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A phonological system at 2 years after cochlear implantation

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Abstract

This report is a description of a developing phonological system as manifested in the productions of a prelingually deafened child approximately 2 years after fitting with a Nucleus 22-Channel Multi-Electrode Cochlear Implant. A probe list consisting of 23 proper nouns familiar to the child was used to elicit samples of her speech; stimulus materials consisted of photographs of those persons (friends and family members) whose names were included in the probe list. Analysis of the child's productions addressed the composition of the phonetic inventory of consonants and vowels and the presence of syllable structure and other phonotactic constraints. Results indicated a rich inventory of speech sound segments (among both consonants and vowels) and a lack of stringent constraints on syllable structure and consonants permitted in specified word positions. A further comparative analysis of correspondences with the ambient language showed a number of patterns that are also common in the speech of children with normal hearing.

Keywords

cochlear implants; phonology; phonetic inventory; syllable structure; substitution patterns

Introduction

The past two-and-a-half decades have witnessed a widespread proliferation of cochlear implants as auditory aids for children with severe or profound sensorineural hearing losses (see House, 1991). A cochlear implant (CI) is an electronic device, part of which is surgically implanted into the cochlea and the remaining part worn externally. The CI functions as a sensory aid, converting mechanical sound energy into a coded electric stimulus that bypasses damaged or missing hair cells of the cochlea and directly stimulates remaining auditory neural elements. Because the cochlear implant is primarily an *auditory* prosthesis, its most obvious benefit is that it provides the user with better perception of both environmental and speech sounds. Cochlear implants were originally used as assistive devices for postlingually deafened adults in order to restore at least some of the perceptual abilities diminished by hearing loss. In addition to its use as a sensory aid for the perception of external sounds, the cochlear implant also provides auditory feedback that can help users monitor their own speech.

The effects of profound hearing loss on the speech production of postlingually deafened adults are minimal (e.g. Leder and Spitzer, 1990), but if a child suffers a profound hearing loss before acquiring a spoken language, the effects are devastating. Not only is hearing itself affected, but the child's ability to acquire a spoken language is severely diminished.

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Thus, although cochlear implants were first developed for use by postlingually deafened adults, many have believed that the ultimate benefits of these devices would be ‘for children, particularly young children’ (Berliner, Eisenberg and House, 1985). Such benefits would, most importantly, include providing the necessary auditory input for the acquisition of accurate speech production and target-appropriate spoken language.

Detailed studies of the speech production characteristics of children using cochlear implants are relatively recent. Tobey, Angelette, Murchison, Nicosia, Sprague, Staller, Brimacombe and Beiter (1991a) examined imitative segmental and non-segmental characteristics, phonological skills, and intelligibility (following Ling, 1976, and McGarr, 1983) in 61 children who used the Nucleus multichannel cochlear implant. Improvement on at least one-third of the measures was reported for 79% of the children. Improvement was most prevalent for imitative segmental aspects (66.7% of the children), followed by intelligibility (62.9%), phonological skills (55.6%), and non-segmental aspects (31.1%). Tobey and Hasenstab (1991) examined speech production by 78 children using the Nucleus device before implantation and up to four times after implantation. The children demonstrated increased scores on both suprasegmental and segmental measures after implantation and with increasing device use. Speech intelligibility was also higher after implantation than before, but mean length of utterance was not significantly changed. Tobey, Pancamo, Staller, Brimacombe and Beiter (1991b) examined consonant production in 29 children before fitting with a Nucleus multichannel cochlear implant and after 1 year of device use. They found that a greater number of children produced stops, nasals, fricatives and glides after implantation than before. Voiced stops were used by more children after implantation than voiceless stops, although voiceless fricatives were produced more than voiced ones. Additionally, consonants with visible places of articulation were used more than those with less visible places.

