3, *SD* = 16.9 months), 12 monolingual English-speaking children with CIs (mean chronological age = 6;1, *SD* = 18.2 months; mean duration of implantation = 3;11, *SD* = 14.3 months), 20 Spanish- and English-speaking children with NH (mean chronological age = 6;5, *SD* = 12.7 months), and 10 monolingual English-speaking children with NH (mean chronological age = 5;10, *SD* = 10.7 months). The two groups of children with CIs all received their implants at or before 4 years of age—most prior to two-and-a-half years of age—and were in oral–aural programs with spoken language as their primary mode of communication. Tables 1 and 2 include the ages of implant activation for all of the participants with CIs. Two monolingual English-speaking children with CIs and one bilingual CI user had a hearing aid in one of their ears.

All of the participants were born in the United States with the exception of one bilingual CI user who was born in Argentina and who arrived in the United States at the age of 4;0.19. The child born outside the United States was implanted at 2;7, so his age of exposure to spoken English was 1;3 after implant activation, considering the duration of implant use, which would make him an early sequential bilingual. All of the other bilingual children—irrespective of hearing status—were born in the United States and were undergoing bilingualism as first language acquisition (cf. Meisel, 2004). Furthermore, bilingual children who participated in our study (including the child not born in the United States) had parent-reported use of both Spanish and English of at least 20%, and the children had to be able to comprehend and speak both languages in order to be considered bilingual (i.e., have functional receptive and expressive language skills in both Spanish and English).

The English variety spoken by all of the children was American English. Considering the recruitment area, children were exposed to varieties of American English spoken in the greater metropolitan Houston area, ranging from southeast Texas to "network standard" American English. Regarding the varieties of Spanish of the bilingual participants, 10 of the 12 bilingual CI users spoke Mexican Spanish, one bilingual CI user spoke a variety from El Salvador, and one from Argentina (the child born outside of the United States). Of the 20 bilingual children with NH, the representation of Spanish varieties was the following: Mexico (*n* = 9),

Table 1. Participant background information for bilingual Spanish- and English-speaking children with cochlear implants (CIs).

Participant	Chronological age (years;months.days)	Gender	Age at implant	CI use duration	Device type and side (R = right ear, L = left ear)	Etiology	Maternal education	Age at hearing loss
13CIBES205	5;10.7	M	1;0.0	4;10.7	Nucleus 5 (R), Nucleus Freedom (L)	Unknown	Trade school	Birth
13CIBES225	7;1.26	F	1;0.0	6;0.26	Nucleus Freedom (R), Phonak Naida III (L)	Premature	High school	Birth
11CIBES015	5;4.6	F	1;2.19	4;1.18	Nucleus 6 (R), Nucleus 5 (L)	Unknown	High school	Birth
11CIBES004	4;10.21	F	1;4.28	3;5.24	Nucleus Freedom (R), Nucleus 5 (L)	Unknown	GED	8 months
11CIBES010	4;10.2	M	1;4.8	3;5.25	Nucleus Freedom (R), Nucleus 5 (L)	Unknown	Elementary	13 months
14CIBES254	6;2.19	M	1;7.0	4;7.0	Nucleus 5 (R, L)	Unknown	Some high school	Birth
13CIBES206	7;8.23	F	1;9.0	5;11.23	Nucleus 5 (R, L)	Unknown	Elementary	Birth
13CIBES202	4;6.20	M	2;0.0	2;6.20	Nucleus 5 (R, L)	Unknown	No school	Birth
11CIBES030	8;9.27	M	2;0.0	6;9.27	Med-El Opus 2 (R, L)	Unknown	Some high school	Birth
14CIBES239	5;4.20	F	2;2.20	3;4.0	Nucleus 5 (R, L)	Neuropathic	Some college	Birth
13CIBES207	5;0.8	F	2;2.29	2;9.10	Nucleus 5 (R, L)	Ear failed to develop	Elementary	Birth
14CIBES259	5;9.1	M	2;7.0	3;2.0	Nucleus Freedom (R, L)	Connexin 26	Bachelor's degree	Birth

Note. All bilingual children but 14CIBES259 were born in the United States. 14CIBES259 was born in Argentina and arrived in the United States at the age of 4;10, having an age of exposure to spoken English of 1;30 postimplantation. GED = general education development.

Table 2. Participant background information for monolingual English-speaking children with cochlear implants (CIs).

Participant	Chronological age (years;months.days)	Gender	Age at implant	CI use duration	Device type and side (R = right ear, L = left ear)	Etiology	Maternal education	Age at hearing loss
14CIME246	4;7.3	M	0;10.0	3;9.3	Nucleus 5 (R), Nucleus 6 (L)	Bacterial meningitis	Associate degree	Infant
11CIME003	4;6.22	M	1;1.0	3;5.22	Med-El Opus 2 (R, L)	Connexin 26	Some high school	Birth
14CIME238	5;2.10	M	1;2.0	4;0.10	Med-El Opus 2 (R, L)	Unknown	Bachelor’s degree	Birth
13CIME208	5;5.29	F	1;5.0	4;0.29	Nucleus 5 (R), Nucleus 6 (L)	Unknown	Some college	Birth
11CIME019	7;0.19	M	1;6.26	5;5.24	CI-Med-El Opus 2 (R, L)	Connexin 26	Some high school	Before talking
11CIME002	4;1.10	F	1;7.19	2;5.21	Med-El Opus 2 (R, L)	Congenital	Graduate degree	Birth
13CIME223	5;9.19	M	2;0.0	3;9.19	AB Harmony (R), AB Neptune (L)	Kidney disease	Some college	Birth
12CIME031	5;0.12	F	2;2.25	2;9.17	Nucleus 6 (R, L)	Unknown	Some grad school	Birth
11CIME029	8;8.20	F	2;7.0	6;1.20	AB Neptune (R); Phonak Naida III (L)	Antibiotics	Some college	29 months
12CIME019	8;2.8	F	3;3.0	4;11.8	Nucleus 6 (R); ReSound Linx9 (L)	Connexin 26	Graduate degree	Birth
11CIME020	7;6.10	F	3;8.26	3;9.14	Advanced Bionics (R, L)	Genetic	Some grad school	Birth
14CIME253	6;6.0	F	4;0.0	2;0.0	Nucleus 6 (R, L)	Unknown	Bachelor’s degree	Infant

El Salvador (*n* = 5), Colombia (*n* = 3), Castilian (*n* = 2), and Honduras (*n* = 1). The varieties of Spanish spoken by the participants are not known to have effects on the acoustic measures used in our study.

