Speech Production Outcomes Before and After Palatometry for a Child With a Cochlear Implant

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Speech production outcomes are reported for 1 child with a cochlear implant at 3½, 4, and 4½ years post-implant. The first 2 speech assessments followed a total communication program with traditional speech therapy. The third followed a 20-session program of palatometry, a computerized visual feedback system providing information about tongue-palate contact points. The child's speech development in the latter period was faster than in previous periods, both for accuracy of specific treatment targets (velars, lingual fricatives and affricates, and consonant clusters) and for conversational intelligibility. Implications for future research are discussed.

Changes in technology are offering new potential for reduction of the impact of hearing and speech impairments. Along with this increase in potential, however, comes an increased need for clinical research that evaluates the impact of the new technologies on impairment and quality of life. In order to determine a technology's impact on both individuals and populations, a variety of research designs are needed. Case studies can provide details of an individual intervention program and serve as a basis for large group studies, where individual trends may or may not be confirmed. This paper describes a case study of one child with a cochlear implant. The child's speech production outcomes are presented at 3½, 4, and 4½ years post-implant. The first two speech assessments followed a total

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communication program with traditional speech therapy. The third followed a 20-session program of palatometry. Palatometry (or electropalatography) is a sensory aid that utilizes both auditory and visual feedback about tongue-palate contact points during speech.

Because this is a descriptive single case study, no definitive claims can be made about the relative influences of maturation, the particular cochlear implant and processor, traditional speech therapy, or palatometry on the child's speech production outcomes. The study is presented as an addition to the small literature on speech production development in children with cochlear implants, giving individual data about changes both in speech impairment and in word identification as perceived by untrained listeners. It is also presented as a possible impetus for future large-group experimental studies evaluating visual feedback technology such as palatometry in the speech habilitation process.

Speech Habilitation of Deaf Children

The following speech characteristics have been commonly reported for deaf children, whatever their intervention program: (a) suprasegmental differences in pitch, loudness, rate, intonation, and resonance; (b) omission of speech sounds in word positions with lower intensity and pitch, such as word-final position, consonant clusters, and weak syllables; (c) use of stops (including glottal stops) for other sound classes, with fricatives being particularly difficult; (d) a predominance of front consonants, particularly labials; (e) voicing errors for stops and fricatives; and (f) substitution of neutral central vowels for other vowels, particularly for front vowels and diphthongs (Dagenais, 1992; Smith, 1975; Tobey, Pancamo, Staller, Brimacombe, & Beiter, 1991; Tye-Murray, Spencer, & Woodworth, 1995). Overall, speech sounds with high-frequency and/or weak intensity components tend to be most difficult, and visible speech sounds with low and/or high intensity frequency components tend to be least difficult. For individuals who are prelingually deafened, better access to the auditory signal has therefore been considered crucial for improvements in speech intelligibility (Matthies, Svirsky, Perkell, & Lane, 1996; Tye-Murray & Kirk, 1993).

Overall, studies of speech production in children with cochlear implants have reported significant gains in speech development by 2 years post-implant (e.g., Dawson et al., 1995; Ertmer, Kirk, Sehgal, Riley, & Osberger, 1997; Geers & Tobey, 1992; Grogan, 1995; Osberger, Maso, & Sam, 1993; Sehgal, Kirk, Svirksy, Ertmer, & Osberger, 1998; Spencer, Tye-Murray, & Tomblin, 1998; Tobey et al., 1991; Tye-Murray & Kirk, 1993; Tye-Murray et al., 1995). Phonemic accuracy for implant users has a somewhat higher average across studies than that of users of other aids, whether hearing or tactile (Ertmer et al., 1997; Geers & Tobey, 1992; Sehgal et al., 1998; Spencer et al., 1998; Tobey et al., 1991). For example, in a sentence repetition task, 13 subjects using hearing aids in the Spencer et al. (1998) study had an average of 45.6% correct phonemes, whereas the 25 implant users had an average of 54.2% correct. Both consonants and vowels have shown significant gains after implant use. In a study 1 to 2 years post-implant, subjects in Tye-Murray and Kirk (1993) showed significant improvement for diphthongs and front vowels. Front vowels are often difficult for deaf speakers (Smith, 1975) because of the high frequency of their second formants. Tye-Murray and Kirk (1993) attributed improvement in those vowels to better auditory perception of higher frequencies with the implant. For consonants, Geers and Tobey (1992) noted significant gains in implant users across features of manner, place, and voicing.

Although children with implants have generally shown improvement in speech production, outcomes have been variable across sound classes and children. Although Geers and Tobey (1992) reported gains for all sound classes across subjects, they also noted that gains were not significant for velars, palatoalveolar fricatives, or front vowels in the 2 years of their study. This latter finding contrasted with the significant improvement noted by Tye-Murray and Kirk (1993) for front vowels after a study of similar length. In terms of individual subjects, Dawson et al. (1995) reported a lack of significant change in speech intelligibility after implant use for some subjects. Tye-Murray et al. (1995) also commented that some children, particularly those who had received an implant after age 5, remained relatively unintelligible to the untrained listener after 3 years of implant use. Individual difference is further illustrated in the range of phoneme accuracy scores reported by Tye-Murray et al. (1995) and Spencer et al. (1998). In the Tye-Murray et al. (1995) study, 28 implant users aged 2-15 years (mean age 7;1) had an average of 53% phonemes correct on a story-retell task, but the range varied from a low of 14% (a very severe speech impairment, according to Shriberg & Kwiatkowski's [1982] severity scale for speech impairment) to a high of 92% across subjects (a minimal speech impairment). Spencer et al.'s (1998) 25 implant users (aged 5-16 years, mean age 9;5) showed on a sentence repetition task a similar average and range of 54.2% and 19%-93% phonemes correct, respectively.

A number of variables can influence speech production outcomes for a given child with hearing impairment. Subject variables include etiology of the hearing impairment, a child's cognitive and language abilities, and/or a child's interest in oral communication. Technological variables include type of implant, type of processor, sophistication and frequency of programming, and/or technological aids used in speech therapy. Clinical variables such as age of detection of the impairment and age of implantation are influential. Other environmental variables include educational program and caregiver involvement. Variables pertaining to factors such as etiology or innate abilities are immutable. Age of detection and age of implantation cannot be changed after the fact. Technological variables, however, such as the type of speech processor, or the sensory aids utilized in a speech rehabilitation program, can be manipulated in a way to maximize a child's potential. Palatometry, one such technology, is described in the following section.

Palatometry and Speech Production

The palatometer (or electropalatograph) is a computerized visual-auditory feedback tool that provides an on-line, dynamic display of the tongue's contact on the hard palate. This makes it possible to observe normally unseen tongue-palate contact patterns for lingual consonants and non-low vowels. The client wears a custom-made dental appliance, which fits over their top teeth and palate. Embedded in this acrylic plate are 60 to 90 electrodes, depending on the manufacturer, which are connected to external circuitry through bundled wires. An electronic circuit is completed when the tongue touches the acrylic palate in the areas where the electrodes are placed. These contact points are electronically transmitted to the computer screen and form a visual profile of the particular speech sound. A computerized audio feedback loop allows a person to hear and

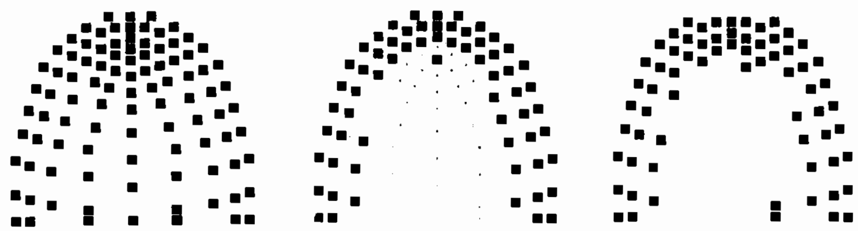

Figure 1. Alveolar stops: Dora's pre-palatometry [d], Dora's post-palatometry [d], and a typical adult [d] (from left to right). *Note.* Top of the figure represents the front of the mouth. Black squares indicate contact points of the tongue on the palate. Child's production changes from full undifferentiated tongue-palatal contact to the "horseshoe" shape characteristic of alveolar stops.

