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Research Article

Initial Stop Voicing in Bilingual Children With Cochlear Implants and Their Typically Developing Peers With Normal Hearing

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Purpose: This study focuses on stop voicing differentiation in bilingual children with normal hearing (NH) and their bilingual peers with hearing loss who use cochlear implants (CIs).
Method: Twenty-two bilingual children participated in our study (11 with NH, *M* age = 5;1 [years;months], and 11 with CIs, *M* hearing age = 5;1). The groups were matched on hearing age and a range of demographic variables. Single-word picture elicitation was used with word-initial singleton stop consonants. Repeated measures analyses of variance with three within-subject factors (language, stop voicing, and stop place of articulation) and one between-subjects factor (NH vs. CI user) were conducted with voice onset time and percentage of prevoiced stops as dependent variables.
Results: Main effects were statistically significant for language, stop voicing, and stop place of articulation on both voice onset time and prevoicing. There were no significant main effects for NH versus CI groups. Both children with NH and with CIs differentiated stop voicing in their languages and by stop place of articulation. Stop voicing differentiation was commensurate across the groups of children with NH versus CIs.
Conclusions: Stop voicing differentiation is accomplished in a similar fashion by bilingual children with NH and CIs, and both groups differentiate stop voicing in a language-specific fashion.

Research on phonological development in monolingual children with cochlear implants (CIs) has found both similarities to and differences from their peers with normal hearing (NH; cf. Blamey, Barry, & Jacq, 2001; Chin, 2003; Ertmer & Goffman, 2011; Flipsen, 2011; Flipsen & Parker, 2008; Ingram, McCartney, & Bunta, 2001; Serry & Blamey, 1999). This is not surprising considering that children with CIs have hearing loss before their implant is activated and because the CI signal differs qualitatively from the sound sensation individuals with NH experience. Nevertheless, the CI does provide its user access to sound—even if qualitatively distinct from what children with NH hear—that promotes speech and language development. The aspects of phonology and speech that develop more readily in children with CIs are at least partially dependent on what the device can transmit well. For example, Caldwell and Nittrouer (2013) note that CIs transmit temporal aspects of speech relatively well; consequently, voice onset time (VOT)—and by extension, stop voicing—presents an opportunity to test how well children with CIs can form phonemic categories. Giezen, Escudero, and Baker (2010) found that Dutch children with CIs differentiate stop voicing contrasts (/bu/ vs. /pu/) better than other phonemic contrasts (/fu/ vs. /su/). However, production data for stop voicing differentiation involving children with CIs are less clear in that some studies find that children with CIs produce stop VOT values within the range produced by typically developing peers (e.g., Uchanski & Geers, 2003), whereas other studies indicate that stop voicing distinctions can be acquired by children with CIs but with VOT values that are outside the typical range (Bharadwaj & Graves, 2008).

For bilingual children with CIs, phonological acquisition has an added level of complexity by virtue of having to acquire the sound systems of two languages. Contrasts that may appear analogous on the surface (such as /p/ vs. /b/ in Spanish and English) may, in fact, have divergent representations as well as different acoustic cues across the two languages. Across languages, the voicing contrast for stops may differ in significant ways (cf. Lisker & Abramson, 1964) that could pose challenges even for typically developing

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young children (e.g., Fabiano-Smith & Bunta, 2012), an issue that may be exacerbated by hearing loss and the use of a diminished signal available via the CI. The present study addresses this complex problem and fills a gap in our current knowledge by investigating the production of stop voicing contrasts by Spanish- and English-speaking bilingual children who use CIs as compared with their typically developing bilingual peers with NH.

VOT, the time interval between the burst of a stop consonant and the beginning of voicing of the following sound, has been identified as a primary acoustic cue in differentiating voiced from voiceless stop consonants in word-initial singleton position across a number of languages (Lisker & Abramson, 1964). As a measurement of duration, VOT can be divided into three categories: prevoicing (lead voicing), short lag, and long lag. Typically, stops that have voicing during the gap preceding the burst are considered prevoiced, stops with a VOT duration between 0 and 20 ms are considered to fall within the short-lag category, and stops whose VOT duration exceeds 40 ms are labeled as having long lag (Kewley-Port & Preston, 1974).

It is more common for languages to make voicing distinctions along two VOT categories rather than all three; however, languages differ with regard to which VOT categories distinguish voiced and voiceless stops (Lisker & Abramson, 1964). For example, languages such as English and German have two categories: voiced stop consonants that fall within the short-lag range, /b d g/, and their voiceless stop consonant counterparts, /p t k/, which fall within the long-lag range in initial, single-onset position. In contrast, languages such as Spanish, Italian, and French also have voiced and voiceless stop categories, but voiced stops in the initial position fall within the prevoiced range, whereas voiceless stops fall within the short-lag range (Lisker & Abramson, 1964). Thus, short-lag VOT corresponds to voiced stops in languages such as English but voiceless stops in languages such as Spanish. These conflicting acoustic cues from two different languages could be problematic if, for example, a bilingual Spanish-English speaking child were to produce a short-lag VOT for the English /p/, which might, in turn, be perceived by an English speaker as a /b/, thus causing the child's production of the English word "pat" to be perceived as "bat" by a monolingual English speaker.

Acquisition of Voiced and Voiceless Stops by Typically Developing Monolingual Children

Typically developing English-speaking children are expected to have acquired /p/, /b/, and /d/ before 3 years of age and the remaining stop consonants /t/, /k/, and /g/ by about age 5;6 (years;months) (Shriberg, 1993). Sander (1972) obtained similar results in that 90% of children acquired /p/ by 3 years of age; /b/, /k/, /g/, and /d/ by 4 years of age; and /t/ by 6 years of age. In a longitudinal study of three typically developing monolingual English-speaking children, Kewley-Port and Preston (1974) found inconsistent and nonadultlike VOT productions even at age 4;6. Eventually, children began to produce alveolar stops with short-lag durations only, merging the voiced and voiceless stops. By age 4;6, children produced only /d/ with adultlike values in the short-lag category, and the VOT values of /t/ were still inconsistent. The authors suggested that because both the voiced and voiceless stops were within the short-lag category first during development, the short-lag duration was easier to produce (Kewley-Port & Preston, 1974).

Macken and Barton (1980a) identified three distinct stages of acquisition of the voiced versus voiceless stop contrast in English, using VOT measurements that were based on a longitudinal study of the speech samples of four typically developing English-speaking children from the time they were approximately a year and a half old until age 2;2. In the first stage, children produced all voiced and voiceless stops within the short-lag VOT category, showing no distinction between voiced and voiceless stops. In the second stage, the children began to show a contrast between voiced and voiceless stop consonants, but the phonemes still displayed short-lag VOT durations. In other words, the children's production of each category was different from the other, but the VOT values were not yet adultlike. Finally, by approximately age 2;0, children achieved an adultlike voicing contrast. Note that these results differ from those of Kewley-Port and Preston (1974) in terms of the age at which children produced adultlike VOT values (i.e., mastery of VOT by 2;2 found in Macken & Barton, 1980a, as opposed to beyond 4;6 in Kewley-Port & Preston, 1974).