None of the participants had any known cognitive, speech, or language disorders other than the delayed access to spoken language in the case of CI users. Tables 1, 2, and 3 contain more detailed information about participants’ demographics, including individual chronological age, duration of implantation, gender, age at implantation for CI users, etiology of HL for CI users, device type for CI users, maternal education, and age at HL for CI users.

Task and Materials

After volunteering for our study, parents provided informed consent in Spanish or English, and the children provided verbal or written assent before participating. The parents also completed a detailed demographic and language background questionnaire. Children with NH completed a pure-tone hearing screening at 500, 1000, 2000, and 4000 Hz at 25 dB hearing level, binaurally. Children with CIs had their devices checked before the study. A single-word picture elicitation task was administered to the participants in the languages they spoke (English for monolingual English-speaking children and Spanish and English for bilingual participants). The elicitation technique used followed well-established criteria used in phonological studies (cf. Bunta, Goodin-Mayeda, et al., 2016; Fabiano-Smith & Goldstein, 2010a, 2010b). First, children were shown a picture and asked to identify what the image depicted (i.e., the experimenter would ask the child, “What is this?” The child would be expected to respond by naming the item, such as *chair*). If the child did not produce the target item, the second level of prompting included a semantic cue (e.g., “You can sit on this. What is it?”). The third level of prompt was sentence completion (e.g., “You sit on a ___.”). Last, if needed, delayed imitation was used (e.g., “This is a chair. What is it?”). Spanish and English speech samples were collected separately and by different experimenters so as to minimize code switching. All of the experimenters were fluent in the languages they tested and have had experience working with children from culturally and linguistically diverse backgrounds.

The word list was designed by the second author and specifically targets age-appropriate items that are linguistically and culturally appropriate for both monolingual English-speaking children and bilingual Spanish- and English-speaking children. More than 80 words in each language were selected, designed to target the phonemes of the respective languages multiple times in order to assess the phonological skills of the children. Items containing the target sounds (English /s/, /ʃ/, and /tʃ/ and Spanish /s/ and /tʃ/) in initial position were chosen for analysis. The English words tested included *chair, cheese, chicken,* and *church* for the /tʃ/ target; *scissors, sun, sock,* and *six* for the /s/ target; and *sheep, shovel, shark,* and *shirt* for the /ʃ/ target. The Spanish words tested include *silla* (*chair*), *sol* (*sun*), *cepillo* (*brush*), and *zapato* (*shoe*) for the /s/ target and *chancla* (*slipper*), *chango* (*monkey*), *chile* (*pepper*), and *chicharos* (peas) for the /tʃ/ target. If a child did not produce an item, that token was excluded from the acoustic analyses

Table 3. Participant background information for monolingual English-speaking children with normal hearing and bilingual Spanish- and English-speaking children with normal hearing.

Participant	Chronological age (years;months.days)	Gender	Language status	Maternal education
14NHBES244	7;4.7	M	Spanish–English bilingual	Elementary
14NHBES250	7;0.0	M	Spanish–English bilingual	Bachelor's degree
14NHBES251	6;0.16	F	Spanish–English bilingual	Bachelor's degree
13NHBES219	7;10.18	M	Spanish–English bilingual	High school
13NHBES204	5;2.0	F	Spanish–English bilingual	High school
13NHBES209	7;9.7	F	Spanish–English bilingual	Some grad school
14NHBES232	5;5.21	F	Spanish–English bilingual	Bachelor's degree
13NHBES228	7;2.29	F	Spanish–English bilingual	Some college
13NHBES210	5;5.10	F	Spanish–English bilingual	Bachelor's degree
13NHBES227	7;3.25	F	Spanish–English bilingual	Some grad school
13NHBES216	7;9.22	F	Spanish–English bilingual	Some high school
13NHBES212	6;3.0	F	Spanish–English bilingual	Some college
14NHBES243	7;1.11	M	Spanish–English bilingual	GED
14NHBES230	4;6.0	F	Spanish–English bilingual	Bachelor's degree
14NHBES240	7;7.12	M	Spanish–English bilingual	High school
14NHBES245	5;5.10	M	Spanish–English bilingual	High school
13NHBES217	6;0.0	M	Spanish–English bilingual	Some high school
13NHBES211	7;10.11	F	Spanish–English bilingual	Some college
13NHBES231	7;5.20	F	Spanish–English bilingual	Bachelor's degree
13NHBES203	5;7.28	M	Spanish–English bilingual	Bachelor's degree
16NHME676	5;10.5	M	English monolingual	Bachelor's degree
16NHME677	5;10.5	M	English monolingual	Bachelor's degree
16NHME680	4;6.14	M	English monolingual	Bachelor's degree
16NHME681	6;11.5	M	English monolingual	Graduate degree
16NHME682	6;11.5	M	English monolingual	Graduate degree
16NHME683	6;10.21	F	English monolingual	Graduate degree
16NHME685	6;3.9	M	English monolingual	Bachelor's degree
16NHME689	4;6.28	M	English monolingual	Some college
16NHME691	4;10.29	F	English monolingual	High school
16NHME694	5;6.1	F	English monolingual	High school

Note. GED = general education development.

(e.g., due to dialectal variation, a few children used *mono* [mono] instead of *chango* [tʃaŋgo] to describe the picture of the monkey in Spanish).

Acoustic Measurements

Children' productions were digitally recorded using a Marantz PMD 661 MKII solid-state recorder (D&M Holdings, Tokyo, Japan) with a 44100 Hz sampling rate and 16-bit quantization that saved the samples onto a secure digital drive as uncompressed wave (.wav) sound files. These audio recordings were then further processed using Praat (Boersma & Weenink, 2005). A total of 885 tokens were initially selected, of which 825 were submitted for acoustic analysis after removing tokens that were not suitable for acoustic analysis due to the experimenter overlapping the child's speech, background noise or poor recording conditions, and nonfricative or affricate substitutions (such as stops or nasals). For fricatives, duration was measured from the point of frication emergence to the first glottal pulse of the following vowel. Rise time was defined as the time lapse from the beginning of frication to the point of maximum intensity. The measurement of duration and rise time is the same for affricate productions except that the beginning was marked as stop burst. To calculate centroid frequency, a middle 40-ms window was extracted from the frication noise of each fricative and affricate. The centroid frequency is the mean frequency of the Multitaper spectrum that was created on the basis of the 40-ms noise slice using the Multitaper package (Rahim, 2010) in R (R Development Core Team, 2011). Each Multitaper spectrum was high-pass filtered (above 1000 Hz) to eliminate potential low-frequency noise, such as wind blowing or door opening/closing. The whole procedure was automated, and the measurements were obtained through executing Praat and R scripts written by the first author.