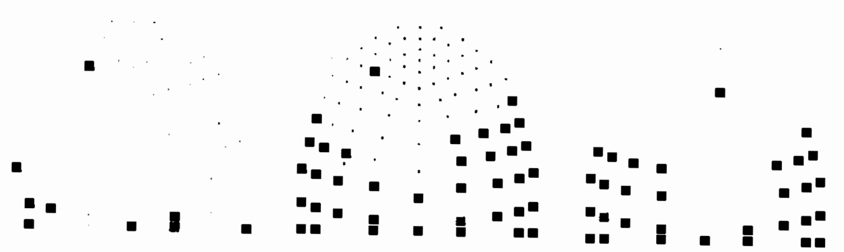

Figure 2. Velar stops: Dora's pre-palatometry [g], Dora's post-palatometry [k], and a typical adult [g] (from left to right). *Note.* Pre-palatometry, Dora has minimal tongue palatal contact for velars. Post-palatometry, an adult-like "bowl-shaped" back contact is evident.

see an utterance simultaneously, either on-line, or from a stored file. Clients match their productions to clinician models, to their own (stored) productions, or to stored templates. Computer files and printouts of palatograms allow for comparisons and analyses at different points during the course of intervention. (Fig-

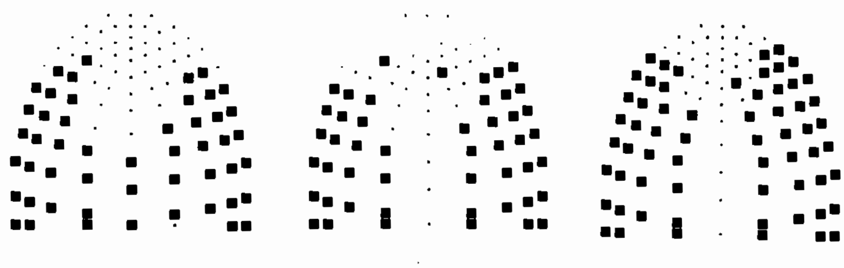

Figure 3. Affricates: Dora's pre-palatometry [tʃ], Dora's post-palatometry [tʃ], and a typical adult [tʃ] (from left to right). *Note.* Dora showed accurate *place* of articulation pre-palatometry, but no central groove for the [ʃ] portion of the affricate. Post-palatometry, there was an adult-like groove, that is, no contact in the vertical median.

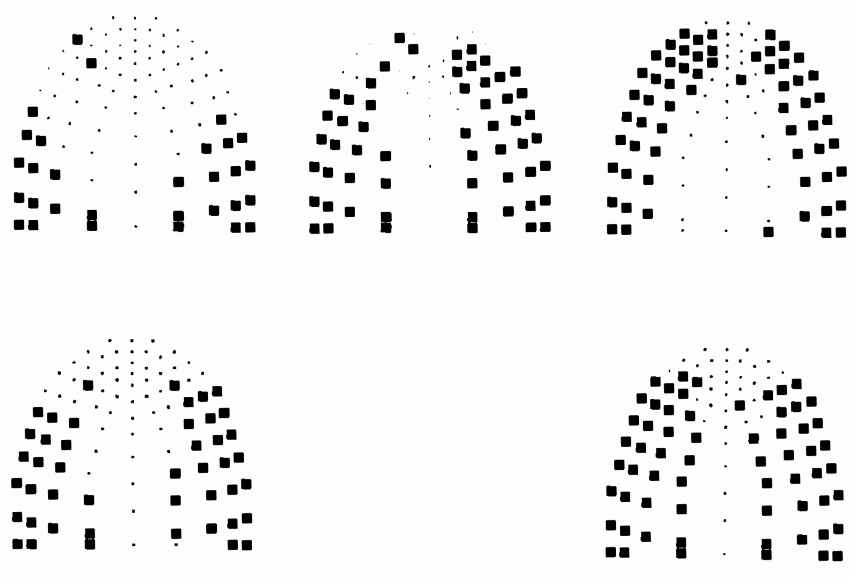

Figure 4. Sibilant place: Dora's pre-palatometry [s], Dora's post-palatometry [s], and a typical adult [s] (top row, left to right). Dora's pre-palatometry [ʃ], and a typical adult [ʃ] (bottom row, left to right). *Note.* Dora differentiated place and groove width of [ʃ] and [s] post-palatometry.

ures 1 through 4 are examples of palatograms, with the top of the palatogram representing the front of the mouth.)

Although the palatometer does not yet have widespread use, research reports indicate that it has been an effective speech therapy tool for persons with speech impairments with a variety of origins, such as cleft palate (e.g., Fletcher, 1985; Gibbon & Hardcastle, 1989), motor speech impairment (e.g., Howard & Varley, 1995; Morgan, 1992), primary articulation disorders (Dagenais, 1995; Gibbon, Hardcastle, Dent, & Nixon, 1996), and hearing impairment (Crawford, 1995; Dagenais, 1992; Fletcher, Dagenais, & Critz-Crosby, 1991; Fletcher & Hasegawa, 1983; Fletcher, Hasegawa, McCutcheon, & Gilliom, 1980).

Fletcher and Hasegawa (1983) reported improved palatal contact patterns and speech production for a child of 3½ years after the use of two technologies utilizing artificial palates: glossometry, which measures and displays the space between tongue and palate, and palatometry, which measures contacts of tongue and palate. Prior to introduction of the visual feedback technologies, their subject used lip and jaw gestures more than tongue gestures in articulation. The only identifiable pre-treatment phonemes were the labial stop /b/, the low front vowel /æ/, and the neutral central vowel /ʌ/. The glossometric display was used to teach the vowels /i/ and /ɑ/, whereas the palatometric display was used to teach the alveolar stop /t/ in CV syllables with the high front vowel /i/ and the low back vowel /ɑ/. After treatment, she could produce both the high vowel [i] and the low vowel [a] and could combine them with the lingual alveolar consonant [t] in monosyllabic and disyllabic words. The visual feedback appeared to have a positive effect on speech production for this preschool subject.

In a study of five older deaf girls (aged 10-16 years), Fletcher et al. (1991) reported further positive results using palatometry. Neither hearing aids nor implants were mentioned in the article, but it is assumed that the girls did not have implants. By the end of an intensive treatment period (two 1-hr sessions a day for a month), all subjects had made significant gains for lingual consonants in imitated CV syllables, both in tongue-palate contact patterns and in phonetic accuracy. Four subjects learned to distinguish alveolar versus velar stops. Five out of 6 subjects learned to produce distinguishable sibilants. The authors noted only minimal gains for nasality and voicing and for those speech sounds which had been close approximations to the adult models pre-treatment. Palatometry does not easily address nasality and voicing. Overall, subjects who showed the greatest gains were those with the most severe impairments. Age did not appear to influence results. Although the study did not directly compare palatometry outcomes with traditional therapy outcomes, the authors commented that phonetic gains made during the 1-month palatometry period contrasted notably with their previous treatment results in phonetic accuracy. Dagenais (1992) suggested that gains made in that study were at the phonetic level only, however; the new speech sounds were not yet produced in conversational speech.