Tobey, Geers and Brenner (1994) analysed the speech production skills of 13 matched groups of children with cochlear implants, tactile aids and hearing aids, as well as 13 children with pure tone averages (PTAs) between 90 and 100 dB HL. All children except the last group were tested once a year for 3 years in both imitative and spontaneous speech tasks; the last group was tested once at the end of the study for comparison with the other three groups. For imitated speech production, significant differences among groups were apparent first at the 24-month interval, when cochlear implant user performance was better than tactile aid and hearing aid user performance on suprasegmentals and diphthongs. By the 36-month interval, however, cochlear implant users outperformed the other two groups on most measures, although differences were not significant. In spontaneous speech the cochlear implant users also showed significantly greater improvement than the two other groups. Finally, after 3 years of device use, the cochlear implant group showed similar performance to the children with PTAs between 90 and 100 dB HL.

Kirk, Diefendorf, Riley and Osberger (1995) compared consonant feature production in CV syllables by 24 multichannel cochlear implant users at two points in time and further compared this with production by 32 hearing aid users. Cochlear implant users demonstrated significant improvements in the production of voicing, place and manner features after approximately 2.6 years of device use. Additionally, production by the cochlear implant users was in some cases better than many hearing aid users at the second interval. Another study by Sehgal, Kirk, Svirsky, Ertmer and Osberger (1998) examined consonant feature production in CV syllables by cochlear implant users and vibrotactile aid users. Both groups were tested before implantation and again approximately 1.5 years after implantation. Both groups showed relatively poor production of voicing, place and manner features at the preimplant interval. Both groups also showed improved production at the postimplant interval, but improvement by the cochlear implant users was significantly greater. Cochlear

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implant users improved performance on one place feature and all of the manner features. Ertmer, Kirk, Sehgal, Riley and Osberger (1997) examined longitudinal changes in imitative vowel and diphthong production in 10 children using cochlear implants and 10 children using tactile aids. From the preimplant interval to the postimplant interval, cochlear implant users showed significant improvement on seven of nine vowel and diphthong production measures, whereas the tactile users significantly increased performance on only one measure. Additionally, at the postimplant interval, cochlear implant users had significantly higher scores on eight of the nine measures than the tactile aid users.

Published research thus indicates that cochlear implants are beneficial for the development of speech production. However, most published studies regarding speech production by paediatric cochlear implant users are like the works just cited; that is, either longitudinal or cross-sectional or both, but always involving groups of children and therefore grouped data. A widespread phenomenon in the paediatric cochlear implant literature is a large amount of individual variation. Although grouped data are useful for discerning broad patterns in the population of paediatric cochlear implant users, the problem of inter-subject variability cannot seriously be addressed if complete, in-depth descriptions are not available for individual subjects. The goal of this report is to provide a description of a developing phonological system manifested in the speech productions of a single prelingually deafened child approximately 2 years after fitting with a cochlear implant.

By ‘phonological system’ we do not refer to a system of analysis or methodology, but rather simply to the sound pattern of a language. In approaching this child's speech productions we initially make the basic assumption that the productions represent a unique and independent language, with its own set of rules and constraints, that is, without regard to the correctness or appropriateness of productions relative to the ambient language (English, in this case). This approach has been adopted, because internal systematicity in a developing phonology can be obscured if productions are considered only in the context of their relation to the ambient language (in much the same way, it is no longer believed that a synchronic linguistic description of French is incomplete without repeated reference to Latin; e.g., Tranel, 1981, 1995). However, given that a major purpose of fitting with a cochlear implant is to allow its user to function linguistically in a speech community, we have also noted those points at which the developing system and the ambient system differ, as well as those points where differences are themselves systematic. Furthermore, although our description is based on five elicitations of identical material over 7 weeks, we are treating this as a synchronic description rather than a diachronic one.