In a subsequent study, Macken and Barton (1980b) investigated typically developing, monolingual Spanish-speaking children's production of the voicing contrast between the short-lag stops /p, t, k/ and the prevoiced stops /b, d, g/ as well as the continuant allophones of the latter, [β, ð, ɣ], also referred to as spirants or fricatives. Although spirantization is gradient, and the process depends on a variety of factors such as speech rate, register, and dialectal variation, the distribution of continuant and noncontinuant allophones as described by Harris (1984) is generally accepted among Spanish phonologists: [b, d, g] occur in utterance-initial position and after nasals and [d] also occurs after /l/, whereas [β, ð, ɣ] occur elsewhere. Macken and Barton (1980b) reported that typically developing Spanish-speaking children, similarly to their English-speaking peers, acquired short-lag stops first. However, unlike English-speaking participants, the Spanish participants did not appear to produce adultlike VOT values for the prevoiced stops, even by age 4. At 4 years old, only two of the six children in the study produced adultlike VOT values for prevoiced stops and even then, only at the bilabial place of articulation. Instead, spirantization appeared to be a more reliable indicator of Spanish-speaking children's acquisition of the stop voicing contrast because children produced adultlike VOTs for /p, t, k/ and spirants for voiced /b, d, g/, even in contexts in which traditional descriptions of Spanish predict noncontinuant allophones, such as utterance initially. This is not surprising in light of the fact that the continuant allophones occur considerably more frequently in adult speech than their noncontinuant counterparts due to wider distribution (Barlow, 2003; Macken & Barton, 1980b). For example, upon examination of the adult experimenters in the study, Macken and Barton (1980b) found that even adults produced continuants utterance initially up to 40% of the time.

Fabiano-Smith and Goldstein (2010a) investigated acquisition patterns of monolingual Spanish-speaking children and outlined a list of early-, middle-, and late-developing phonemes in Spanish. Unlike in English, /t/ and /k/ seem to be early-acquired phonemes in Spanish, whereas /p/ and the allophonic variations of /b/ and /g/ are middle-acquired phonemes, with the allophonic variation of /d/ listed as a late-acquired phoneme in Spanish. It is important to note that the authors accepted the continuant allophones for /b/, /g/, and /d/ as correct wherever their production was appropriate. However, Jimenez (1987) reported that monolingual Spanish-speaking children mastered /p/, /b/, and /t/ by age 3;3, /k/ by age 3;7, and /d/ and /g/ by age 4;7. Thus, although these two studies are in accord regarding the early acquisition of the phonemes /p/, /b/, and /t/ relative to /d/, they propose different timing for the acquisition of /g/.

Acquisition of Voiced and Voiceless Stops by Typically Developing Bilingual Children

Because bilingual children are acquiring two phonological systems and receive potentially conflicting input from Spanish and English when it comes to initial stop VOT, bilingual phonological development differs from that of monolingual. Paradis and Genesee (1996) proposed three phenomena unique to bilingual language development: transfer, delay, and acceleration. Fabiano-Smith and Goldstein (2010b) have since applied these notions to bilingual phonological development and also have opted for the term *deceleration* rather than *delay* in order to avoid the connotation of impairment. *Transfer* refers to the application of the rules of one language to another (Fabiano-Smith & Goldstein, 2010b; Paradis & Genesee, 1996).

Kehoe, Lleó, and Rakow (2004) found examples of transfer in a study of four German-Spanish bilingual children between 2 and 3 years of age. In one case, a child produced German voiced consonants (/b d g/) with lead voicing (as in Spanish) instead of short-lag voicing, which would be expected in German. In contrast, another child produced Spanish voiceless stops with long-lag VOT, an example of transfer from German to Spanish. The authors suggested that transfer was likely related to the amount of contact a child had with a given language; the language with which the child had more contact was likely to transfer to the language with which the child had less contact (Kehoe et al., 2004).

In contrast to transfer, *deceleration* and *acceleration* refer to the rate of development of one phonological system as a result of the influence of the other (Fabiano-Smith & Goldstein, 2010b; Paradis & Genesee, 1996). Deceleration in bilingual children describes a relatively slower rate of acquisition than that of monolingual peers as a result of interaction with another language. Fabiano-Smith and Bunta (2012) compared VOTs of /p/ and /k/ between monolingual English speakers and bilingual Spanish-English speaking peers. The bilingual speakers produced English /p/ and /k/ within the long-lag category but with shorter than typical values as compared with their monolingual English-speaking peers. In this instance, the influence of Spanish may have slowed the acquisition of the voicing contrast in English for the bilingual speakers (Fabiano-Smith & Bunta, 2012). Procter, Bunta, and Aghara (2015) also reported similar results among monolingual English, monolingual Spanish, and bilingual Spanish-English speaking children on the acquisition of voiced and voiceless stop consonants. Evidence of deceleration was found in the English productions of bilingual speakers on /b/, /p/, and /g/. Specifically, /b/ and /p/ were produced with the expected lag ranges: short and long, respectively. However, the mean durations of both /b/ and /p/ were significantly shorter than the values of monolingual English-speaking peers. We found it interesting that the English productions of /g/ by bilingual speakers were produced with VOT values significantly longer than those of monolingual speakers and outside the typical range. The findings for the exaggerated [g] productions may indicate an effort on the part of the bilingual speakers to differentiate the English and Spanish /g/ phonemes in an extreme way (Procter et al., 2015). Similar to the findings of Fabiano-Smith and Bunta (2012), evidence of deceleration was reported in bilingual speakers' English productions of stops, specifically /b/, /p/, and /g/, due to the influence of Spanish phonological development.

Acceleration, an increased rate of acquisition of a phonological structure as a result of the interaction between two language systems as compared to the rate of acquisition of the same structure in monolingual children, has also been attested in bilinguals (Fabiano-Smith & Goldstein, 2010b; Paradis & Genesee, 1996). For example, Lleó, Kuchenbrandt, Kehoe, and Trujillo (2003) reported that German-Spanish bilingual children acquired codas in Spanish faster than Spanish monolingual peers because the acquisition of codas occurred earlier and at a faster rate in German than in Spanish.