Statistical Analysis

We performed repeated-measures analyses of variance (ANOVAs) for each language to determine the effects of bilingualism, CI use, and their interaction. Separate ANOVAs had to be conducted for each language because the data were not balanced: Three targeted fricatives/affricates were tested in English (/s/, /ʃ/, /tʃ/), and two were tested in Spanish (/s/ and /tʃ/). Comparisons were first conducted on the English language production across four child groups for each acoustic parameter: English production of bilingual children with CIs (CIBE), monolingual English-speaking children with CIs (CIME), bilingual children with NH

(NHBE), and monolingual English-speaking children with NH (NHME). The dependent variable was the acoustic parameter used (i.e., duration, rise time, or centroid frequency). The independent between-subjects variables were language status (monolingual vs. bilingual) and hearing status (NH vs. CIs). The independent within-subject variable was target fricative and affricates (/s/ vs. /ʃ/ vs. /tʃ/).

For each acoustic parameter, comparisons were then made on the Spanish language production between the two bilingual child groups: Spanish produced by bilingual children with CIs (CIBS) and Spanish produced by bilingual children with NH (NHBS). These comparisons would reveal the effect of CIs. For these models, the independent between-subjects variable was hearing status (NH vs. CIs), and the independent within-subject variable was target fricative and affricates (/s/ vs. /tʃ/). Last, for both groups of bilingual children (i.e., NH and CI), comparisons were made between their English and Spanish for the analogous sounds, /s/ and /tʃ/, for the establishment of language-specific phonological systems.

Results

Duration

English

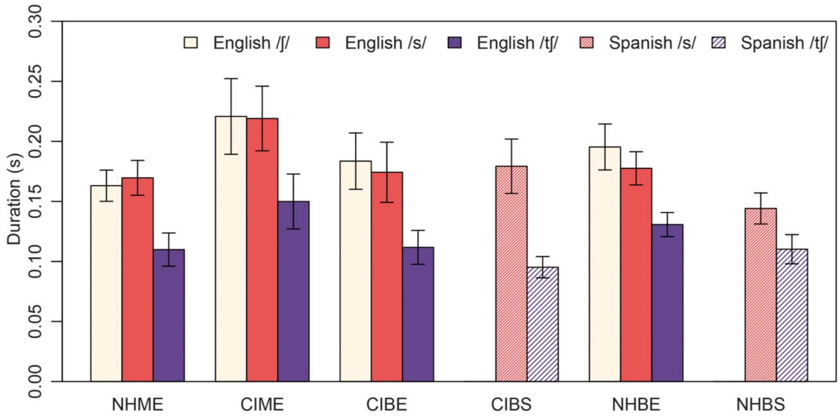
Table 4 lists the group averages and their respective standard deviations for the three acoustic parameters for children's English and Spanish productions, respectively. The group averages are also graphically displayed in Figures 1, 2, and 3. A three-way, repeated-measures ANOVA was conducted on four groups of children (CIBE, NHBE, CIME, and NHME) with language status (monolingual vs. bilingual) and hearing status (NH vs. CI) as between-subjects variables and target consonant (/s/ vs. /ʃ/ vs. /tʃ/) as the within-subject variable. A main effect of target consonant was found, $F(2, 96) = 44.0$, $p < .001$, partial $\eta^2 = .16$. Post hoc Tukey's honestly significant difference (HSD) test revealed a statistically significant difference between /s, ʃ/ and /tʃ/ ($p < .001$) but not between /s/ and /ʃ/ ($p > .05$). No interaction was found between target consonant and the other two variables, which indicated that all four groups of children separated the target consonants and in a similar fashion. The interaction between the two factors, language status and hearing status, was statistically significant, $F(1, 42) = 13.4$, $p < .001$, partial $\eta^2 = .06$. Post hoc Tukey's HSD tests indicated that the interaction was due to having a statistically significant difference between monolingual children with NH versus CIs ($p < .001$ for NHME vs. CIME) but no statistically significant difference between the two groups of bilingual children ($p = .14$ for CIBE vs. NHBE). Mean frication duration for each sound per group and language are displayed in Figure 1, from which it is clear that the durational patterns of all three consonants are comparable between children in the CIBE and NHBE groups, and duration is longer across the three consonants for CIME than for NHME group members.

Table 4. Means and standard deviations of the three acoustic parameters for each target consonant for the four groups of children in their English and Spanish, respectively.

Measurement	Group	English			Spanish	
		/ʃ/	/s/	/tʃ/	/s/	/tʃ/
Segment duration in seconds	Monolingual English-speaking children with NH (NHME)	0.164 (0.050)	0.170 (0.044)	0.109 (0.048)	N/A	N/A
	Monolingual English-speaking children with CIs (CIME)	0.221 (0.109)	0.215 (0.094)	0.150 (0.080)	N/A	N/A
	Spanish–English bilingual children with CIs (CIBE/CIBS)	0.177 (0.076)	0.168 (0.077)	0.107 (0.045)	0.179 (0.101)	0.095 (0.040)
	Spanish–English bilingual children with NH (NHBE/NHBS)	0.190 (0.088)	0.187 (0.066)	0.131 (0.045)	0.141 (0.060)	0.115 (0.058)
Rise time in seconds	Monolingual English-speaking children with NH (NHME)	0.141 (0.055)	0.123 (0.046)	0.069 (0.042)	N/A	N/A
	Monolingual English-speaking children with CIs (CIME)	0.158 (0.105)	0.144 (0.075)	0.098 (0.080)	N/A	N/A
	Spanish–English bilingual children with CIs (CIBE/CIBS)	0.121 (0.078)	0.131 (0.078)	0.066 (0.045)	0.130 (0.087)	0.062 (0.042)
	Spanish–English bilingual children with NH (NHBE/NHBS)	0.128 (0.061)	0.149 (0.080)	0.074 (0.041)	0.107 (0.058)	0.074 (0.057)
Spectral mean frequency in Hz	Monolingual English-speaking children with NH (NHME)	4728.1 (1103.6)	7176.2 (1017.7)	4927.3 (1225.5)	N/A	N/A
	Monolingual English-speaking children with CIs (CIME)	5589.7 (1297.9)	7286.2 (2331.0)	5209.9 (1536.5)	N/A	N/A
	Spanish–English bilingual children with CIs (CIBE/CIBS)	5864.8 (1298.1)	7267.1 (1825.8)	5678.6 (1355.3)	7244.6 (2029.6)	6004.3 (1397.9)
	Spanish–English bilingual children with NH (NHBE/NHBS)	5194.5 (1099.8)	7921.7 (1737.8)	5220.5 (1256.4)	8221.6 (2065.2)	5458.1 (1680.3)

Note. NH = normal hearing; CI = cochlear implants; N/A = not applicable.