We characterize the system described here as ‘developing’, primarily because of the child's age (approximately 5 years, 8 months) and the relatively short length of auditory experience with a cochlear implant (approximately 2 years). The description of this child's phonological system concentrates on two characteristics: (1) the inventory of consonants and vowels—that is, the inventory of speech sounds that can be combined to form meaningful linguistic units; and (2) phonotactic constraints—that is, constraints on possible sequences of sound segments. Accounting for at least these two characteristics, an inventory and a set of phonotactic constraints, is necessary for the accurate description of any language, be it developing or fully developed. That is, no language has yet been found that does not constrain the set of speech sound segments used to form meaningful units, and no language lacks constraints on how those sounds can be sequenced (see Maddieson, 1984). In approaching the child's phonological system from these perspectives we are applying elements of basic principles and methodology of both descriptive and theoretical linguistics (e.g. uniqueness of the system, initial descriptive adequacy—Chomsky, 1965); such principles and basic methodology have also been adopted for clinical linguistics (e.g. Elbert and Gierut, 1986; Dinnsen, Chin, Elbert and Powell, 1990).

Methods

Subject

The subject G.K. (not initials) was a white female, age 5;8 (years;months) at the time of first elicitation (described below). Profound hearing impairment was congenital and attributed to Waardenburg Syndrome. Bilateral hearing aid fitting (Phonak Pico-Forte PPC-L) took place at 0;10. Fitting of the right ear with a Nucleus 22-Channel Multi-Electrode Cochlear Implant (Cochlear Corporation) was performed at the Indiana University Medical Center (Indianapolis, Indiana, USA) at age 3;10. The surgery achieved full insertion of 22 electrodes, with subsequent mapping for 19 electrodes. A Mini Speech Processor (MSP) implemented the Multi-Peak (MPeak) processing strategy (see below).

Unaided pure-tone audiometric testing under headphones was performed approximately 4 months prior to fitting with the cochlear implant. Because the subject refused to continue wearing the headphones, testing was performed for puretone frequencies only between 250 and 2000 Hz. However, even these partial results indicated a severe to profound bilateral loss; all tested frequencies showed thresholds≥ 85 dB HL for both ears, and thresholds increased as frequency increased. Thresholds for the right ear appeared slightly higher than for the left, and at 750 Hz the threshold was > 120 dB HL. Tympanometry of equal date was within normal limits.

G.K. was seen for both testing and speech–language therapy at the DeVault Otologic Research Laboratory at the Indiana University School of Medicine (Indianapolis, Indiana). Testing sessions took place at 6-month intervals for the first 3 years after fitting with the cochlear implant, whereas speech–language therapy sessions were conducted twice weekly. Data for the present study were collected during therapy sessions (see below), during a period between the 1.5-year and 2.0-year postimplant testing sessions. Testing sessions included a battery of speech perception and speech production tasks (see Kirk, Diefendorf, Pisoni and Robbins, 1997, for a description of the complete speech perception battery). Tests of speech perception included both open-set and closed-set tasks; scores from one of each type from the 1.5- and 2.0-year postimplant sessions are reported in the Appendix. Also included in the Appendix are measures of intelligence and language, also taken at 1.5 and 2.0 years after implantation. No specific claim is being made in the present work regarding any relation between the measures presented in the Appendix and the phonological description below.

Device

As mentioned earlier, a cochlear implant consists of both internal and external components. External components are a microphone, a signal processor, and a transmitter. The microphone (worn above the ear) receives acoustic signals (speech or otherwise), transducing them into an analogue electrical signal that is sent to the processor. The processor modifies (amplifies, compresses, filters, shapes) the signal into a desired pattern (various processing schemes are available) and sends this modified signal to an external transmitter placed on the skin above the mastoid. This transmitter transfers the signal across the skin using radiofrequency transmission to a subcutaneous receiver/stimulator embedded in the mastoid bone directly beneath the transmitter. An array of one or more electrodes extends from the receiver/stimulator and is inserted into the cochlea, generally through the round window and around the scala tympani of the basal turn of the cochlea. Thus positioned, the electrodes can deliver electrical stimulation to excite the cochlear neurons of the auditory nerve, bypassing hair cells that may be missing or damaged, producing a sensation of sound.