Fabiano-Smith and Goldstein (2010b) proposed a variation on the notion of acceleration that allowed the rate of development in bilingual children to be within the range of monolingual development, even though bilingual children were learning two language systems. This study compared bilingual Spanish-English speaking children with monolingual Spanish- and English-speaking peers on accuracy of speech sounds. The authors found evidence of transfer, deceleration, and a variation of acceleration in the speech productions of the participants. Transfer was evident in some of the stop productions in English of two bilingual participants in that some word-initial /t/ and /k/ productions were unaspirated. The authors also found evidence of deceleration in the accuracy of production, for example, in bilingual children's production of Spanish fricatives, glides, and the trill. In addition, bilingual children's production of English stops and fricatives were less accurate than those of their English-speaking monolingual peers. These same participants fell within typical monolingual limits for production of other sound classes in both English and Spanish. In sum, the authors discussed the probability that all three types of phenomena could occur throughout a bilingual child's phonological development including the variation of acceleration that the authors postulate (Fabiano-Smith & Goldstein, 2010b).

Voiced and Voiceless Stop Production by CI Users

Hearing loss in children could delay phonological development due to limited access to the speech signal and self-hearing (Blamey et al., 2001; Chin, 2003; Serry & Blamey, 1999). Factors known to influence the speech pattern of a child with a CI include age of implantation, duration of device use, the communication mode used after implantation (oral vs. total language), and others (cf. Ertmer, 2007; Miyamoto, Kirk, Svirsky, & Sehgal, 1999). Even when controlling for some of these factors, CI users may still display differences in phonological acquisition compared with typically developing peers with NH (Blamey et al., 2001; Chin, 2003; Serry & Blamey, 1999).

Monolingual children with hearing loss may experience difficulty contrasting voiced and voiceless stop consonants even without the effects of bilingualism. In terms of timing of acquisition, studies show that /t/, /k/, and /g/ are problematic for CI users and may still be undergoing development 5–6 years postimplantation (Blamey et al., 2001; Chin, 2003; Serry & Blamey, 1999). These sound segments are often substituted with other sounds, English and non-English alike, by monolingual English-speaking CI users (Chin, 2003).

Bharadwaj and Graves (2008) analyzed the VOT durations of /t/ and /d/ produced by 10 monolingual prelingually deaf English CI users between the ages of 7 and 16 years. Five of the 10 participants produced mean VOT values outside the typical ranges as compared with age-matched typically developing peers with NH. Specifically, two participants showed longer than average VOT values for /t/, whereas another displayed longer than average VOT values for /d/. A fourth participant demonstrated longer than average values for /t/ with VOT durations for /d/ falling within the long-lag range instead of the short-lag range, and a fifth participant produced longer than average lag voicing for /t/ but lead voicing for /d/. Thus, this study provides evidence for widely varied results in VOT production by CI users. In contrast, Uchanski and Geers (2003) found more homogeneous results in a study of 181 8- and 9-year-old monolingual English-speaking children with CIs. The participants in the study consisted of 89 children with CIs in total communication classrooms and 92 children with CIs in oral communication classrooms. The authors found that 62% of total communication participants and 85% of oral communication participants produced /t/ with average VOT durations within typical limits. The average VOT durations of /d/ were within typical limits for 79% of total-communication participants and 88% of oral communication participants.

To date, very little research has been conducted on the phonological development of monolingual Spanish-speaking children with CIs (Moore, Prath, & Arietta, 2006); however, there are data available from languages similar to Spanish in terms of VOT. Croatian, like Spanish, has prevoiced VOT durations for voiced stops and short-lag durations for voiceless stops (Smiljanic & Bradlow, 2008). Horga and Liker (2006) compared samples of acoustic measures, including VOT of /t/ and /d/, of 10 monolingual Croatian children with CIs with age-matched peers with hearing aids and typically developing children with NH. The results indicated that children with CIs and those with hearing aids did not contrast the VOT values of /t/ and /d/, and although the VOT durations were not significantly different between the two groups of children with hearing loss, the authors reported that pronunciation and voice quality of the CI users were perceived as better than those of the children who used hearing aids. It is important to note that the CI users in this study were implanted between 3;11 and 11;11 years of age (chronological ages 9;7 to 15;2) with age at start of rehabilitation reported anywhere from 2;11 to 7;8 years. It is likely that the large range of implantation age, considerable chronological age range, and age at start of rehabilitation may have affected the results of the study.

Research on the development of a voicing contrast in monolingual children with CIs has led to varying results, necessitating further research in the field. In addition, the effects of bilingualism on children with CIs in terms of stop voicing differentiation are unknown. The present study focuses on the production of initial voiced and voiceless stops by bilingual children with CIs and their bilingual peers with typical language and NH to investigate the effects of acquiring two spoken languages via a CI on phonemic category differentiation.

Research Questions and Hypotheses

The research questions of the present study are as follows: Do bilingual Spanish- and English-speaking children with CIs differentiate initial voiced and voiceless stops in a similar fashion to their bilingual peers with NH? In particular, do bilingual children with CIs and with NH show distinct stop voicing patterns in Spanish versus English, and is there an interaction between type of hearing (CI versus NH) and stop voicing by language? On the basis of previous research reviewed in the introduction, we propose the following hypotheses:

1. Bilingual children with NH will have separate voiced and voiceless initial stop categories in each of their languages, and those patterns will differ on the basis of the language spoken.
2. We adopt the null hypothesis for stop differentiation produced by bilingual children with CIs because we do not yet know whether bilingual children with CIs can reliably produce distinct initial voiced and voiceless stops in their languages, and the results of studies on stop differentiation in monolingual children

with CIs were inconclusive (cf. Bharadwaj & Graves, 2008, vs. Uchanski & Geers, 2003).

3. We also posit the null hypothesis regarding group differences between bilingual children with CIs versus their peers with NH because as Caldwell and Nittrouer (2013) note, VOT can be conveyed well via the device, but as reviewed in previous paragraphs, children with CIs may display delay in some aspects of language relative to their peers with NH. Thus, it is not known whether bilingual children with CIs will produce stop voicing contrasts in a similar fashion to their peers with NH due to the perceptual salience of the contrast or whether there will be differences due to hearing loss.

Method

Participants

Twenty-two bilingual Spanish- and English-speaking children participated in our study; half had typical speech and language and NH, and the other half had hearing loss and used CIs. Approval for this study was obtained from the institutional review board of the University of Houston. All the participants provided written or verbal assent, and their parents provided consent to taking part in the study prior to the commencement of data collection. Parents also completed a detailed questionnaire about their child's background relevant to evaluating the speech and language skills of their children (such as demographic information as well as hearing and language background).