Figure 1. Bar plot of mean frication duration (and standard error of the mean) for the three target consonants by language and group. NHME = monolingual English-speaking children with normal hearing; CIME = monolingual English-speaking children with cochlear implants; CIBE = English production of bilingual children with cochlear implants; CIBS = Spanish produced by bilingual children with cochlear implants; NHBE = English produced by bilingual children with normal hearing; NHBS = Spanish produced by bilingual children with normal hearing.



Spanish

A two-way, repeated-measures ANOVA was conducted for children's Spanish productions with hearing status (NH vs. CI) as the between-subjects variable and target consonants (/s/ vs. /tʃ/) as the within-subject variable. A main effect of target consonant was found, suggesting that children produced different frication durations for /s/ and /tʃ/, $F(1, 29) = 45.4$, $p < .001$, partial $\eta^2 = .13$. A statistically significant interaction between target consonant and hearing status, $F(1, 29) = 8.4$, $p = .007$, partial $\eta^2 = .03$, was also found. Figure 1 demonstrates the nature of this interaction: The two groups of children differ markedly in the duration of their /s/ production ($p = .04$ from post hoc Tukey's HSD test) with bilingual children with CI (CIBS) producing /s/ with longer duration than their peers with NH (NHBS).

Bilingual Children: English Versus Spanish Systems

Last, in order to find out whether or not CI use would affect how children acquired the two phonological systems, a repeated-measures ANOVA was conducted for the two groups of bilingual children (i.e., the bilingual CI group and the bilingual NH control group). The between-subjects variable was hearing status (NH vs. CI), and the within-subject variables were language (English vs. Spanish) and the target consonants (/s/ and /tʃ/) that occurred in both languages (albeit their language-specific characteristics may vary across the two languages). In a similar manner to what has been reported for each language, a statistically significant main effect of target consonant was found, $F(1, 28) = 63.9$, $p < .001$, partial $\eta^2 = .15$. The interaction between language and hearing status was also statistically significant, $F(1, 26) = 9.6$, $p = .005$, partial $\eta^2 = .01$. Although

Figure 2. Bar plot of mean frication rise time (and standard error of the mean) for the three target consonants by language and group. NHME = monolingual English-speaking children with normal hearing; CIME = monolingual English-speaking children with cochlear implants; CIBE = English production of bilingual children with cochlear implants; CIBS = Spanish produced by bilingual children with cochlear implants; NHBE = English produced by bilingual children with normal hearing; NHBS = Spanish produced by bilingual children with normal hearing.

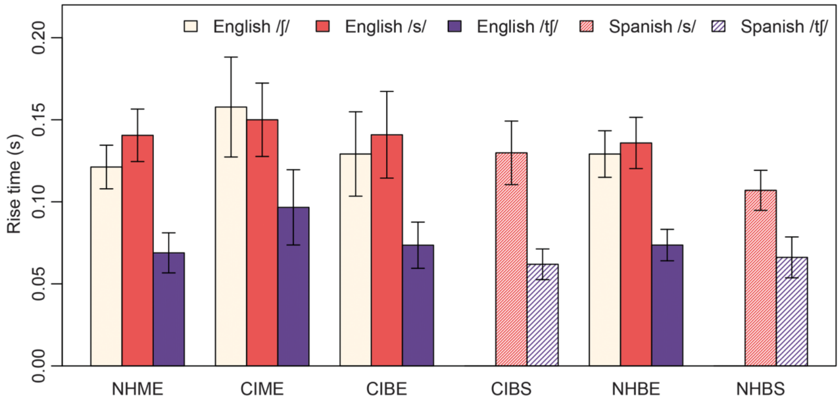
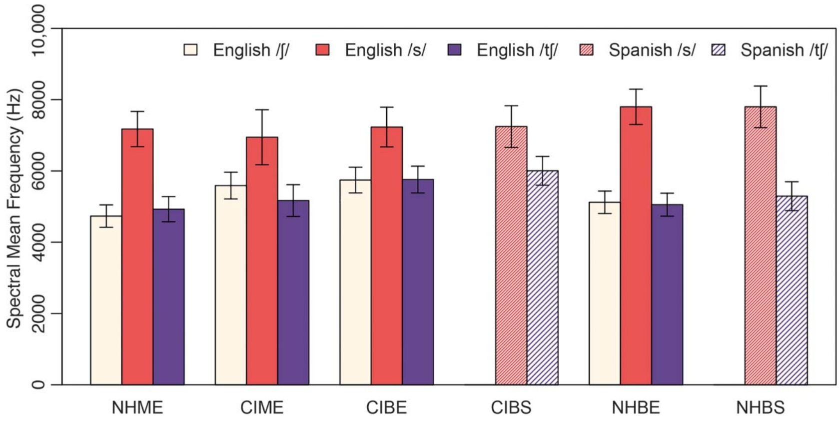


Figure 3. Bar plot of spectral mean frequency of the frication noise (and standard error of the mean) for the three target consonants by language and group. NHME = monolingual English-speaking children with normal hearing; CIME = monolingual English-speaking children with cochlear implants; CIBE = English production of bilingual children with cochlear implants; CIBS = Spanish produced by bilingual children with cochlear implants; NHBE = English produced by bilingual children with normal hearing; NHBS = Spanish produced by bilingual children with normal hearing.



the results indicated that having CIs may have affected the acquisition of the two languages in bilingual children, the effect size was quite small. In addition, a statistically significant interaction between hearing status and target consonant was found, $F(1, 28) = 4.6$, $p = .040$, partial $\eta^2 = .02$.