Dagenais (1992) reported results from two additional studies in which palatometry was used with deaf subjects. In the first study, two groups of 9 subjects each participated in either palatometry or traditional aural/oral speech therapy (Ling, 1976), receiving 28 sessions over a 3- to 4-week period. Subjects in the palatometry group showed greater immediate post-treatment gains for velar consonants and vowels /æ/, /a/, and /u/ and also showed improved tongue-palatal contact patterns for sibilants. Subjects receiving traditional therapy showed greater gains immediately post-treatment for /i/ and also had higher scores on the CID Picture Speech Intelligibility Evaluation (SPINE; Monsen, Moog, & Geers, 1987). Six months following these intensive programs, children in both groups had regressed, although the palatometry group had not regressed to the same degree. Based on that study, Dagenais concluded that the palatometer was an effective tool for teaching specific speech sounds in nonsense syllables, but that communicative approaches using real words were useful for addressing intelligibility. Thus, a third study was initiated with four 10-year-olds over 2 years, using both palatometry and traditional treatment. The palatometry appeared to be most effective in the first year of the 2-year study. Subjects learned to produce speech sounds that they had not mastered previously with traditional speech therapy. After 12 months, a learning plateau appeared to be reached with palatometry, although intelligibility and post-alveolar (palatoalveolar) fricatives did continue to improve. At that point, more traditional communicative speech therapy approaches generally appeared to have greater success. Teachers commented that children appeared to lose interest in the technology and that they were then able to imitate sounds more easily without the visual models provided by the palatometer.

Rationale and Predictions for the Current Study

Although there have been few research studies using palatometry in speech habilitation, a review of the literature suggests that the technology has potential, and that further investigation is warranted. Thus, a study was initiated in order to observe effects of palatometry across a small and varied group of 11 subjects as a basis for future larger-scale experimental studies (Bernhardt, Loyst, & Muir, 1996). One of the subjects was Dora, the 7-year-old deaf subject discussed in this study. In Fletcher et al.'s (1991) palatometry study, deaf subjects with the most severe speech impairments showed the greatest gains in speech production. Because Dora had a severe speech impairment, it was predicted that she would show significant improvement in speech production after palatometry. Unlike other deaf subjects discussed in the palatometry literature, however, Dora had a cochlear implant. By the time of this palatometry study, 4 years had passed since her implantation, but her speech remained unintelligible. Because studies with implant users have generally shown significant gains in speech intelligibility within 2 years post-implant (Spencer et al., 1998; Tye-Murray et al., 1995), fewer gains in her speech production at 4 years post-implantation were expected without a change in either the speech processor, the speech habilitation program, or both. It was predicted that visual information, such as that provided by palatometry, would aid in the speech habilitation process.

In evaluating the effects of palatometry on speech production, a number of variables can be examined. In the literature on speech production outcomes, speech sound data and physiological data, such as tongue-contact patterns, tend to be reported in addition to general intelligibility data. Both speech sound data and physiological data focus on impairment or "body," as defined by the World Health Organization (1997). Although such information is critical and valuable for research and clinical purposes, the question remains whether a particular treatment has any impact on a person's quality of life, such as the person's daily activities or participation in society. How intelligible is the person to people outside the clinic? Does the person have more social and economic opportunities as a result of changes in speaking ability? The World Health Organization's (1997) model of ability suggests a need to evaluate outcomes of intervention at all three levels: body, activity, and participation. The current study was designed to evaluate results of speech intervention both in terms of body (impairment) and of activity level as evaluated by non-experts in speech. It was predicted that Dora would show significant gains at both levels after palatometry treatment.

METHOD

Subject Description

Dora was prelingually deaf, as a result of prenatal Cytomegalovirus. Her hearing impairment was identified at 8 months, with observed aided thresholds of 40 to 50 dB HL. By 3;7, she had lost her residual hearing and had no aided response at the limits of the audiometer. She thus received an implant with a Mini Speech Processor at age 3;11. A full insertion of the electrode array was done with complete activation. The SPEAK (Spectral Peak) speech-coding strategy was used, and dynamic ranges appeared to be acceptable. Post-implant audiological reports with the speech processor indicated a pure tone average of 38 dB from 250 to 4000 Hz (30 dB at 1000 Hz to 45 dB at 250 Hz), and speech awareness in the range of 30 dB. Closed-set word identification accuracy was 77% (Elliott & Katz, 1980), and open-set word identification was 45% (Haskins, 1949). Her speech comprehension was described as better than her speech production.

Dora attended a well-established total communication program in preschool and early primary grades in British Columbia. At least some of her bilingual sign/English teachers had normal hearing. Her family was very involved in her program and supportive of educational and clinical initiatives. She received speech therapy throughout her educational program from speech-language pathologists (SLPs) knowledgeable in signing and in speech habilitation techniques with the deaf. The school and private SLPs' reports for Dora at age 7;4 (1 month prior to this study) noted that she had good sign language skills, speech comprehension, and literacy skills but low speech intelligibility. Her nonverbal skills appeared average to above-average. She was reported to be somewhat isolated socially. No scores were available to support the preceding summary statements, but the first and second authors' interactions with this child concurred informally with those generalizations.

Procedures

The project had the following general format (subject ages are indicated in parentheses): the initial assessment (7;5), a traditional speech therapy baseline program (7;6-7;11), a post-baseline probe (7;11), a palatometry treatment program (7;11-8;4), and a final assessment (8;5). Within the palatometry program, there were two treatment blocks, with each including the various specific speech goals. While one treatment target was being addressed, the others were ignored. Procedures for the various components of the program are discussed in the following sections.

Initial Assessment

The initial speech samples for this project were collected at 3½ years post-implant when Dora was 7;5. Single word and connected speech samples were recorded in a quiet room using a portable Marantz tape recorder with a PMZ33-1090B table-top microphone placed 12 to 16 in. from Dora's mouth. The second author (and SLP for the study) elicited 153 primarily spontaneous single words from Bernhardt's (1990) list. This list contained 85 monosyllabic, 61 disyllabic, and 7 multisyllabic words with all phonemes of English in all syllable contexts, including morphological contexts such as *tub/tubby* or *eat/eating*. The connected speech samples included a spontaneous conversation with the SLP and an oral reading of the Rainbow Passage (Fairbanks, 1960). The latter was used in order to have referents for words in connected speech and to have a standard connected speech sample for between-subject comparisons in the larger study. Immediately following the assessment, a plaster cast of her upper dental arch was made by an orthodontist and sent off to the palatometer manufacturer as a model for her pseudopalate.

Only the single word list was used as a basis for the following analysis of Dora's speech for two reasons: (a) her intelligibility was low, making word identification challenging in connected speech passages and comparison with adult targets difficult, and (b) the Rainbow Passage was elicited through reading, meaning that it might have been less representative of her conversational speech. The transcriptions and quantitative analyses were performed by listeners experienced in narrow phonetic transcription and phonological analysis of disordered speech.

The speech-language pathologist who collected the sample did the initial transcription using the International Phonetic Alphabet (International Phonetics Association, 1989) and some project-specific diacritics. The first author of this paper transcribed the sample independently. Agreement was 88% for phonemes and diacritics. For disagreements, a consensus transcription was constructed by the first two transcribers and a third speech-language pathologist also involved in palatometry treatment. Each segment and diacritic was examined, with consensus resulting in addition of glottal stops, recategorization of some labiodental fricatives as labiodental stops, addition of "r"-coloring to [w], and exact characterization of the "distorted" ungrooved lateralized palatoalveolar fricative. Changes were thus primarily in use of diacritics rather than in segments. The following section describes Dora's speech profile at the initial assessment (see also Tables 1 through 4 and Appendix B).