Participants for the present study were selected from a larger database at the University of Houston that includes samples from bilingual Spanish- and English-speaking children with hearing loss who use CIs, bilingual children with NH, and monolingual English-speaking children with hearing loss who use CIs. Participants for this study had to meet the following selection criteria:

- be current bilingual Spanish-English speakers (i.e., actively use both languages);
- be able to communicate orally (understand and speak) in both languages;
- use each language at least 20% of the time on the basis of parental estimates;
- be exposed to both languages before 3 years of age;
- have at least 3 years of exposure to both languages;
- have no concerns or diagnoses of cognitive disorders;
- have no speech or language issues other than related to hearing loss for CI users;
- be between the ages of 4;3 and 6;1 (hearing age); and
- have a speech production sample that is based on a single-word picture elicitation task with the word-initial target stop consonants.

Besides our specific selection criteria listed above, the children in the two groups were matched as closely as possible on demographic and language background variables, such as hearing age, language exposure, and socioeconomic status. Furthermore, all participants and their families resided in the same metropolitan area (Houston, TX). Tables 1 and 2 display information about the participants' background. Additional criteria for each group are listed by group in the following sections.

Children With Typical Speech and Language and Normal Hearing

Eleven of the participants had NH and typical speech and language on the basis of passing a pure-tone hearing screening at 500, 1000, 2000, and 4000 Hz at 25 dB HL and passed the chronological age–appropriate level of the bilingual version of the Preschool Language Scales–Fifth edition (Zimmerman, Steiner, & Pond, 2012). These measures were taken to ensure that children with NH had hearing within normal limits and no speech or language issues (i.e., typically developing auditory comprehension and expressive language). Children with NH had a mean age of 5;1 (*SD* = 6.28 months), and all but three were born in the United States and were exposed to both Spanish and English from an early age. One child arrived in the United States at 5 months of age, one at 1;9, and the latest arrival at 2;6. The dialect of Spanish spoken at home was Mexican for six of the 11 children, two spoke a Cuban variant, one Colombian, and two Salvadoran. Participants were recruited from the greater metropolitan Houston, TX, area.

Children With Hearing Loss Using CIs

There were 11 bilingual Spanish- and English-speaking participants with hearing loss who used CIs; their mean hearing age was 5;1 (*SD* = 8.26 months, matching participants in the other group), and their mean chronological age was 6;7 (*SD* = 8.26 months). The mean age of initial implant activation was 1;6 with a range of 1;0 to 2;4; thus, all CI users received relatively early implantation. Table 2 includes more detailed information about the participants who used CIs (such as device type and date of hearing loss). All bilingual children with CIs were born in the United States and were exposed to both spoken Spanish and English from birth or as soon as their implant was activated, whichever occurred first. Seven of the 11 CI users had severe to profound hearing loss from birth, and the remaining four experienced profound hearing loss at ages 0;3, 0;8, 1;1, and 1;5 (see Table 2). The home dialect of Spanish was Mexican for all CI users. As indicated above, a conscious effort was made to match the participants in the two groups as closely as possible on a range of background variables. Children with CIs were recruited from the same metropolitan area; specifically, the Center for Hearing and Speech in Houston, TX.

Participants had received or were receiving auditory-verbal therapy, which utilizes oral communication as the only mode of communication, and therefore, the primary mode of communication for all of the participants was oral. On the basis of parent reports, all of the children used spoken language as their primary mode of communication;

Table 1. Participant background information: Children with normal hearing.

Participant code	Gender	Hearing age	Chronological age	Age of arrival to the U.S.	Mother's education
14NHB233	F	4;3	4;3	1;9	GED
14NHB230	F	4;6	4;6	Birth	Bachelor's degree
14NHB267	M	4;7	4;7	0;5	High school
13NHB215	M	4;9	4;9	Birth	Some elementary
14NHB248	M	5;10	5;10	2;6	Graduate school
13NHB204	F	5;2	5;2	Birth	High school
14NHB270	M	5;3	5;3	Birth	Elementary school
14NHB245	M	5;5	5;5	Birth	High school
13NHB210	F	5;5	5;5	Birth	Some college
14NHB232	F	5;6	5;6	Birth	Some college
13NHB203	M	5;8	5;8	Birth	Some college

Note. Age is presented in years;months format. GED = General Educational Development Test.

one mother reported that her child had limited sign language, one mother did not report whether her child knew any sign language, and the rest of the parents reported that their child was unable to communicate using sign language. Participants received speech services through the Center for Hearing and Speech, a private clinic, or through the public school system. Families of the children with CIs were also encouraged to use both Spanish and English because the Center for Hearing and Speech encourages and supports home language use as a means to support speech and language development in children with hearing loss.

Materials and Procedure

Voiced (/b d g/) and voiceless (/p t k/) stops were targeted in word-initial, singleton position in at least three target words per phoneme using the same words for all participants to ensure consistency across the participants' samples and control for the phonetic environment of the test items. Pictures (predominantly black-and-white line drawings and a few items depicting colors) were used to elicit a list of words with target phonemes through a naming task (described in more detail below). The children's productions were audio-recorded digitally at 44 kHz and 16 bits using a Marantz PMD 661 MKII Professional Field recorder that captures the uncompressed sound files onto a secure digital memory card. The recorder was positioned on a flat surface (such as a table) and the microphone directed toward the child approximately 10 in. (25.4 cm) from the participant to ensure consistency. The sound files were downloaded from the secure digital card of the recorder onto a computer for analysis.

Picture-Naming Task

The words used for analysis in this study are part of a comprehensive list of single words (more than 80 items

Table 2. Participant background information: Children with cochlear implants.

Participant code	Gender	Hearing age	Chronological age	Age at ID	Age at earliest implant	Age of arrival to the U.S.	Etiology	Device(s)	Sign language	Mother's education
12CIB006	M	4;10	6;3	0;3	1;5	Birth	Unknown	Nucleus 6 (bilateral)	Limited	Bachelor's degree
12CIB035	F	4;6	6;0	0;8	1;4	Birth	Unknown	Nucleus Freedom (R), Nucleus 5 (L)	None	GED
13CIB004	F	5;5	6;10	1;1	1;5	Birth	Unknown	Nucleus Freedom (R), Nucleus 5 (L)	None	Elementary school
12CIB040	F	4;6	5;7	Birth	1;1	Birth	Unknown	Nucleus Freedom (bilateral)	None	Not reported
14CIB334	M	4;4	6;8	1;5	2;4	Birth	CMV	Nucleus 5 (bilateral)	None	High school
13CIB028	F	6;1	7;4	Birth	1;3	Birth	Unknown	Nucleus 6 (R), Nucleus 5 (L)	None	High school
13CIB205	M	4;10	5;10	Birth	1;0	Birth	Unknown	Nucleus 5 (R), Nucleus Freedom (L)	None	Trade school
14CIB254	M	4;7	6;2	Birth	1;7	Birth	Unknown	Nucleus 5 (bilateral)	Not reported	Some high school
13CIB201	M	4;8	6;8	Birth	2;0	Birth	Unknown	Nucleus 6 (R), Nucleus 5 (L)	None	Elementary school
13CIB206	F	6;0	7;9	Birth	1;9	Birth	Unknown	Nucleus 5 (bilateral)	None	Elementary school
13CIB225	F	6;1	7;2	Birth	1;1	Birth	Premature	Nucleus Freedom (R) Hearing Aid (L)	None	High school