Table 4 reveals that fricative and affricate durations were, in general, shorter for bilingual children's Spanish productions than for their English productions. Furthermore, the Spanish duration values were especially lower for bilingual children with NH than those with CIs, particularly with respect to the sound /s/ ($p = .004$, Tukey's HSD test) but not for /tʃ/. This can be clearly viewed in Figure 1, which demonstrates that bilingual CI users produced English and Spanish /s/ and /tʃ/ similarly (i.e., CIBE and CIBS), and the bilingual NH group varied the duration in response to the specific language they spoke: They produced English fricative and affricates with longer durations than their Spanish analogs (i.e., NHBE vs. NHBS).

Rise Time

English

Results of the three-way, repeated-measures ANOVA (Target Consonant × Language Status × Hearing Status) revealed a statistically significant main effect of target consonant, $F(2, 96) = 41.1$, $p < .001$, partial $\eta^2 = .16$. Post hoc Tukey's HSD test suggested that children distinguished /s, ʃ/ from /tʃ/ ($p < .001$ for /s/ vs. /tʃ/ and $p < .001$ for /ʃ/ vs. /tʃ/) but did not distinguish /s/ and /ʃ/ ($p = .64$) with respect to rise time. Meanwhile, the interaction between language status and hearing status was also statistically significant but with a rather small effect size, $F(1, 42) = 4.4$, $p = .043$, partial $\eta^2 = .01$. As shown in Figure 2, the interaction could be attributed to the statistically significant difference between the two groups of monolingual children with and without CIs (CIME vs. NHME, $p = .03$). No such difference was found between CIBE and NHBE ($p > .05$), the two groups of bilingual children. This finding is similar to what has been found in the durational dimension of children's speech production.

Spanish

A two-way, repeated-measures ANOVA (Hearing Status × Target Consonant) for NHBS and CIBS revealed a statistically significant main effect of target consonant, $F(1, 29) = 41.1$, $p < .001$, partial $\eta^2 = .14$. The interaction between hearing status and target consonant was not statistically significant. These results suggest that children's Spanish fricative and affricate productions were not affected by bilingualism or CI use in the dimension of rise time.

Bilingual Children: English Versus Spanish Systems

A three-way, repeated-measures ANOVA (Hearing Status × Language × Target Consonant) showed a statistically significant main effect of target consonant, $F(1, 28) = 68.6$, $p < .001$, partial $\eta^2 = .18$, which indicated that both children with NH and those with CIs were able to differentiate /s/ and /tʃ/ in the two languages using rise time. Unlike the results in duration, the interaction between language and target consonant did not reach statistical significance ($p = .065$).

Spectral Mean Frequency

English

Results of a three-way, repeated-measures ANOVA (Target Consonant × Language Status × Hearing Status) revealed a main effect of target consonant, $F(2, 96) = 88.1$, $p < .001$, partial $\eta^2 = .29$, and a statistically significant interaction between hearing status and target consonant, $F(2, 96) = 4.7$, $p = .012$, partial $\eta^2 = .03$. As shown in Figure 3, the interaction effect was due to the differentiated ways of producing /s/ and /ʃ/ by children with CIs and their peers with NH (*p* = .003). In particular, the acoustic distance between /s/ and /ʃ/—as measured by spectral mean frequency—is reduced in children with CIs as compared with their peers with NH.

Figure 3 illustrates the reduced acoustic distance between /s/ and /ʃ/ (and between /s/ and /tʃ/) in the monolingual and bilingual children with CIs (CIME and CIBE) in comparison with monolingual and bilingual children with NH (NHME and NHBE). The distance ranged from about 1400 to 2000 Hz for children with CIs and 2500 to 2800 Hz for children with NH. Because spectral mean frequency is the primary acoustic correlate for place differentiation between alveolar and postalveolar fricatives and affricates (Forrest et al., 1988; Jongman et al., 2000; Nittrouer et al., 1989), these results indicate that although all groups of children display differences with respect to the spectral mean frequency of alveolar and postalveolar fricative/affricate, children with NH show clearer differentiation of place of articulation than their peers with CIs irrespective of monolingual or bilingual status.

The smaller acoustic distance between /s/ and /ʃ/ in children with CIs as compared with their peers with NH can also be viewed in Figures 4 and 5, respectively, that plot the spectral mean frequency values averaged over each child against children's duration of CI implantation or chronological age (for children with NH). In each figure, the best-fitted lines and 95% confidence intervals were overlaid on the scatterplot. These statistics were calculated on the basis of linear models fitted over children's data for each target consonant. For each linear model, the dependent variable was the averaged spectral mean frequency produced by each child for a specific consonant, and the independent variable was children's age in the case of children with NH or duration of CI use in the case of children with CIs.

Figure 5 demonstrates that monolingual and bilingual children with NH produce alveolar (i.e., /s/) and postalveolar (i.e., /ʃ/ and /tʃ/) obstruents in two parallel and nonoverlapping regions. This pattern suggests that the place distinction is robust when comparing across subjects. In contrast, as Figure 4 clearly illustrates, although the two groups of children with CIs produced /s/ versus /ʃ, tʃ/ in separate ranges, the 95% confidence interval bands partially overlapped, suggesting that the place distinction was not completely acquired when comparing across subjects. Therefore, even if children with CIs are able to distinguish the target fricative and affricates individually (see the repeated-measure ANOVA results reported earlier in this section), the distinction was not as robust at the group comparison level.

It is also important to note that no clear age-related changes were identified from Figure 4 and Figure 5. In Figure 5, the best-fitted lines stayed stable across the tested age range. In Figure 4, there seems to be a diverging pattern for /s/ and /ʃ, tʃ/, but no statistical significance was reached. The age-related differences in discriminating /s/ from /ʃ, tʃ/ were statistically verified using a multiple linear regression (dependent variable: spectral mean frequency; independent variables: duration of implantation, target consonant, and the interaction between the two factors). No statistically significant difference was found for the

Figure 4. Scatterplots of spectral mean frequencies of the three English target consonants (i.e., /s/, /ʃ/, and /tʃ/) as a function of children's chronological age produced by the two groups of children with cochlear implants: bilingual children (CIBE) and monolingual English-speaking children (CIME). Each data point represents the averaged spectral mean frequency value for a specific target consonant produced by a single child. Lines/dashed lines indicated the best-fitted lines for the regression models of each target. For each model, the dependent variable is spectral mean frequency and the independent variable is children's duration of cochlear implant use. Shaded bands indicate 95% confidence interval.