Initial assessment: word length and structure. Dora had near-normal production in terms of numbers of syllables produced per word: 92.2% of the 153 words had the same number of syllables as adult targets for words up to four syllables in length, for example, *television* [t_vʌbɪʔbɪʃˡɪv]. The subscript [$_v$] designates a partially voiced stop, the strikethrough indicates an ungrooved sibilant, and the superscript [^{l}] indicates lateral release. The few words that did not match adult targets in terms of word length had additional syllables. These extra syllables typically arose from glottal stop interruption of the word, as in *sweater*

Table 1

Initial Assessment: Singleton Consonant Inventory Across Word Positions

		Coronal			
	Labial	Alveolar (or dental)	Palatoalveolar (or palatal)	Velar/ uvular	Glottal
Nasal	m-9, m-33 ^{m}b-4, ^{b}m-3[b] ɱ-2	n-13[a]		ŋ-3	
Stop	p_v[c]-2, p-2 b-21, b̃-5	t_v-16[c], t-12 d-22			ʔ-10
Fricative	f-5, f_p-2[d] v-6, v_b-5[d]	ð-1	ʃ^l-19[e,f] ʒ^l-3[e,f]		h-6
Approximant	w-7, ɰ-1[g]		j-3 (medial)		

Note. Numbers equal tokens in the inventory across positions and words. Use of a phone does not imply a match with the adult target.

[a]No [n] in word-initial position. [b]Prenasalized stop (superscript [m]) or prestopped nasal (superscript [b]). [c]Partially voiced stop (word-initial position). [d]Labiodental stop. [e]Strike-thru = ungrooved sibilant. [f]Superscript [l] = lateralized sibilant. [g][ɰ] = "r" colored.

[ʃˡʔbɛtʔtɘ].

This glottal interruption (in 19/153 words) did not always result in extra syllables but did affect word timing, giving a prosodic impression of "choppiness" to her speech, such as [t$_v$ufʔbʊʃˡ] for *toothbrush.*

Another positive aspect of Dora's phonology was the fairly large inventory of word shapes. (Note. Word shape designates the CV sequences of words. For example, *bat* is a CVC word and *black* is a CCVC word.) These included word shapes with some of the more challenging structural targets, such as syllable-final consonants and consonant clusters, for example, *orange* as [ʔɔwĩnʃˡ] or ʔVCVCC and *brushing* as [bw̢ʊʃˡt$_v$ĩn] or CCVCCVC. The hook under the [w̢] represents "r"-coloring. Table 2 shows the variety of consonant sequences.) In spite of the complexity noted for the inventory of word shapes, only 32.3% of the 153 words matched adult word-shape targets, however. There were common reduction patterns such as consonant cluster reduction and final consonant deletion. However, there were also additions of consonants such as glottal and alveolar stops. These additions negatively affected word shapes by creating clusters where the adult target had none. For example, in *brushing* above, a CC cluster was created word-medially. The other major unusual pattern negatively affecting word shape accuracy was the frequent use of a syllabic consonant [m̩] for the vowel /i/, with *see* as [hm̩] or CC, not CV, or *eat* as [m̩t] or CC, not VC.

Initial assessment: vowels. The vowel system was reasonably well-established. All vowels occurred at least some of the time in the 153-word sample, and

Table 2

Initial Assessment: Consonant Sequence Inventory

	Place of articulation of first consonant in sequence				
		Coronal			
Word position	Labial	Alveolar	Palatoalveolar	Velar/ uvular	Glottal
Initial	bw-2, bw̢-1[a] bɢ-1, fw-4		ʃˡp-1,[b,c] ʃˡt-9 ʃˡd-1, ʃˡʔ-4	kw-1	
Medial	mp-2, bʔ-1 bw-1, fʔ-2 fw-1, vʔ-1 mʃˡvw-1	nd-3, nʔ-2 nm-1, dn-1 tʔ-3	ʃˡt-3, ʃˡʔ-2 ʒˡʔ-2		ʔp-1, ʔb-1 ʔt-1, ʔd-2 ʔk$_v$-1[d] ʔh-2
Final	bʃˡ-1, vf-1 vʃˡ-1	tm-1, nʃˡ-1	ʃˡt-1	ŋn-1	ʔp-1

Note. Numbers equal tokens in the inventory across positions. Presence does not imply a match with the adult target. Medial consonants may be in different syllables.
[a][w̢] = "r"-colored. [b]Strike-thru = ungrooved sibilant. [c]Superscript [l] = lateralized sibilant. [d]Partially voiced stop.

69% of vowels matched adult targets in those words. In terms of resonance a mild hypernasality was evident but was ignored for the calculation of vowel accuracy. The major sources for vowel inaccuracy were the use of [ɘ] for the rhotic vowel [ɤ] and the frequent use of syllabic [m̩] for the high front vowel /i/. Of the 32 /i/ targets in the sample, 26 were produced as [m̩], and only 6 as [i].

Initial assessment: consonants. Dora's consonant system was more limited than her vowel system, and thus more detail will be presented here about consonants. In terms of consonant inventory and accuracy, the most prevalent categories were stops, labials, and voiced consonants, as shown in Tables 1 through 3. Overall, only 16.8% of consonants in the 153-word sample matched adult targets (a severe level of phonological impairment, according to Shriberg & Kwiatkowski, 1982). The following description summarizes consonant production in terms of place of articulation, manner of articulation, and voicing.

In terms of manner, stops and nasals were the most frequent categories. Adult stop targets were realized as stops 75.9% of the time (88/116). When manner was inaccurate for stops that were not deleted, fricatives or nasals were substituted for them. Nasals were frequent because of the syllabic [m̩] for /i/. However, adult nasal targets were realized as nasals only 64.2% of the time, with most inaccuracies occurring word initially. Thus, word-initial /n/ was produced as [b] or [w], and word-initial /m/ as a partially nasalized stop [b̃], as in *noise* [b̃ɔɪʒ^{l}] or *milk* [b̃ɪʊ]. Fricatives matched the adult target for manner 38.7% of the time while affricates did not match adult targets at all. Stops generally replaced fricatives, or an intrusive stop appeared along with the fricative (see *soap* above). Word initially, stops also replaced affricates, as in *chair* [t$_{v}$ɛɘ] or *jump* [dʌm]. In other word positions, fricatives or fricative clusters replaced affricates, such as *watch* [bɑʃ^{l}t] and *cage* [deɪʒ^{l}]. Approximants /l/, /j/, and /r/ were absent. The approximant [w] appeared inconsistently word-initially but sometimes in word-initial clusters as a substitution for /r/ or /l/, with a trace of "r"-coloring (as in *brushing* above). Otherwise, stops replaced approximants, as in *laugh* [^{m}bæʔ], *red* [bɛːʔ], *you* [bu], and *wagon* [bædɪ̄n]. Overall, the inventory of speech sounds included both English and non-English phonemes, the latter including prenasalized stops ([^{m}b]), devoiced nasals ([m$_{o}$]), "r"-coloring as in [w̨], ungrooved palatoalveolar fricatives with lateral release ([ʃ^{l}]), and stopped labiodentals ([f$_{p}$], [v$_{b}$]).

In terms of place of articulation, labials (particularly [p], [b], [w], [f$_{(p)}$], and [m$_{(o)}$]) were the most accurate (99% match for place) and the most frequent (including the syllabic [m̩] for /i/ in the calculation of frequency). Looking only at consonant targets, alveolar coronals [t], [d], and [n] and palatoalveolar coronals [ʃ^{l}] and [ʒ^{l}] were the most frequent consonants in the inventory. However, coronals (alveolars and palatoalveolars) matched the adult targets only 53% of the time in terms of place. Only the stops [t] and [d] were accurate in terms of actual coronal place in all word positions. Labials replaced other coronals 53/91 times. For coronal fricatives, the lateralized ungrooved palatoalveolar [ʃˡ] was the usual substitution (as in *sweater* above), although labial stops or labiodental fricatives also substituted for coronal fricatives, as in *tooth* [$t_v$uf], or *snow* [v_boʊ]. Palatoalveolar affricates were typically produced as alveolar stops word initially (see *chair* and *jump* above), but as *palatoalveolar fricatives* in other word positions (see *watch* and *cage* above). The velars [k], [g], and [ŋ] were absent except for one accurate token of [k] in *quarter* [kwʊːʔtə] and three tokens of [ŋ], only one of which matched the adult target. Coronals frequently replaced velars (e.g., [dʌ̃m] for *gum*); although in clusters, labials often appeared for velars ([fwɑʔ] for *clock*), and in positions other than word-initial, glottal stops sometimes appeared ([tʊʔ] for *cook*).