Note. Age is presented in years;months format. ID = identification; GED = General Educational Development Test; R = right; L = left; CMV = human cytomegalovirus.

per language) that target phonemes multiple times in word-initial and word-final positions. The target words were predominantly nouns depicting items familiar to children, and a few slides (fewer than 5% in each language) displayed colors (such as *yellow*). Most of the images were black-and-white line drawings chosen specifically for their phonological content. The drawings were appropriate for young children in the age range tested and did not demonstrate cultural bias. The elicitation for the present study was part of a larger experiment in which the goal is to investigate phonological development in bilingual and monolingual children who use CIs. The vocabulary was determined to be common, effective, and appropriate for the age range being tested (Procter et al., 2015). First, each child was asked to independently name each picture presented to him or her after a prompt such as "What is this?" If the target word was not identified on the basis of the first level of prompting, the child was given a description of the object such as "This is an animal that goes 'woof.'" If the target word was still not elicited, then the child was given a sentence to complete such as "A Dalmatian is a type of ______." Finally, delayed imitation was used to elicit the target word with a phrase such as "This is a <u>dog</u>. What is it?"

Before collecting the data, parental consent and the child's assent were obtained. The children were assessed during two separate sessions, one language at a time, in order to minimize code-switching and code mixing. The experimenters were proficient in the languages they tested and were knowledgeable of appropriate ways to interact with children from culturally and linguistically diverse backgrounds. After obtaining consent and assent, children with NH completed a hearing screening using pure tones at 500, 1000, 2000, and 4000 Hz at 25 dB HL, bilaterally, as previously noted. Children with CIs had their devices checked the day of the sample. All of the children completed the single-word list in both languages.

Measurements of VOT and Prevoicing

The VOT of /p t k/ and /b d g/ were measured on the selection of samples that had the targeted phonemes in initial, singleton position of words elicited during the picture-naming task. VOT duration was analyzed by measuring the time between the beginning of the burst and the onset of voicing for the following vowel, as described by Lisker and Abramson (1964). In addition to VOT measurements, we investigated the presence or absence of prevoicing (i.e., lead voicing) for all stops. We did not measure the duration of lead voicing but only the presence or absence thereof because once listeners detect the presence of voicing before the burst, the segment is identified as voiced, and so prevoicing may operate as an all-or-nothing phenomenon. All acoustic measurements were conducted with Wavesurfer using a time waveform and a wide-band spectrogram with the following parameters: bandwidth of 350 Hz, preemphasis factor at 0.8, and frequency range from 0–5000 Hz.

Instances of word-initial spirantization were also analyzed because Macken and Barton (1980b) found that in Mexican Spanish, spirantization is common involving word-initial voiced stops even in the absence of a determiner or preceding phrase. For the purposes of our prevoicing analyses, cases of spirantization of initial stops were considered prevoicing because they are voiced throughout their production.

Reliability of Measurements

The VOT measurements were conducted by the first and the second authors of this article, both of whom measured 100% of the data. Allowing for a 10-ms buffer (typically used in such analyses; cf. Peterson & Lehiste, 1960), initial interrater agreement on the English VOT measurements was 96.3%, and on the initial Spanish VOT calculations, interrater reliability on the entire sample was 96.7%. There were 506 English and 657 Spanish VOT measurements (a total of 1,163 items). Agreement on identification of prevoicing and spirantization exceeded 98%.

VOT measurements that lacked agreement were reverified independently by both judges, and eight items that were not in complete agreement were discarded from the analyses. We also discarded items that included substitutions other than the voicing pair of the item in question (e.g., if the child substituted [b] for /p/, it was measured due to its effect on the VOT pattern, but any other substitution was not considered, of which there were fewer than a dozen). Items that were not measurable due to background noise or the experimenter talking over the child were also excluded from the analyses. Finally, child productions that included hesitation, language transfer (such as Spanish for English or vice versa), or other interferences (such as coughing) were also not included in the analyses. After removing the eight items for which the judges' duration measurements differed and other problematic items, the entire sample consisted of 1,029 VOT measurements (43 English and 91 Spanish items were excluded).

Statistical Analyses

There were two sets of analyses: one for VOT production and one for prevoicing. Each analysis set involved a mixed analysis of variance (repeated measures, general linear model) with three within-subject factors (language: Spanish vs. English; stop voicing: voiceless vs. voiced; and stop place: labial, alveolar/dental, or velar) and one between-subjects factor (NH vs. CI user). Stop place of articulation was included as a variable because labial stops typically have shorter VOTs than alveolar/dental stops, which, in turn, tend to have shorter VOTs than velar stops. The dependent variable for the first set of analyses was VOT measured from the beginning of the stop burst to the beginning of the following vowel as previously disclosed. For the prevoicing analysis, the dependent variable was the presence or absence of lead voicing.

Results

On the basis of existing research on the topic, we had one directional hypothesis predicting that bilingual children with NH would display initial stop voicing differentiation in their languages. We also stated two null hypotheses according to which (a) there would be no stop voicing differentiation in the productions of bilingual children with CIs, and (b) there would be no group differences with respect to initial stop voicing patterns between bilingual children with NH and their bilingual peers with CIs. Before reporting the relevant results, it must be noted that for the within-subject factors, we report the statistics with sphericity assumed because none of Mauchly's tests of sphericity were statistically significant for the within-subject effects and their interactions, indicating that the variances of the differences between all pairs of related groups were equal; therefore, the *F* ratios are valid and interpretable.

VOT Production

Our findings revealed that there was a statistically significant main effect for language, $F(1, 20) = 121.37$, $p < .001$, partial $\eta^2 = .589$; stop voicing, $F(1, 20) = 194.94$, $p < .001$, partial $\eta^2 = .907$; and stop place of articulation, $F(2, 40) = 55.36$, $p < .001$, partial $\eta^2 = .735$. Polynomial analyses for stop place of articulation revealed that the trend was linear going from labial to velar, $F(1, 20) = 92.63$, $p < .001$, partial $\eta^2 = .822$. However, there was no statistically significant main effect for group differences between bilingual children with NH and their peers with CIs, $F(1, 20) = 0.55$, not significant, partial $\eta^2 = .027$.