The particular device used by G.K. was the Nucleus 22-Channel Multi-Electrode cochlear implant (see Clark, Blamey, Brown, Gusby, Dowell, Franz, Pyman, Shepherd, Tong, Webb, Hirshorn, Kuzma, Mecklenburg, Money, Patrick and Seligman, 1987). This device received government approval for use in paediatric patients in the United States in 1990 and consists of the components described in the preceding paragraph, including an active electrode array of 22 platinum bands for multiple channel stimulation. G.K. used a Mini Speech Processor (MSP), which implemented the signal processing strategy called Multi-Peak (MPeak). The MPeak strategy takes advantage of the multiple-channel capabilities of the Nucleus device by combining feature extraction and waveform processing strategies. Separate zero-crossings detectors provide estimates of F0 (from the output of a 270 Hz low-pass filter), F1 (280–1000 Hz) and F2 (800–4000 Hz). The foregoing feature-extraction strategy is further augmented by a representation of envelope variations in three high-frequency bands (2000–2800, 2800–4000 and 4000–6000 Hz) of the input signal. Stimulus frames consisting of four pulses each are presented at a rate equal to the estimated F0 during voiced segments. Two of these pulses are sent to electrodes chosen based on the F1 and F2 estimates, and the other two pulses are sent to fixed electrodes associated with the 2000–2800 and 2800–4000 Hz frequency bands. During voiceless segments the four-pulse stimulus frames are sent at quasi-random intervals averaging between 200 and 300 pps. The electrodes stimulated during voiceless segments are three fixed ones associated with the three high-frequency bands and a fourth one chosen based on the current F2 estimate (see Wilson, 1993).

Materials

Stimulus materials consisted of 23 pictures of faces similar to the subject, including those of friends, family members and laboratory staff members. Stimulus materials were digital reproductions of 3-inch × 5-inch colour photographs produced with Adobe Photoshop software. The photographs were scanned on a UMAX UC1260 scanner, and for each face a digital file was created. The digitized images were edited on a Macintosh Quadra 840AV in order to remove all background images, so that only the head and upper torso (including headwear and clothing) remained. A Tektronix Phaser 200E wax transfer printer was used to generate suitable colour stimulus materials. The images were then trimmed, mounted individually on white stock for presentation, randomized, and bound in a looseleaf notebook.

The use of proper nouns for the probe list addressed the question of lexical development in a child with profound hearing loss and the resulting severe delay in onset of production. The child was able to sign with some facility (speech–language pathologists and audiologists working with her noted some delay, although no formal measures were obtained), but it was not clear whether the development of a phonologically based lexicon had kept pace, and it was equally unclear whether any items other than names would be present in that lexicon; that is, whether specific semantic concepts had corresponding phonological representations. Finally, this being a synchronic study, it was felt that names would form a relatively stable component of the lexicon, and that both representations and productions would not change radically through multiple elicitations. Thus, in order to avoid possible training effects with unknown lexical items, it was assumed that names of persons familiar to the child would be already present in her lexicon and therefore available for elicitation in a non-imitative production task.

Procedure

The description of G.K.'s phonological system is based on data collected from five elicitation sessions that were incorporated into G.K.'s regular therapy sessions. The first elicitation session took place 647 days after fitting with the cochlear implant, with the remaining sessions completed by 693 days after fitting, or within approximately 7 weeks.

For each elicitation session the number of days following cochlear implant fitting was thus as follows: session 1: 647, session 2: 652, session 3: 659, session 4: 680, session 5: 693.