Voicing was inconsistently accurate for stops and fricatives. Across word positions voiced stop targets were usually voiced, with voiceless stops appearing primarily in word-medial and word-final positions. Word-initial voiceless stops were never aspirated, and were often produced with partial voicing (as in *television* above). The most common fricatives were voiceless [ʃˡ] and [f], although there were a few tokens of [ʒˡ] and [v].

Baseline Period Traditional Intervention

Traditional speech therapy with home practice continued in the baseline period (subject ages 7;6-7;11). This baseline period was longer than anticipated, because of an unexpectedly long delay in receiving Dora's custom-fit palate from the manufacturer. Dora received five 30-45 min therapy sessions with the project SLP during this time and at least 10 similar-length sessions with the school SLP. The vowel /i/ and the velar stop /k/ were targeted in the university program. The same targets, the approximant /l/ and sibilants, were targeted in the school program which was completely independent of the university program. The syllabic nasal [m̩] substitution for /i/ was considered to be interfering significantly with intelligibility because of its negative impact on both word structure and segmental accuracy. Furthermore, the Tye-Murray and Kirk (1993) study suggested that there might have been more accurate production for /i/ after 3½ years with the implant. The lack of success with auditory input alone suggested a need for focused speech therapy targeting this vowel. By targeting /k/, /l/, and sibilants, new categories in terms of place (the velar /k/), manner (the approximant /l/ and sibilants), and voicing (the voiceless stop /k/) could be addressed. Traditional speech therapy methods were employed, introducing the sounds in isolation, then targeting them in progressively longer units, using visual (mirror and adult models), tactile and verbal cues, and models. For example, the project SLP used a mirror and verbal cues to demonstrate the lack of lip closure for /i/. In the last few weeks of the baseline period, Dora wore a hockey mouth guard intermittently at home (10 min a day approximately), in order to become accustomed to having an appliance in her mouth. This was encouraged because she had expressed some apprehension about wearing a mouth appliance.

A post-baseline speech probe with associated palatograms was recorded on the palatometer at the end of this period (subject age 7;11). The subject could see the palatometric displays but had been given no information about their meaning at this point. The 74-word sample included consonants of English (except labiodentals /f/ and /v/, /w/, /ð/, and /ʒ/) in a variety of vowel contexts in initial and final position (word shapes CVC [42], VC [10], CV [21], CVCVC [1]).

Results of the post-baseline treatment. The 5-month post-baseline speech sample showed consistent production of treatment target [i], but no change for the untreated rhotic vowel /ɤ/. The change for /i/ had a positive effect on word shape, in that all vowels were produced as vowels post-baseline, rather than as consonants. The establishment of /i/ in comparison with the lack of change for /ɤ/ suggested a traditional treatment effect.

Consonantal changes were minimal, however. Dora was able to use [l] and [k] some of the time during structured therapy activities. There were no changes for sibilants.

Palatometry Speech Therapy Program

General Program Outline

Following the baseline probe, the palatometry program was initiated. The program consisted of 20 sessions of 40-50 min each in the first author's university office, distributed across 5 months of contact time (subject ages 7;11-8;4). The program had two treatment blocks of eight sessions each, a 1-month treatment break, and a final maintenance phase (four sessions over 6 weeks). A minimal amount of traditional therapy continued in the latter portion of this period with the school SLP.

The project SLP (second author), who also had a custom-fit palate, conducted the sessions. Speech sounds were modeled with and without the palatometer at the appropriate level of complexity (isolation, syllable, word, phrase). Dora was asked to repeat the model while trying to match the visual display of the clinician. Her production was displayed visually and played back as a sound file through the computer. Printed cues and stories containing the speech targets were used as motivators and visual supports. In addition, a mirror was available for visual models and feedback, and tactile cues were also used when necessary. Words from the assessment word lists were not used in treatment, thus reducing bias in the post-palatometry probe and allowing for an evaluation of generalization across words. Prompts, cues, and verbal models were gradually faded with the child being asked to attempt the targets on her own, first using the clinician's stored models on the computer as a guide and then on her own without the guide. At the beginning of the program, the pseudopalate was used initially for about 10 to 15 min, increasing up to 20 to 30 min, as the child became accustomed to wearing the pseudopalate. Time spent wearing the pseudopalate decreased again as the child gained competence with a given target. Time in therapy without the pseudopalate allowed her to practice in more normal speaking conditions. This was considered to be important because studies such as Hamlet and Stone (1978) and McFarland and Baum (1995) suggest that there are fairly lengthy accommodation periods to mouth appliances or obstructions, even for normal speakers. Furthermore, Dagenais' (1992) research with deaf students suggested that a combination of palatometry drill and more communicative approaches were more likely to result in stable changes. Small prizes and stickers were used as motivators throughout the program.

A parent sat in the room for each session. The parent would interpret for the child in sign if verbal instructions were misunderstood. Palatogram printouts and lists of sounds, syllables, words, or phrases were given to the family for home reminders and practice.

Palatometry Intervention Targets

Because changes for consonants had been few in the baseline period, the more extensive 153-word assessment sample, rather than the 74-word post-baseline sample, was examined to determine targets for the palatometry program. The following targets each had equal time allocation in the program: (a) the velar stop /g/ as a contrast with the alveolar stop /d/; (b) coronal fricatives and affricates /s/, /ʃ/, /tʃ/, and /dʒ/; and (c) /r/ in clusters. Rationales for the targets of choice follow.

First, velar place was virtually absent in her speech, and was thus a continuing goal. When she first put the pseudopalate into her mouth, however, a gag reflex resulted in production of only velars and not alveolars. Thus, it was decided to target both /d/ and /g/ as a contrasting pair, both with the pseudopalate in and out of her mouth. The voiced stops were chosen rather than /k/ and /t/ because voiced stops were better established in general. The focus could be on place of articulation, rather than on both place and voicing. The velar nasal was not chosen because /ŋ/ is not used word initially in English and thus had limited generalization potential. It was predicted that the /g/-/d/ contrast would generalize to the /k/-/t/ contrast because she had produced a [k] at initial assessment and was able to produce [k] occasionally as a result of baseline treatment. Less generalization was expected to the nasal [ŋ] because nasals were overall a weaker category than stops.

Secondly, targeting sibilants and affricates allowed a number of goals to be addressed: (a) general expansion of the fricative category, (b) tongue grooving for turbulent airflow, (c) distinction of alveolar and palatoalveolar place, and (d) voicing contrasts. Dora already used labiodental fricatives /f/ and /v/, but sibilants were restricted in use. Targeting sibilants provided an opportunity to increase the fricative category. On the palatometer, tongue grooves for the alveolar, palatoalveolar fricatives, and affricates are distinctly displayed, allowing accurate imitation for turbulent airflow. A variety of fricatives and affricates requiring tongue grooving were therefore selected as targets (/s/, /ʃ/, /tʃ/, /dʒ/). This choice also contrasting of alveolar (/s/) and palatoalveolar place (/ʃ/, /tʃ/, /dʒ/), and voicing contrasts within the fricative category. It was anticipated that Dora's ability to produce voiced stops would facilitate production of /dʒ/, and by extension, possibly /z/ and /ʒ/. Targeting the sibilants might also result in establishment of other coronal fricatives /θ/ and /ð/.