There were three statistically significant interaction effects: Stop Voicing × Language, $F(1, 20) = 100.40$, $p < .001$, partial $\eta^2 = .834$; Stop Voicing × Stop Place of Articulation, $F(1, 40) = 3.57$, $p = .037$, partial $\eta^2 = .152$; and Language × Stop Place of Articulation, $F(1, 40) = 4.05$, $p = .025$, partial $\eta^2 = .168$. None of the other interactions (two way, three way, or four way) were statistically significant.

To summarize the VOT results, bilingual children with NH and with CIs used VOT reliably to differentiate voiced and voiceless stops in word-initial position. Bilingual children in both groups also displayed differential patterns in Spanish and English, and the place of articulation of the initial stop consonants had a statistically significant effect on VOT. However, there was no statistically significant group effect comparing children with NH versus CI users, indicating that bilingual children with CIs did not produce significantly different VOTs from their peers with NH for initial, singleton stops. Furthermore, statistically significant interaction effects indicated that stop voicing production depended on the language spoken (Language × Voicing) as well as on stop place of articulation, and stop place of articulation depended on the language spoken, when it came to initial stop VOTs. Notably, stop voicing or place of articulation did not depend on whether the children had NH or CI.

Prevoicing and Spirantization

There was a statistically significant main effect for language, $F(1, 20) = 11.83$, $p = .003$, partial $\eta^2 = .372$; stop voicing, $F(1, 20) = 36.98$, $p < .001$, partial $\eta^2 = .649$; and stop place of articulation, $F(2, 40) = 5.10$, $p = .011$, partial $\eta^2 = .203$. Polynomial analyses for stop place of articulation revealed that the trend was linear going from labial to velar, $F(1, 20) = 12.87$, $p = .002$, partial $\eta^2 = .392$. However, there was no statistically significant main effect for group differences between bilingual children with NH and their peers with CIs, $F(1, 20) = 0.09$, not significant, partial $\eta^2 = .004$.

There were two statistically significant interaction effects: Stop Voicing × Language, $F(1, 20) = 11.26$, $p = .003$, partial $\eta^2 = .360$; and Stop Voicing × Stop Place of Articulation, $F(1, 40) = 4.04$, $p = .025$, partial $\eta^2 = .168$. None of the other interactions (two way, three way, or four way) were statistically significant.

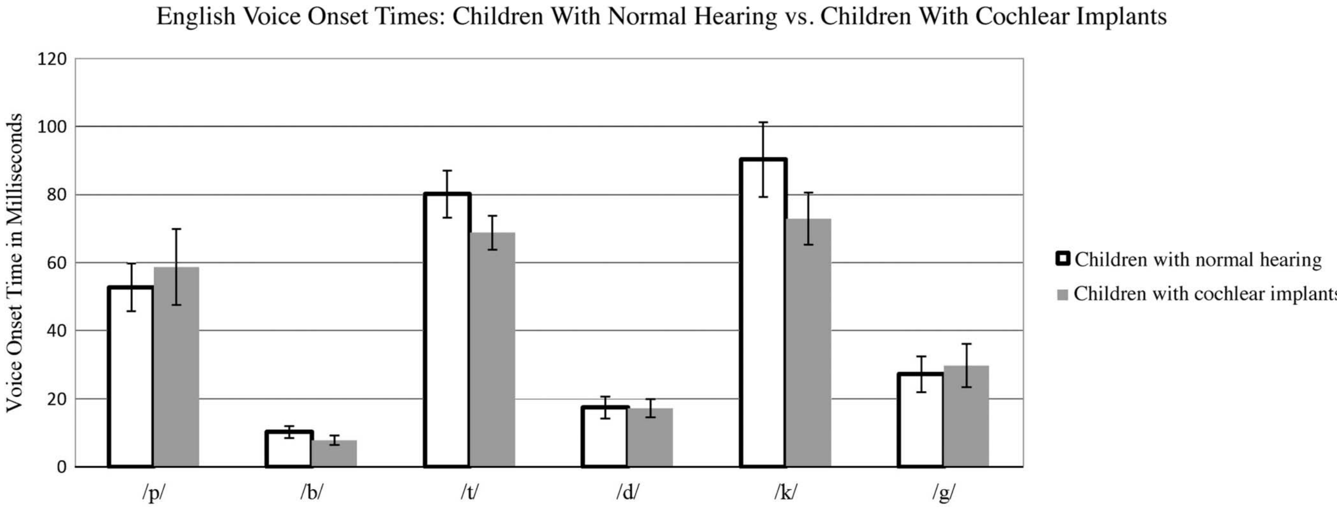
The pattern of prevoicing was similar to the findings reported for VOT in that voicing, place of articulation, and language all had statistically significant main effects on prevoicing, indicating that prevoicing depended on whether the initial stop was voiced or voiceless, the place of articulation, and the language spoken. There was also a statistically significant Stop Voicing × Language interaction, indicating that prevoicing of the initial stop depended on whether it was Spanish or English. The second statistically significant interaction effect (Stop Voicing × Stop Place of Articulation) showed a dependence of prevoicing on the place of articulation of the stop. Unlike in the VOT results, there was no statistically significant Stop Place of Articulation × Language interaction. Regarding nonsignificant effects, as with VOT, it is notable that the prevoiced stops produced by children with CIs did not differ from those produced by their bilingual peers with NH.

Overall, the VOT and the prevoicing results indicate that bilingual children with NH and with CIs do not differ at a statistically significant level when it comes to initial stop voicing differentiation. Both bilingual children with CIs and with NH differentiate stop voicing, and they do so differently in Spanish and English. Place of articulation also affects how initial stops are differentiated. These issues are explained and elaborated further in the next section.

Discussion

On the basis of the results, we retain the directional (first) hypothesis predicting that bilingual children with NH would display initial stop voicing differentiation, as indicated by a statistically significant main effect for voicing. Furthermore, the statistically significant Stop Voicing × Language interaction effect revealed that initial stop voicing contrasts are made differently in Spanish and English by the bilingual children who participated in this study. As Figures 1 and 2 illustrate, bilingual children produce longer VOTs in English than in Spanish, and they also produce fewer prevoiced stops in the former language

Figure 1. English mean voice onset time values and standard error bars.



than in the latter (see Figures 3 and 4). These results are in line with existing research that has found stop differentiation in bilingual children as well as differential patterns on the basis of the languages spoken (cf. MacLeod & Stoel-Gammon, 2009).