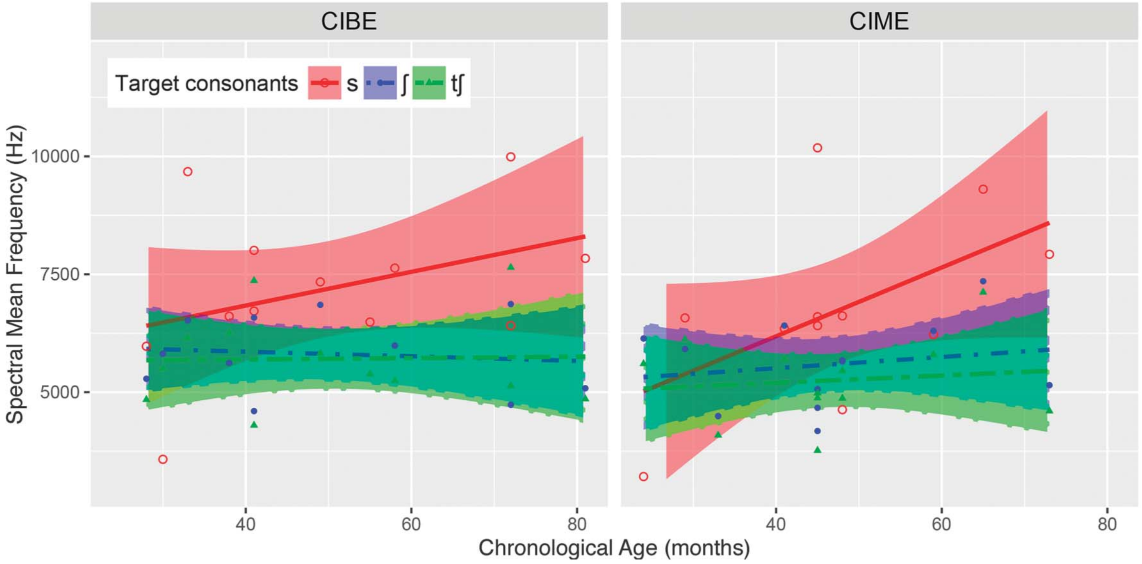
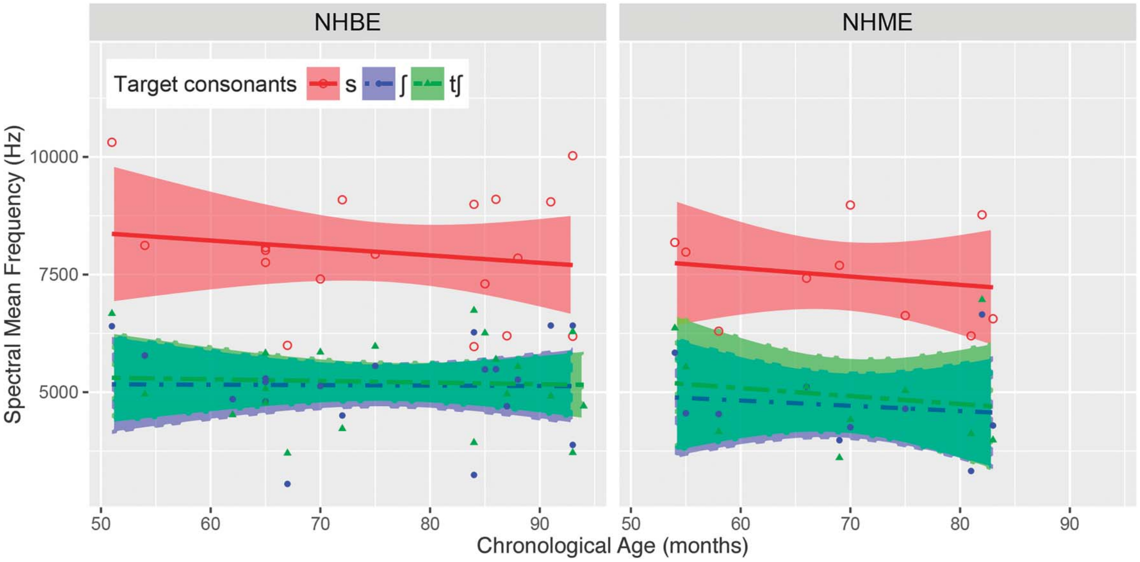


Figure 5. Scatterplots of spectral mean frequencies of the three English target consonants (i.e., /s/, /ʃ/, and /tʃ/) as a function of children's chronological age produced by the two groups of children with normal hearing: bilingual children (NHBE) and monolingual English-speaking children (NHME). Each data point represents the average spectral mean frequency value for a specific target consonant produced by a single child. Lines/dashed lines indicated the best-fitted lines for the regression models of each target. For each model, the dependent variable is spectral mean frequency, and the independent variable is children's chronological age (in months). Shaded bands indicate 95% confidence interval.



interaction for either monolingual or bilingual CI groups (*p* > .05 for CIME and CIBE for the place distinction between /s/ and /ʃ, tʃ/).

Spanish

Results of a two-way, repeated-measures ANOVA (Hearing Status × Target Consonant) on bilingual children's Spanish production revealed a statistically significant main effect of target consonant, $F(1, 29) = 65.7$, $p < .001$, partial $\eta^2 = .25$. Furthermore, a significant interaction between children's hearing status and target consonant was found, $F(1, 29) = 5.7$, $p = .024$, partial $\eta^2 = .04$. In a similar manner to the English results, it appears that bilingual children with NH produced a more robust distinction between the alveolar fricative and the postalveolar affricate than their bilingual peers with CIs. This result can be further substantiated by comparing the CIBS and NHBS groups in Figure 6, from which it is clear that the differentiation between /s/ and /tʃ/ in NHBS group members was more evident and extensive than in the CIBS group.