Finally, approximants were also limited in her system. The glide [w] was present some of the time at initial assessment. Because /i/ was present at the post-baseline point, the related glide /j/ was expected to develop spontaneously. The post-baseline probe showed that /l/ was beginning to develop. The approximant /r/ can be difficult to learn, however, both because its spectral characteristics overlap with those of the other approximants and because its articulatory configuration is complex and variable depending on vowel and word position contexts. The palatometer provides potentially useful visual feedback about back tongue-palate contact patterns for /r/, a consonant with low visibility. Thus, /r/ was the target of choice among the approximants. The /r/ appeared more stimulable in clusters at the beginning of treatment; therefore /r/ was targeted in word-initial clusters. It was hypothesized that the focus on this approximant would lead to other gains within the approximant category. It was also predicted that focus on /r/-clusters would lead to greater use of clusters in general, which were often reduced.

The choice of these targets reflected both Dora's needs and the type of displays available on the palatometer. Velar and sibilant targets were common in other palatometry studies with the deaf for similar reasons (Dagenais, 1992; Fletcher et al., 1991). Dora's study was unique in targeting /r/-clusters and affricates.

Outcomes Evaluation Procedures

The first two levels of the World Health Organization's (1997) model of ability were addressed in this study: body (or impairment) and activity limitations (formerly labeled disability). Speakers with severe speech impairment tend to converse most often with listeners familiar with disordered speech because unpracticed listeners often have difficulty understanding them. Thus, impairment level evaluations are relevant as measures of change for persons with severe speech impairments. But one of the goals of speech habilitation is to enable people to perform with greater ease daily activities in contexts where there are people who are not necessarily familiar with disordered speech. Thus, activity level evaluations are equally important. Evaluation procedures used in this study are outlined below.

The major impairment level evaluation was a quantitative comparison of initial and final assessment accuracy for treatment and non-treatment targets. This was based on narrow phonetic transcription of 153 single words from audiotapes. Only these word lists were utilized for the major analysis because consonant changes had been negligible between the initial assessment and the post-baseline probe. The word lists and taping methods were equivalent between the initial and final assessments. The intermediate post-baseline probe had only 74 words and was recorded on the palatometer, rather than on audiotape. For the final assessment, the first author, who did not participate in the intervention, transcribed the 153-word sample. A second listener who had not been involved in the project transcribed 20% of that sample. Because the second author had conducted the intervention, his participation in transcription and analysis of the final tapes was considered potentially biasing. Thus he did not participate in the final evaluation. Reliability between the two transcribers was 71% for phonemes and diacritics, with differences equally reflecting vowel quality, aspiration, place of articulation, and "r"-coloring. A final consensus transcription was constructed by the two transcribers, in which the least favorable variant to the study was selected, if there was uncertainty.

The fourth author of this paper conducted an activity level evaluation, focusing on word and sample identification (Williams, 1998). For that evaluation, 16 untrained listeners (between 17 and 32 years of age) performed two tasks: (a) an orthographic transcription of words and sentences and (b) a judgment task identifying which of two samples (pre- or post-treatment) was easier to understand. All listeners had completed high school, had normal hearing, and were native speakers of English. No listener had prior experience with disordered speech. They attended two 1-hr listening sessions, which were a minimum of 2 to 3 days apart. Stimuli for the listening tasks were selected from audiotaped recordings of Dora's initial and final assessments, both from the 153-word list and from the Rainbow Passage (see Appendix A). All stimuli were digitized with a sampling rate of 20 kHz using the Computerized Speech Research Environment 45 (CSRE45) software and the Tucker Davis Technologies (TDT) hardware. The Ecosgen program in CSRE45 was used to set up the experimental protocol with randomized blocks. Due to the different recording levels of the original audiotapes, sound files were attenuated or amplified during pre-processing so that pairs of stimuli were presented at similar (comfortable) levels as determined by the experimenter. Stimuli were presented to the listeners using Ecosgen via the TDT; participants listened through Madsen TDH 39P 10W headphones levels in a sound-attenuating, double-walled Industrial Acoustical Company booth.

For the judgment task, listeners identified which of each pair of 20 sentences or phrases was easier to understand and made their selection on the computer. For Dora, the 20 pairs of sentences came from a doubling of 10 initial and final assessment phrases or sentences from the Fairbanks (1960) Rainbow Passage (see Appendix A), that is, 10 pairs in an initial-final order, and 10 pairs in a final-initial order (randomly presented). All phrases or sentences for judgment were about the same length, hence the subdivision of some of the long sentences in the Rainbow Passage. Listeners performed the identification tasks after the judgment task, so that they would have some minimal exposure to the disordered speech. The word and sentence transcription task also used the Ecosgen program. For word identification, listeners were asked to identify 20 words in writing (open set with no visual cues), 10 words from the 153-word assessment tape, and the same 10 from the final assessment tape. The words were chosen semi-randomly from the list. Words had a variety of word lengths and structures, with the sample containing 10 phonemes targeted in therapy. Not all words contained therapy targets. Words from the initial assessment were presented to listeners during the first 1-hr session, and words from the final assessment were presented during the second 1-hr session. Again, randomization of stimuli was used to minimize practice effects. For the sentence/phrase transcription tasks, three different sentences or phrases each were chosen from the initial and final assessment Rainbow Passages. This was not optimal because the sentences/phrases had been heard in the judgment task, but no other options were available. During these tasks, listeners again heard the stimuli over headphones at the computer terminal. Listeners could control the time spent on each stimulus; however, they could not replay the stimuli.

RESULTS

Outcomes: Impairment Level

Final Assessment: Word Structure

Word shape accuracy in terms of consonant and vowel sequences improved to 71.5% accuracy by the end of the study (see Table 3). Some of this improvement reflected changes in vowel accuracy that had occurred in the baseline period for the vowel /i/. However, other changes in word shape occurred during the palatometry period: an increase in final consonant use, elimination of intrusive consonants around sibilants, and an increase from 45.5% to 81.5% in the use of consonant clusters for cluster targets. Some of the syllable-initial clusters were produced with the epenthetic vowel [ə] post-treatment, which negatively impacted actual word shape match because of the addition of a vowel. Quantitative results were calculated by the first author according to procedures described in Bernhardt (1990).

Final Assessment: Consonants

Consonant accuracy increased notably in the palatometry period. At final assessment, 51.8% of the consonants in the 153 words matched adult targets, reflecting a gain of 35% in accuracy from the initial assessment and a similar gain from the post-baseline probe. Gains were noted for palatometry targets and other

Table 3

Percentage Match of Child Consonants with Adult Targets at Initial and Final Assessments

Category all C's[a]	Specific segments	Initial assessment 64/380 (16.8%)	Final assessment 197/380 (51.8%)	Difference 35%
Manner[b]	Stops (as stops)	88/116 (75.9%)	104/116 (89.7%)	13.8%
	Nasals (as such)	43/67 (64.2%)	59/67 (88.1%)	24.1%
	Fricates and affricates (as such)	41/106 (38.7%)	80/106 (75.5%)	36.8%
	SI approximants (as such)	37/54 (68.5%)	46/54 (85.1%)	16.6%
Place				
Velar	/g/[c]	0/12 (0%)	7/12 (58.3%)	58.3%
	/k/[d]	1/30 (3.3%)	20/30 (66.7%)	63.4%
	/ŋ/[d]	1/23 (4.3%)	0/23 (0%)	-4.3%
Alveolar	/s/[c]	0/33 (0%)	13/33 (39.4%)	39.4%
	/z/[d]	0/14 (0%)	10/14 (71.4%)	71.4%
Palatoalveolar	/ʃ/[c]	5/5 (100%)	5/5 (100%)	0%
	/ʒ/[d]	1/1 (100%)	1/1 (100%)	100%
	/tʃ/[c]	5/9 (55.6%)	7/9 (77.8%)	22.2%
	/dʒ/[c]	4/8 (50%)	4/8 (50%)	0%
Details for sibilants	/tʃ/: Place + affrication[c]	0/9 (0%)	7/9 (77.8%)	77.8%
	/dʒ/: Place + affrication[c]	0/8 (0%)	2/8 (25%)	25%
	Lateral release (inaccurate)[c]	46/49 (97.9%)	3/60 (5%)	92.9%
	Accurate tongue grooving[c] on sibilants produced	0/49 (0%)	12/60 (20%)	20%
Clusters	/r/-clusters[c]	0/15 (0%)	0/15 (0%)	0%
	CC sequence for CC target[d]	22/52 (42.3%)	41/52 (78.9%)	36.6%