During sessions, which were conducted in a quiet therapy room, the book of pictures was shown to the subject, who was asked to say aloud the name of the person pictured on each page. If a verbal reaction was not forthcoming spontaneously, the subject was prompted by the clinician with questions such as ‘Who's that?’ or ‘Can you tell me who that is?’ No training on the names, except acknowledgement repetition during elicitation sessions or normal use of the names in everday use, was provided. Elicitation sessions were recorded on cassette audiotape using a lapel microphone attached to the front of the child's clothing and connected to a Marantz PMD430 audiocassette tape-recorder. The child's productions of the names were phonetically transcribed by the first author, who subsequently retranscribed all of the utterances to determine reliability. Intra-judge reliability was 72% for consonants and 77% for vowels (see discussion). Differences between transcriptions were generally found in voicing for consonants and in tenseness for vowels.

Phonetic and phonological targets

Target phonetic and phonological representations of names

The 23 names and target pronunciations associated with the 23 faces were as in table 1. Target pronunciations are those of G.K.'s mother, who spoke a variety of General American English common in the area of Indianapolis, Indiana, USA. Syllabification in this table is based upon a simple principle of onset maximization, with the single qualification that resulting syllable onsets must also be permissible word-initially (but see the discussion of the form *Alfred* below).

Target phonetic inventory and distribution of segments

Consonants—The target inventory of consonant (more exactly, non-syllabic or non-vocalic) segments contained in the elicitation probe is listed in table 2. A phonetic symbol indicates that the segment was contained at least once in the name elicitation probe; empty brackets indicate that the English segment at that position was absent from the elicitation probe.

Not elicited in this probe were thus the following six English segments: the voiced velar stop /g/, the voiced fricatives /\l=eth\ z \l=ezh\/, the voiceless affricate/t\m=int\/, and the velar nasal /ŋ/. Additionally, not all consonant segments were elicited in all possible word positions. Table 3 shows the nine word positions in the probe in which consonant segments could occur, as well as the number of segments that actually did occur in those positions. In this table, ‘X’ indicates any segment not a word-boundary. For instance, the three medial consonants in *Alfred* were considered to be two two-segment clusters, so that their components were distributed as follows: [l] occurred in the context [X_CX] (i.e. initial in [lf]); [f] occurred in the contexts [XC_X] and [X_CX] (i.e. final in [lf] and initial in [fr]) ; and [r] occurred in the context [XC_X] (i.e. final in [fr]). This analysis of *Alfred* (reflected in table 3) constitutes an exception to the basic principle of onset maximization in table 2; the medial cluster in this form is by far the most complex sequence of consonants in the target corpus, and the analysis in table 3 reflects potential syllabification strategies that G.K. might have used.

Vowels—Table 4 shows the target vocalic segments that were included in the probe list. Oral and nasal versions are collapsed under the oral representative. Table 5 gives the number of occurrences of each of the vowels and diphthongs in the target probe list. Target forms in the probe included five monosyllabic names, 16 disyllabic names, and two trisyllabic names.

In total, the probe list contained 27 open syllables and 16 closed syllables and contained the syllabic structure types indicated in table 6.

Results

Productions of the 23 names from the five elicitation sessions are listed in table 7. Normal orthographic representations of the names are listed in the leftmost column. The remaining five columns contain transcriptions of the names as produced by G.K. and are headed by the elicitation session number. All data reported here were collected within a span of 46 days, or just under 7 weeks. In a few cases two clear responses appeared on the tape recording; both of these appear in table 7.

Segmental inventory

Inventory of consonants—The production inventory of consonants for the forms listed in table 7 are given in table 8. This inventory is based on all productions of the names across the five elicitation sessions. As this table indicates, G.K.'s consonant inventory contained a number of non-English segments: non-English stops included [b̥ d̠]; fricatives included [s̠ z̥ sʂ ç] and the voiceless lateral fricative [ɬ]; additionally, the inventory contained the nasalized glide [w̃]. English consonants absent from the inventory included the voiced velar stop [g], the fricatives [ð z], the velar nasal [ŋ], and the liquid [ɹ]. The absence of /g ð z ɹ/ is explained quite simply by their absence from any of the names in the probe list. On the other hand, /ɹ/ did occur on the probe list. Among hearing children, /ɹ/ is mastered relatively late (see Sander, 1972), and it is not surprising that is had yet to develop in G.K.'s inventory.