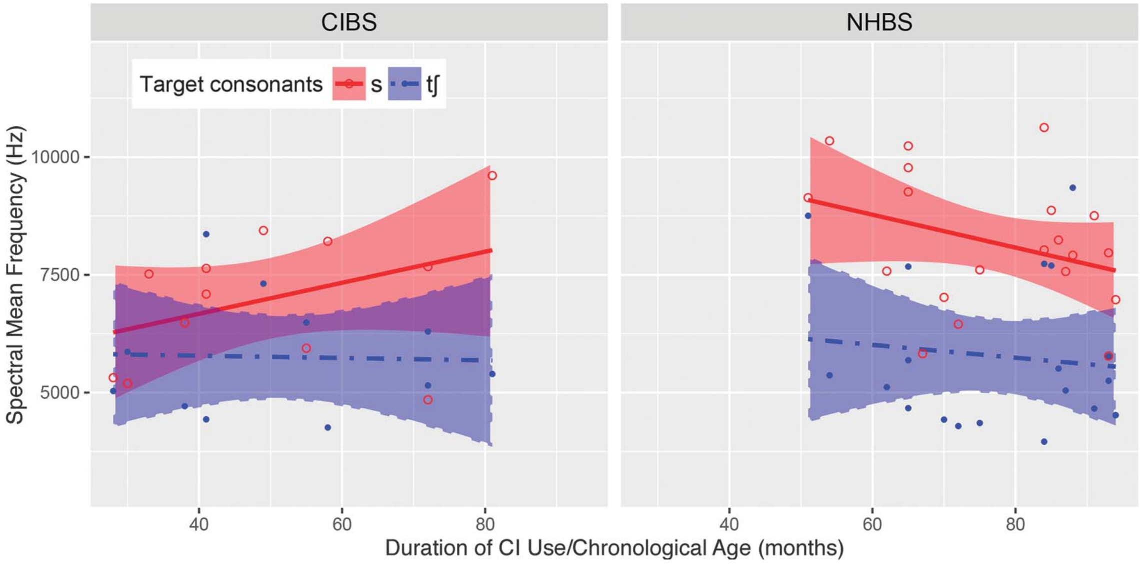
Bilingual Children: English Versus Spanish Systems

A three-way, repeated-measures ANOVA (Hearing Status × Language × Target Consonant) displayed a statistically significant interaction between hearing status and target consonant, $F(1, 28) = 115.6$, $p < .001$, partial $\eta^2 = .28$, which indicated that both children with NH and those with CIs were able to distinguish /s/ from /tʃ/ in English and Spanish. In addition, a statistically significant interaction effect between hearing status and target consonant, $F(1, 28) = 8.4$, $p = .007$, partial $\eta^2 = .03$, was found. Again, this interaction can be readily attributed to the reduced place contrast in children with CIs as compared with their peers with NH.

Discussion

The present study explored voiceless alveolar and postalveolar fricatives and affricates produced by bilingual Spanish- and English-speaking children with HL who used CIs, their bilingual peers with typical speech and language and NH, monolingual English-speaking children with HL who used CIs, and monolingual English-speaking children with typical speech and language and NH. According to our findings, both children with CIs and with NH who are bilingual Spanish–English speakers or monolingual English speakers could differentiate the target phonemes on the basis of frication duration, rise time, and frequency in each language (/s/, /ʃ/, and /tʃ/ in English and /s/ and /tʃ/ in Spanish). To be specific, duration and rise time were used reliably to differentiate fricatives from affricates in production, and so was centroid frequency for place distinction, but the latter yielded less categorical separation for children with CIs (monolingual or bilingual) than for children with NH. These findings indicate that CIs provide their users sufficient access to the speech signal so that these children—irrespective of whether they are bilingual or monolingual CI users—are able to differentiate phonemes using temporal (duration or rise time of fricatives vs. affricates) and frequency (alveolar or postalveolar)

Figure 6. Scatterplots of spectral mean frequencies of the two Spanish target consonants (i.e., /s/ and /tʃ/) as a function of children's chronological age produced by the two groups of bilingual children: children with normal hearing (NHBS) and children with cochlear implants (CIBS). Each data point represents the average spectral mean frequency value for a specific target consonant produced by a single child. Lines/dashed lines indicated the best-fitted lines for the regression models of each target. For each model, the dependent variable is spectral mean frequency, and the independent variable is children's chronological age (for NHBS) or their duration of cochlear implant use (for CIBS). Shaded bands indicate 95% confidence interval.



cues. These results are consistent with existing studies that found that children with CIs can have phonological skills commensurate with those of their peers with NH when matching the chronological age of children with NH to the duration of device use for children with CIs (Flipsen, 2011). Nevertheless, our results also indicated that for children with CIs, the robustness of the temporal cues (duration and rise time) yielded more reliable differentiation of the fricative–affricate dimension than the frequency cue (centroid frequency), distinguishing place of articulation.

On the basis of our findings, duration and rise time had larger effect sizes than centroid frequency, and the latter cue was used more reliably by children with NH than by children with CIs (see Table 4 and Figures 1, 2, 3, and 4). These results are in line with research indicating that differentiating fricative place of articulation that is reliant on relatively good frequency discrimination dependent on spectral cues is challenging for children who use CIs (Liker et al., 2007; Mildner & Liker, 2008; Peng et al., 2008; Todd et al., 2011). However, phonemic distinctions that rely on temporal cues—such as stop voice onset time—prove relatively less challenging for young CI users who are monolingual (cf. Caldwell & Nittrouer, 2013; Giezen, Escudero, & Baker, 2010; Uchanski & Geers, 2003) or bilingual (cf. Bunta, Goodin-Mayeda, et al., 2016).

Our data also indicate an interaction between bilingualism and the diminished speech signal provided by the CI. To be specific, bilingual children with NH outperformed their peers with CIs on using centroid frequency as a cue for place differentiation, but bilingual children with CIs displayed more robust separation using duration as a manner cue for Spanish. Furthermore, bilingual children with NH but not with CIs used duration differently in their English versus Spanish productions, showing less differentiation in Spanish than in English for manner along friction duration and rise time. In other words, although bilingual children with NH are better able to use frequency as a cue for obstruent place discrimination, their bilingual peers with CIs maintain better separation of their Spanish /s/ and /tʃ/ along the duration dimension (a temporal cue). The fact that bilingual children with CIs maintain more separation in Spanish of their fricative versus affricate duration could be due to the fact that bilingual children with CIs who participated in this study received speech and language support in both Spanish and English, potentially leading to better maintenance of Spanish than their peers with NH. Furthermore, bilingual Spanish- and English-speaking children in the United States with NH are typically more exposed to Spanish in their early years, but as time progresses, their exposure shifts more to English (cf. Rojas et al., 2015), which may have contributed to our findings.