[a]Each consonant in child's word judged in comparison to adult target in that word, that is, cluster segments evaluated separately. [b]Manner judged in terms of manner features only; place judged in terms of place features only. [c]Treatment targets. [d]Generalization targets.

phonemes, both in transcriptions (see Appendix B and Table 3) and in the general patterns of contact on the palatograms. Figures 1 - 4 show representative samples of pre- and post-palatograms and adult models. Palatograms were evaluated descriptively by the first two authors. The child's patterns were compared to those of the following expected adult patterns: (a) velars required contact across the back third of the palatogram; (b) sibilants required lateral contact and a central groove, with the alveolars requiring more contact in the front section of the palatogram compared to palatoalveolars; and (c) alveolar stops required a "horseshoe" shape.

In terms of the velars, the treatment target /g/ matched the adult target 58.3% of the time (7/12). The velar generalization target /k/ was a 66.7% match (20/30; with only 2/13 word-initial targets showing any voicing). There were no matches for the velar nasal. When velars were inaccurate, alveolars usually substituted for them. However, uvulars occasionally appeared, or stops were over-articulated with heavy aspiration, affrication ([kχ], [gɣ]), or insertion of an epenthetic [ə] after a word-final [g]. As they had in the initial assessment, the contrasting treatment targets /d/ and /t/ consistently matched the adult target for place and manner. Unlike /k/, untreated /t/ and /p/ showed no improvement in voicing word initially. The related untreated alveolar nasal /n/ did show gains word initially (3/4).

Sibilants and affricates also showed gains. Coronal fricatives and affricates were no longer released laterally. One or two tokens each of /s/, /z/, /ʃ/, and /tʃ/ exactly matched adult targets (e.g., *noise* [nɔəz], *brushing* [waʃĩn]). There continued to be inaccuracies in grooving, exact place, or voicing for many tokens. (The treatment target /s/ and generalization target /z/ were produced some of the time with accurate place as alveolars, 50% for /s/, and 71% for /z/, showing contrast in place with palatoalveolars /ʃ/, /tʃ/, /dʒ/, and generalization target /ʒ/.) Of the affricates, /tʃ/ was completely accurate 80% of the time (8/9), compared with 0% (0/9) in the initial assessment. Word-initial /dʒ/ was still produced as a stop, although [dʒ] did appear as a word-initial substitution for /tʃ/. Elsewhere in the word, /dʒ/ was accurately produced 25% (2/8) of the time. Only 12/60 tokens showed appropriate tongue grooving for sibilance. In terms of voicing, there were a few tokens of voiced fricatives and affricates. In terms of the fricative category, there were general gains. Coronal generalization target /θ/ was accurately produced 6/8 times and also substituted for the voiced interdental /ð/ which showed no change otherwise. Untreated /h/, which could be classified as a noncoronal fricative, matched the target 100% of the time (6/6), compared with 3/6 in the initial sample. Labiodental fricatives showed improvement in non-word-initial positions, in that they were less likely to be deleted.

In terms of the approximant goal, no /r/ appeared in the sample, although /r/-clusters had been produced in treatment sessions. There were changes in substitution patterns for manner, however. Whereas [b] had substituted for word-initial /r/ in the initial assessment sample, the approximant [w], sometimes with "r"-

coloring, was the typical substitute in the final assessment. Other untreated approximants also showed gains: all syllable-initial /l/'s were accurate (even in clusters), and /w/ and /j/ only showed one nonmatch each.

Labials and /h/ were least likely generalization targets in the palatometry program and were less likely to improve because of their high level of accuracy pretreatment. However, some improvements were noted. Labiodental fricatives and /h/ were less often deleted. The nasal /m/ was produced less often with a labial stop component (3/10 compared with 6/10 in the initial assessment). However, the voiceless /p/ showed minimal gain in word-initial position for voicing, with 2/7 targets showing aspiration.

Outcomes: Activity Limitations

Sixteen untrained adult listeners chose an average of 91.25% of post-therapy sentences as easier to understand in the judgment task (range of 75% to 100%). As Table 4 shows, there was a significant increase in accuracy of identification of single words, words in sentences, and palatometry speech sound targets after palatometry, from less than 12% accuracy at Time 1 (range of 0% to 29%) to over 50% accuracy at Time 2 (range of 30% to 76%).

Discussion

In spite of strong language skills in sign and reading and good speech comprehension, Dora had unintelligible speech after almost 4 years with an implant and total communication program. The etiology of CMV, the age of implantation, and the particular speech processor may have been relevant factors in her slow progress in speech production.

Dora's phoneme accuracy on the single-word list at initial assessment was

Table 4

Activity Limitation Outcomes: Accuracy of Consonant and Word Identification by Untrained Listeners for Assessment and Post-Palatometry Samples

Task	Initial assessment	Final assessment	Difference
Single word identification	10.6% (0%-20%)[a]	54.4% (30%-70%)	43.8%
Identification of words in sentences	12.0% (0%-29%)	51.9% (24%-77%)	39.9%
Identification of therapy targets in words	6.3% (0%-30%)	59.4% (40%-80%)	53.1%
Identification of therapy targets in sentences	1.3% (0%-20%)	38.8% (15%-75%)	37.5%

[a]Range of responses in parentheses.

equivalent to that of the least successful subjects (i.e., a 16% range of consonant accuracy) in Tye-Murray et al. (1995) and Spencer et al. (1998). Their samples were based on connected speech, a condition in which Dora's speech was even more unintelligible. Her phonological patterns were generally typical of deaf speech, irrespective of intervention method. She had particular difficulty with fricatives, less visible consonants, approximants, front vowels, consonant clusters, and final consonants. One unusual characteristic was the use of syllabic [m̩] for the vowel /i/. This latter pattern and the lack of /s/ and /z/ possibly reflected difficulty in perceiving the high third formant of the vowel /i/ (Bernhardt & Stemberger, 1999; Tye-Murray & Kirk, 1993). Treatment for /i/ in the baseline period included frequent use of a mirror to make her aware of the fact that the mouth did not close for the vowel /i/. With that additional visual feedback, she did acquire the phoneme /i/. However, consonants showed minimal gain after 5 months of traditional treatment in that period.

In comparison with the slow progress for consonants in the baseline traditional treatment program, her speech production improved notably in the palatometry period (an equivalent time period). Of the 380 consonants in the 153-word sample, 51.8% matched adult targets in the final assessment, compared with 16.8% in the initial assessment. This improvement represented a considerable reduction in speech impairment. Her final assessment accuracy level compared favorably to that of the better subjects in the Tye-Murray et al. (1995) and the Spencer et al. (1998) studies, although in those studies, more difficult connected speech samples were used. In terms of activity level limitations, untrained listener word identification tasks showed a significant increase from less than 12% to over 50% word identification, which again compared favorably with the better subjects in the Tye-Murray et al. (1995) study.

The most stringent evaluations of efficacy involve complex experimental designs across large groups of subjects with statistical support. This case study was not of that type; therefore the specific gains observed cannot be convincingly attributed to the use of palatometer. However, it is possible to examine the treatment, generalization, and non-treatment targets qualitatively to ascertain whether there might have been suggested effects. Significant gains for treatment targets in comparison to non-treatment control targets suggest tentative treatment effects. When consonants related to treatment targets also show significant gains, this further suggests treatment effects through generalization within sound classes, across voicing cognates, from one type of cluster to another, and across word positions.