We reject the null hypothesis according to which children with CIs do not differentiate initial voiced and voiceless stops, because there was a statistically significant main effect for voicing, a significant Voicing × Language interaction, and no statistically significant group differences between CI users and their peers with NH with respect to initial stop voicing contrast. Therefore, bilingual children with CIs in this study did appear to distinguish initial voiced and voiceless stops in both languages on the basis of VOT and prevoicing, and they seemed to do so in a language-specific fashion. In both English and Spanish, bilingual children with CIs produced significantly longer VOTs for voiceless than for voiced stops, and voiced stops displayed a significantly higher percentage of prevoicing than their voiceless counterparts. Furthermore, when comparing the English and Spanish patterns for initial voiced and voiceless stop pairs, the English VOT values were considerably longer than their Spanish counterparts. Prevoicing was also less common for English voiced stops than for their Spanish analogs. These results move the field forward by documenting that bilingual children with CIs can differentiate voiced and voiceless initial stops on the basis of VOT and prevoicing despite a diminished auditory signal. Furthermore, the differentiation of stop voicing by bilingual children with CIs appears to be accomplished in a

Figure 2. Spanish mean voice onset time values and standard error bars.

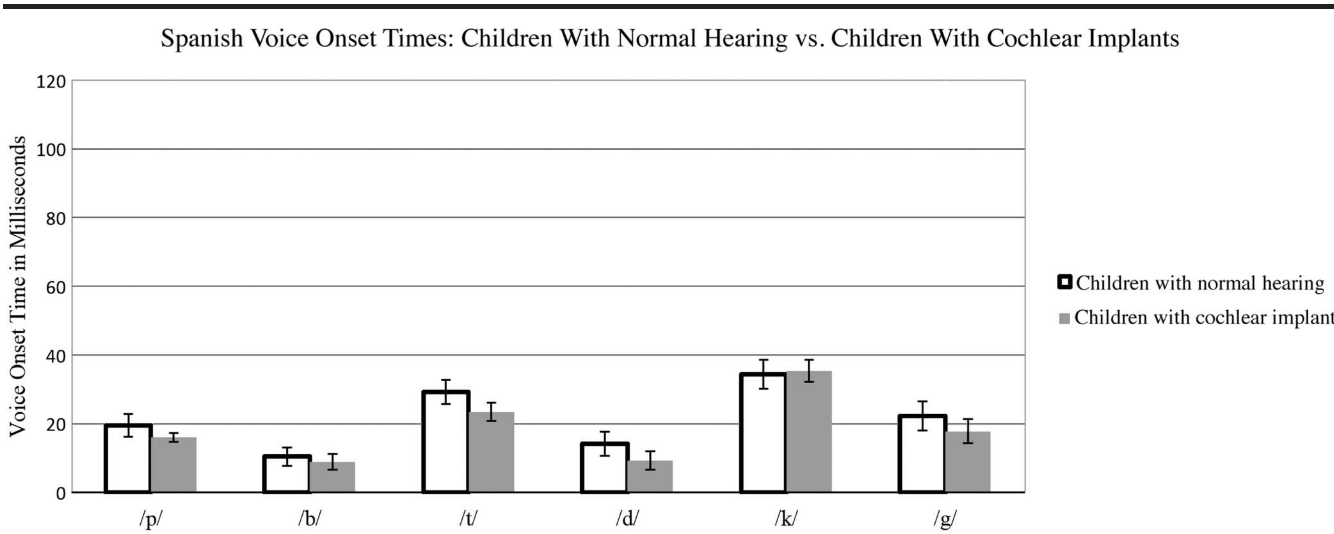
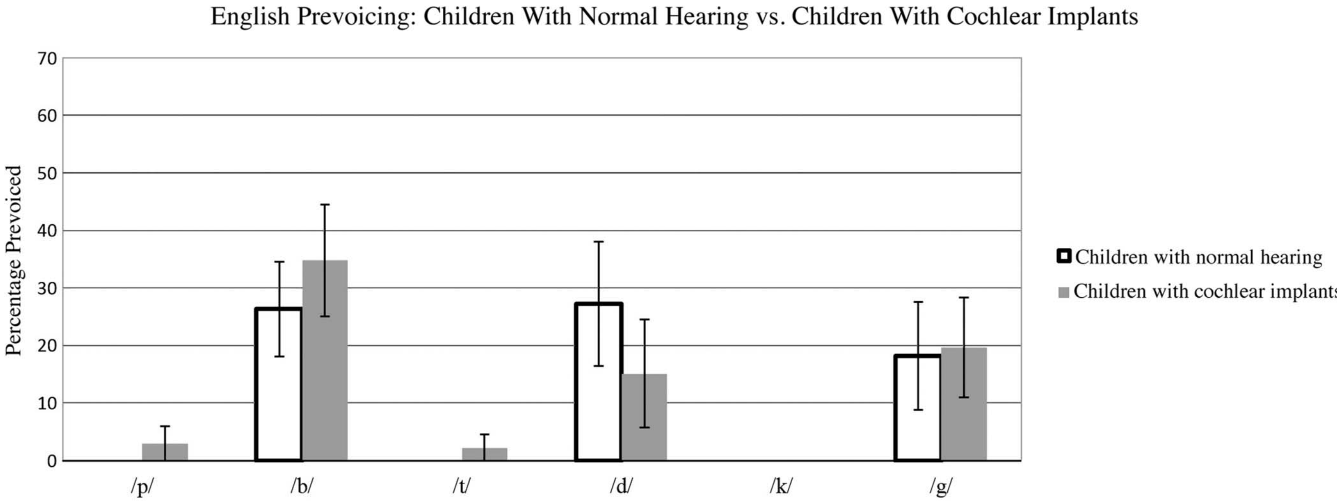


Figure 3. English percentage of prevoicing and standard error bars.

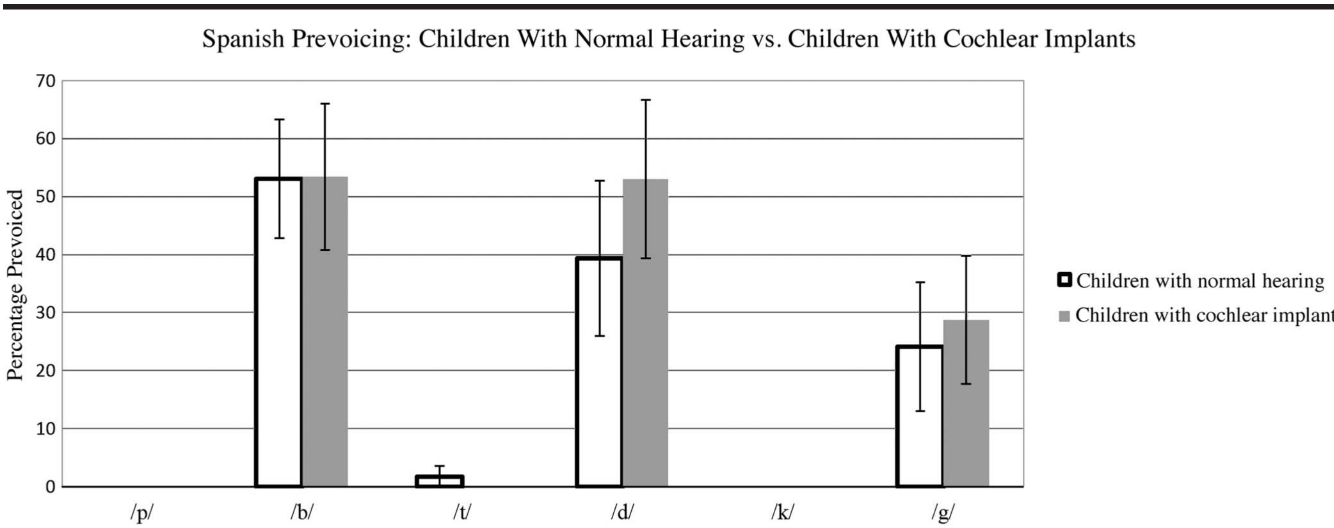


language-specific fashion, indicating not only acquisition of the contrast but also language differentiation.