Inventory of vowels—The production inventory of vowels for the forms listed in table 7 is given in table 9. As this table indicates, G.K.'s vowel inventory contained a number of non-English segments or segments not included in the target probe list of names. Non-English segments included the nasal vowels [ẽ ə̃] (i.e. nasal vowels produced in the absence of following surface nasal consonants) and the front rounded vowel [œ]. Somewhat marginal English segments (e.g. occurring in dialects not the ambient one for this child) were the monophthongal [e] and [a] and the diphthongal [əɪ] and [ao]. Finally, G.K. produced the back vowel [ɔ] (appropriately) in the form *Sawyer*.

Summary discussion—An examination of these production data reveals a fairly large inventory of consonants and vowels in this child's phonological system. All manners of articulation were represented at least once in the consonant inventory; in fact some manners were overrepresented: the fricative series, for instance, included a voiceless dental, a voiceless retroflex, and a voiceless true palatal. Additionally, the affricate series included both a voiceless and voiced labial, a voiceless dental, and voiceless and voiced alveolars, in addition to the correct voiceless and voiced alveopalatal affricates.

In addition to the occurrence of expected forward, that is, visible, consonants such as labials and dentals, less visible consonants also occurred, including (alveo-)-palatals and velars. Productions of names such as *Josh*, *Kristin*, *Marge*, and *Nick* indicate the development of non-visible sounds as well as visible ones. This serves as evidence that production indicators were being transmitted by the prosthesis and not just through the visual channel alone.

The absolute inventory of vowel segments was also fairly complete. Although it appears that back rounded vowels were for the most part absent, as indicated in table 9, it is also the case that these vowels were absent from the probe list itself, as shown in table 4.

Phonotactic constraints

Syllable structure—As illustrated in table 6, the target probe list contained two relatively marked types of syllable structure: syllables with consonant clusters and closed syllables. Compared to singleton consonants, consonant clusters are acquired relatively late in phonological development (Templin, 1957;Ingram, 1976). Ingram also notes that the exclusivity of open syllables in production (the correlate of ‘final consonant deletion’) is common in children up to about age 3 years. Although it would not be unreasonable to expect that, given her limited auditory experience, G.K.'s productions would fail to evidence consonant clusters and closed syllables, an examination of the data in table 7 does not bear out such an expectation. As seen there, G.K.'s productions did in fact contain both consonant clusters and closed syllables. With regard to initial consonant clusters, there were a number of consonant sequences that could be regarded as affricate-like (i.e. a stop followed by a homorganic fricative), among them, [pf] in *Shanan* in session 3, [pv] in *Josh* in session 3, [bv] in *Yvonne* in session 5, [ts] in *Shanan* in session 2, [dz] in *Josh* in session 5, and [tʃ] in *Sarah* in session 5. The exact analysis of these sequences is problematic, especially as many of these initial sequences are not considered to be affricates in English. However, when these problematic cases are set aside, there do remain initial consonant sequences that must be regarded as clusters; these include [fw] in *Dwayne* and *Kris* in session 1, [θɬ] in *Shanan* in session 4, [ʃːt] in *Sarah* in session 1, [ʃːd] in *Debbie* in session 3, and [çɬ] in *Shanan* in session 5.

With regard to the occurrence of closed syllables, it is also true that these relatively marked structures were by no means absent from G.K.'s productions. Given the limitations of the probe list itself (only 37% of the syllables in the probe list were closed), it appeared that a number of different types of consonants could occur in the coda: nasals (e.g. *Haley* in session 1, *Kristin* in session 1); fricatives (e.g. *Cathy* in session 4, *Josh* in session 3) ; affricates (e.g. *Josh* in session 4); and stops (e.g. *Josh* in session 5, *Kristin* in session 3).