All palatometry targets were used some of the time in spontaneous speech, with the exception of /r/-clusters. Of the treatment targets, the greatest gains were for velars. Stops were already generally accurate for manner; thus, place could be the focus of treatment. As predicted, the velar generalization target /k/ showed considerable gains, both in place and voicing. In English, /k/ is generally more heavily aspirated. Her tendency to overarticulate the velar /g/ may have facilitated production of a strongly articulated voiceless stop. In comparison, non-treatment targets /t/ and /p/ showed only minimal improvement for the feature [-voice] word initially. For the velar nasal, there was a slight regression at the end of the palatometry period. Minimal generalization from /g/ to /ŋ/ had been predicted because nasals were less accurate than stops overall, although a regression had not been anticipated. It is possible that transcription of the velar nasal was inaccurate in the assessment sample. Accuracy level for velar stops after palatometry were equivalent to those of age-matched better-performing subjects in the Tye-Murray et al. (1995) study and thus represented a notable gain from a pre-palatometry comparison with the subjects in that study. Overall, the changes in velar production suggest a possible effect of palatometry treatment for this subject; both the treatment target and major generalization target were reasonably well-established after palatometry. Generalization target /k/ showed changes in voicing accuracy, which was not observed for /t/ and /p/.

The coronal fricatives and affricates improved in terms of place of articulation and in the change to central rather than lateral release. One or two tokens each of /s/, /z/, /ʃ/, and /tʃ/ were produced completely accurately in terms of tongue grooving, place, and voicing. The place and tongue grooving distinctions suggest an effect of visual feedback given by the palatometer, which has direct information on tongue contact points for those fricatives. Another coronal fricative, [θ], also appeared in the post-palatometry assessment, both as a match and as a substitution for /ð/. Dentals are produced with a front and ungrooved articulation (not unlike her ungrooved [s̺]); as predicted, the [θ] may have generalized from training on the other coronal fricatives, although that cannot be determined from the design. Dora's alveolar and dental fricative production compared favorably with age-matched average performance for those targets in the Tye-Murray et al. (1995) study which was also a notable improvement for Dora from a pre-palatometry comparison. Her palatoalveolars were more accurate than best performance in the Tye-Murray et al. (1995) study, particularly after palatometry. The general category of fricative showed a 36.8% gain in manner accuracy to a level just below that of the other manner categories. The specific changes in coronal fricatives suggest effects of palatometry because of the precision in tongue-palate contact patterns. Whether the general improvements in fricative production (especially for labiodental fricatives and /h/) can also be attributed to palatometry cannot be determined.

Although she had done so in treatment sessions, Dora did not produce /r/ or /r/-clusters accurately in the post-treatment assessment sample, but she did show a predicted gain of 36.6% in consonant production in clusters. Cluster reduction was less common: 78.9% of clusters were produced with two consonants. Improvement was seen for untreated sonorant consonants: /l/, nasals, glides /j/ and /w/. All of those sonorant consonants had been improving before palatometry;

therefore further gains might have occurred spontaneously. It is possible also that treatment for the sonorant /r/ helped accelerate their development although that cannot be determined.

As stated at the outset, no definitive claims can be made on the basis of this case study about the direct relative benefits of palatometry for this child. Her progress in this palatometry period was much faster than her progress in the previous 4 years, however, suggesting that palatometry was not disadvantageous to her rehabilitation program. Gains for velars and sibilants in comparison to other speech sounds do suggest some specific effects of palatometry. Her rate of progress was reminiscent of that of other deaf subjects with severe speech impairment in palatometry studies (Fletcher et al., 1991). Visual feedback as provided by palatometry appears to have been at least a useful adjunct in a speech habilitation program for this child who had a cochlear implant and unintelligible speech. Whether strict experimental designs with larger subject groups will confirm initial trends observed here is a question for future research.

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APPENDIX A

STIMULI USED FOR LISTENER EVALUATION TASKS

Sentences and Phrases from the Rainbow Passage (Fairbanks, 1960)[a]

a. The sunlight strikes raindrops in the air.
b. They act like a prism and "from" a rainbow.
c. The rainbow is a division of white light into many beautiful colors.
d. These take the shape of a long round arch.
e. Two ends apparently beyond the horizon.
f. Boiling pot of gold at one end.
g. People look, but no one ever finds it.
h. No one ever finds it.
i. A man looks for something beyond his reach.
j. His friends say he is looking for a pot of gold at the end of the rainbow.

Words from the Single Word List

screwdriver	frog
mouthy	noisy
glasses	boot
snow	bib
truck	on

Underlined phonemes in this sample were targeted in palatometry therapy (10 total).

[a]Long sentences were subdivided into phrases to create stimuli of approximately the same length.

APPENDIX B

EXAMPLES FROM THE INITIAL AND FINAL ASSESSMENTS

Target	Adult Pronunciation	Initial Assessment	Post-Palatometry
eating	(ʔ)itĩŋ	m̩fĩn	itʰə̃n
music	mjuzɪk	buʆˡdɪtm̩	mjuz$_{o}$ɪt [a]
pouring	pʰɔr̃iŋ	p$_{v}$ɔbwẽĩn	p$_{v}$ɔw̢ĩn [b]
television	tʰɛləvɪʒə̃n	t$_{v}$ʌbɪʔbɪʆˡɪv	t$_{v}$ɛləvɪʃə̃n [c,d]
truck	tʰrʌk	fwʌʔ	fwʌkx, tʊwʌkx
dollhouse	dɑlhaʊs	dɑːʊʔaʊʆˡ	dɑːʊhaʊʆ [<e]
dress	drɛs	bɢɛʆ [f]	wɛs>ʃ [g]; ˈdəwɛʆ [<]
candle	kʰæ̃ndl	t$_{v}$æ̃ːndoʊ	kʰæ̃ə̃ndl
glovey	glʌvi	fwʌbm̩	gəlʌˈvi
fishing	fɪʃĩŋ	fːʔf$_{p}$ɪʆˡdĩn [h]	fiʆĩn
frog	frɑg	w̢ɑd̚d	fwɑːˈgəʔ
throw	θroʊ	w̢oʊ	θloʊ
Santa Claus	sæ̃n(t)əkʰlɑz	t$_{v}$æːnʔtɛmʆˡvwɑʆˡ	çæ̃ntəkʰəlɑs [>]
sis	sɪs	ʆˡdɪʆˡ	ʆɪʆ; ʆɪs [>]
s̲oap	soʊp	ʆˡoʊm$_{o}$	ʆoʊp
spoon	spũn	ʆˡpuə̃m	spuə̃n
sweater	swɛrɤ	ʆˡʔbɛtʔtə	çwɛrə
zipper	zɪpɤ	v$_{b}$ɪbə	djɪpɛə
church	tʃɤtʃ	t$_{v}$ʌʆ̢ˡ	dʒʊətʆ
jump	dʒʌ̃mp	dʌ̃m	dʌ̃mp
red	rɛd	bɛʔ	w̢ɛt
watch	wɑtʃ	bɑʆˡt	wɑtʆ
yellow	jɛloʊ	bɛv$_{b}$oʊ	jɛloʊ
hang	hæ̃ŋ	ʔẽĩm	hẽĩngɪʔ

Note. Adult pronunciations based on Western Canadian dialect. Words chosen are representative of the child's pronunciations at the assessment points.
[a]Devoicing of voiced targets denoted by subscript [$_{o}$]. [b]"r"-coloring indicated by hook [̢]. [c]Voicing of voiceless stops indicated by subscript [$_{v}$]. [d]Stress mark [ˈ] inserted before the stressed syllable where different from adult English target. [e]Fronting indicated by [<], backing by [>]. [f]G = voiced uvular stop. [g]Arrow indicates segment beginning as [s], ending as [ʃ]. [h][f$_{p}$], [v$_{b}$] = labiodental stops.