The better separation of /s/ and /tʃ/ produced by bilingual children with CIs may also be attributed to the greater influence of English that they are exposed to, possibly through the intensive speech and language intervention, a considerable amount of which is in English. It is possible that the separation between Spanish /s/ and /tʃ/ is indeed smaller than the analogous pair of phonemes in English because these phonemes are contrasted in both the temporal and the frequency domains in Spanish due to the lack of a postalveolar fricative. Therefore, unlike English, which has the phoneme /ʃ/ that demands separation from /s/ in the frequency domain and from /tʃ/ in the temporal domain, the combination of both acoustic cues in differentiating Spanish /s/ and /tʃ/ could allow for some degree of reduced contrast in either dimension.

We also found that monolingual English-speaking children with CIs tend to produce longer English /ʃ/ than their bilingual peers with CIs. This finding echoes the results reported in Bunta, DiLuca, and Branum-Martin (2011), who investigated the fricative and affricate productions of bilingual Spanish- and English-speaking children and their monolingual peers with NH. Although their findings were similar to the results of our present study, such a difference in /ʃ/ duration only reached statistical significance in selected words. Nevertheless, the pattern attested in the Bunta et al. (2011) study was similar to ours in that monolingual children exhibited longer frication duration than their bilingual peers regarding their English /ʃ/. Together, these results suggest that effects of bilingualism are attested in both children with CIs and their peers with NH.

Regarding the issue of establishing separate phonological representations for the alveolar and postalveolar obstruents in Spanish and English by bilingual children with CIs, a more complex and complete picture emerges than attested in previous work. Regarding initial stop consonants, Bunta, Goodin-Mayeda, et al. (2016) found that, similar to bilingual children with NH, bilingual Spanish- and English-speaking children with CIs not only differentiated voiced and voiceless stops in their target languages, but they did so differentially across those languages, suggesting language separation. In the present study, it became evident that bilingual children with CIs were able to distinguish fricatives and affricates in their productions of both English and Spanish. However, there was no clear evidence that these children produced the two languages differentially. Unlike bilingual children with NH who varied the durational patterns depending on the language they spoke (i.e., longer durations for English [NHBE] and shorter durations for Spanish [NHBS]), bilingual children with CIs produced the two languages in a similar manner (i.e., comparable durations in CIBE and CIBS). This lack of language specificity could be due to the intensive English therapy that bilingual children with CI received as discussed earlier. As an alternative, this result of not separating the two languages may suggest an incomplete formation of separate phonological systems as a result of delayed language acquisition onset caused by HL, which is further complicated by the challenge of utilizing spectral cues (instead of temporal cues) for separating the two languages.

Clinical Implications

Our study contributes to the current knowledge base of speech production skills of bilingual and monolingual children with HL who use CIs as well as their peers with NH. The findings of our study indicate that there is a complex interplay between bilingualism and phonological acquisition with a diminished signal provided by the CI. One of the most important clinical implications of our article is that learning two spoken languages simultaneously does not pose an insurmountable challenge to children with HL who use CIs, a finding that is consistent with existing studies (Guiberson, 2014; Thomas, El-Kashlan, & Zwolan, 2008; Waltzman, McConkey Robbins, Green, & Cohen, 2003). It is clear from our findings that when it comes to children's productions of voiceless alveolar and postalveolar fricatives and affricates, there are differences on the basis of language status (monolingual vs. bilingual) and CI use versus NH. However, our results also indicate that despite language status or CI use, friction duration, rise time, and spectral mean frequency are used reliably to differentiate voiceless alveolar and postalveolar fricatives and affricates.

Another important result that has potential clinical implications is that bilingual children with HL who use CIs display better separation of their Spanish alveolar fricative and the postalveolar affricate along the temporal (duration) dimension than their bilingual peers with NH. The children with HL and CIs who participated in our study received systematic support in both Spanish and English, which may have contributed to better Spanish language maintenance despite the HL. In fact, supporting the home language can have beneficial effects on the other language. Bunta, Douglas, et al. (2016) compared the language skills of two groups of bilingual children with HL who used CIs (one with Spanish and English support and the other with English-only support) and found that bilingual children with CIs who had dual language support outperformed their bilingual peers with CIs with English-only support on English language measures. Furthermore, Bunta and Douglas (2013) found that bilingual children who used CIs and received dual language support matched the language skills of their monolingual English-speaking peers with CIs. Thus, reinforcing the home language—if there is family support—can have beneficial effects not only for the maintenance of the native language, but those advantages can extend to and support the development of the language of the majority culture (in our case, English).

Limitations

Although offering novel insights into speech production patterns and phonological skills of bilingual children with CIs, their bilingual peers with NH, monolingual English-speaking CI users, and monolingual English-speaking children with NH, the present study has limitations. Our study has only 54 participants, which is not a small sample size compared with other studies focusing on the phonological skills of children with CIs, but such a sample size is still relatively small for drawing definitive conclusions, so larger sample sizes would be desirable. In addition, our data only include elicited single words, so more tokens using more varied techniques (such as both elicited and spontaneous items) would provide more robust data. In addition, having a group of monolingual Spanish-speaking children with CIs and one with Spanish-speaking children with NH would make future studies better rounded—something that was beyond the scope of the present research.

In order to keep the study focused and allow for specific cross-language comparisons, we limited our analyses to voiceless alveolar and postalveolar fricatives and affricates. Future studies need to be conducted on a variety of other segmental and suprasegmental phenomena to further investigate the effects of the CI signal, bilingual spoken language acquisition, and their interaction on the phonological patterns and development of bilingual children with HL who use CIs. As new data and further analyses become available on the speech and language patterns of bilingual children with CIs, a more complete picture will emerge that will inform speech-language pathologists, audiologists, educators, and parents to help them understand and develop strategies for enabling this population to reach its maximum potential.

Conclusion

When it comes to alveolar and postalveolar fricative and affricate production by bilingual children who use CIs, a complex picture emerges displaying a tapestry of speech production patterns that indicate a combination of our participants' ability to construct phonological systems with diminished auditory signal and to do so in both languages showing effects of bilingualism as well as the implant and an interaction thereof. Although our data indicate that acquiring the phonological systems of two spoken languages with a CI do not yield identical patterns to the ones attested in peers with NH, bilingual children with CIs learning spoken Spanish and English simultaneously display differentiation of their voiceless alveolar and postalveolar fricatives and affricates in both languages and are able to use them distinctly. Furthermore, the additional dual language support given to bilingual children may have benefits that extend to both the home language and the language of the majority culture. These and other issues demand further investigation in order to obtain a complete picture of phonological development in bilingual children who use CIs and at the same time move our field forward by providing data for theoretical research as well as information for practicing clinicians who work with bilingual children with HL and their peers with NH.

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