We retain the null hypothesis that predicts no differences between children with CIs and NH when it comes to initial stop voicing contrasts. There were no statistically significant group differences between children with NH and CI users, suggesting that bilingual children with hearing loss who used CIs could and did produce initial stops that were commensurate with those of their bilingual peers with NH in terms of VOT and prevoicing. These findings are similar to the findings of Uchanski and Geers (2003) involving monolingual CI users in the sense that both studies found that the acoustic characteristics of the speech of children with CIs could be within the range attested in typically developing peers with NH. In our study, this held true in the case of bilingual children with hearing loss who used CIs, reinforcing the point made by Guiberson (2014) that learning two spoken languages may not pose an insurmountable challenge for bilingual children with CIs.

In addition, we found that stop place of articulation had a statistically significant effect on both VOT and prevoicing in initial stops. The statistically significant linear trend for VOT indicated that labial stops had the shortest lag and velar ones tended to have the longest lags. Voiced labial stops tended to have the largest proportion of prevoicing relative to the other positions. This is an issue that was not the main focus of the present study; nonetheless, our findings are in line with the results of existing studies, such as the seminal work on VOT by Lisker and Abramson (1964), who found that labial stops tended to have shorter

Figure 4. Spanish percentage of prevoicing and standard error bars.



VOTs than alveolar/dental stops, which, in turn, tended to have shorter VOT durations than velar stops. A related, albeit somewhat different, issue is that children with hearing loss prefer to produce labial and coronal stops rather than dorsal/velar ones. Warner-Czyz and Davis (2008) found that children who receive early implantation produced consonants with predominantly labial and coronal places of articulation, and stops were also well represented in their segmental inventories. Furthermore, the most accurate segments were the same as the most frequent inventory types. For example, labials and stops were the most frequent place and manner features in the inventory and were also the most accurately produced. Dorsals/velars were produced considerably less frequently by either group studied by Warner-Czyz and Davis. For the present study, the important aspect of the stop place differentiation is the degree to which bilingual children with CIs are able to match the patterns attested in their bilingual peers with NH, providing further evidence for the ability of CI users to acquire aspects of the phonological systems of both of their languages even with the use of a diminished signal.

As Caldwell and Nittrouer (2013) note, voicing contrasts for consonants may be relatively more resistant to hearing loss than other phonemic distinctions, a fact that has likely contributed to the results we found regarding how well bilingual children with CIs were able to match their peers' productions when it came to initial stop voicing. Future studies on phonological acquisition in bilingual children with hearing loss who use CIs may focus on a wider range of phonological phenomena, some of which are easily accessible to children with CIs and others that may be more challenging for them (such as certain fricatives; cf. Chin & Pisoni, 2000).

A closer look at VOT values reveals that prevoicing is present in English voiced stops of both bilingual children with NH and those with CIs. This may be due to the influence of Spanish, which would be in line with the work of Kehoe et al. (2004), who also found prevoicing of German voiced stops (monolingual norm being short-lag voicing) in German-Spanish bilingual children. In addition, bilingual children with CIs, but not those with NH, demonstrated prevoicing of English voiceless stops. In some cases, this was simply substitution of the voiceless stop with the voiced counterpart, but in a few cases, these consisted of a period of prevoicing before the release of the stop, which was then followed by a period of voiceless aspiration.

Limitations

The present study provides novel and important information for our field, but the research is not without its limitations. This study included 22 participants (11 in each group); therefore, a replication with a larger sample size would be beneficial to ensure that the results can withstand verification. Our data are also limited to a cross-sectional sample, so besides more participants, future studies should include longitudinal data to follow the development of the voicing contrast from an earlier age when such a contrast does not exist to full mastery of the categories.

Our study was also limited to comparing the Spanish and English of bilingual children with NH with their peers with CIs and did not include monolingual controls. Having monolingual control groups in each language would require four additional groups (Spanish and English monolingual children with NH and with CIs), which would warrant considerably more participants per group, and there are additional challenges that we are currently working on addressing.

Focusing on a specific contrast such as stop voicing in the initial position by bilingual children with NH and with CIs allowed us to have experimental control and observe a specific phenomenon, but it also limited our ability to extrapolate to the larger pattern of phonological representation in the populations studied. More comprehensive investigations of various aspects of phonology and speech are underway in our research laboratories to obtain a fuller picture of phonological acquisition in bilingual children with hearing loss who use CIs and their peers with NH.

Conclusion

A rapidly increasing number of bilingual individuals are receiving CIs, and Hispanic children display a higher prevalence of hearing loss than the general population of the United States (Mehra, Eavey, & Keamy, 2009). Consequently, there is a critical need to do more research on the topic to better understand speech and language development in bilingual children who use CIs. The present article addresses this problem by investigating a specific aspect of speech production—stop voicing differentiation—in bilingual children with NH and their bilingual peers with CIs, comparing both their Spanish and English skills to provide information for researchers as well as practicing audiologists and speech-language pathologists. The main contribution of our study to the fields of bilingual speech and language development and communication disorders is that bilingual children with hearing loss who use CIs can acquire initial stop voicing patterns commensurate with those of their bilingual peers with NH. Moreover, bilingual children with CIs and their peers with NH not only learn to produce those contrasts, but they do so in a language-specific fashion even if those contrasts are analogous.

This line of research has clear implications for researchers in various fields, from language acquisition to linguistics to communication disorders and even cognitive science, because discovering how two languages are acquired with a diminished auditory signal versus an intact hearing mechanism can reveal how speech and language acquisition proceeds under each condition. Moreover, this research also informs practicing clinicians and educators who serve bilingual children with NH and with CIs. Learning more about the phonological interaction in bilingual children with CIs will also aid in making more informed clinical and educational decisions and in distinguishing between a language difference and a language disorder for this growing population.

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