Positional constraints—Evidence from functionally misarticulating children has indicated that, in some cases, particular classes of segments may be limited to specific syllable or word positions in developing phonological systems (see Dinnsen *et al*., 1990). The data here indicated that manners of articulation were generally not restricted to specific syllable positions (i.e. either only onset or only coda). Non-continuants could appear either syllable-initially or syllable-finally; this included both stops (e.g. *Debbie* in all sessions and *Kristin* in session 3), and affricates (e.g. *Sarah* in session 2 and *Josh* in session 4). Fricatives were likewise unrestricted in their syllable position occurrences and could appear initially (e.g. *Tara* in session 1 and *Marge* in session 3). Finally, nasals could appear in both a syllable onset (e.g. *Marge* in session 5) and a syllable coda (e.g. *Patty* in session 1).

Phonotactic constraints in G.K.'s system thus allowed a number of sequencing patterns that approximated the target system. Two relatively marked structures, that is, initial consonant clusters and closed syllables, appeared in her productions, and consonants appeared not to be restricted to specific syllable positions.

Correspondence patterns

Although the elicitation probe used for this study was a relatively limited one, it did reveal a number of correspondence (‘substitution’) patterns that were comparable to those evident in the systems of other children developing language. In particular, a number of correspondences appeared similar to those used in early acquisitional stages by hearing children acquiring the language normally and hearing children with delayed phonological development (see Stoel-Gammon and Dunn, 1985; Elbert and Gierut, 1986; Bernthal and Bankson, 1993).

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One such correspondence pattern showed an unaspirated stop where the ambient language shows an aspirated stop. Stoel-Gammon and Dunn (1985: 41) describe this as assimilation of initial stops to the voicing of following vowels, although Jakobson (1941/1968) asserts that unaspirated stops are acquired earlier than aspirated ones in any case. Examples from G.K.'s productions include target *Patty*, which has an initial aspirated stop, but which was produced by G.K. variously as [badɪm] (session 1) or [baɪdi] (session 2) or [bɑʹti] (session 3), with an initial unaspirated stop. A second correspondence pattern, also evident in younger, hearing children, showed non-continuants where the ambient system shows continuants, that is, stops or affricates corresponding to target fricatives (see Stoel-Gammon and Dunn, 1985: 40). Examples from G.K.'s productions included [təwə] *Sawyer* (session 1), [tɑnɑ] *Shanan* (session 1), [ɑti] *Cathy* (session 1, etc.), and [bvəbvə] *Yvonne* (session 3, etc.), in which an affricate appeared where the target form has a fricative.

Two correspondence patterns were discernible among the target liquid consonants. One pattern showed a glide [w] where the ambient language has an /ɹ/. Attributed to a process called ‘gliding’ in the clinical literature, this pattern is a common one among hearing children acquiring English in prevocalic position and in consonant clusters (Stoel-Gammon and Dunn, 1985). Prevocalically and in clusters was in fact where this pattern held in G.K.'s productions: *Kris* (session 1), *Kristin* (all sessions), *Sarah* and *Tara* (all sessions). The second correspondence pattern for liquids showed a non-sonorant non-lateral (i.e. a [d]) where the ambient language shows a sonorant lateral (i.e. an [l]). This pattern has been noted by Ingram (1976), who believes it to be a very early one in development (for instance, it is not attested in the study by Edwards, 1973). Examples of this pattern included [ɑʹdi] *Haley* (session 2, etc.), [ˀade] *Alice* (session 1), and [aːʰ di] *Allyson* (session 2). Finally, the voiceless alveopalatal fricative [ʃ] often appeared where the target system has a nonlabial: for /s/, as in [ʃːɛwə] *Sarah* (session 3); for /t/; as in [ʃewə] *Tara* (session 1); and for /k/; as in [ʃɛm] *Kim*. This last correspondence pattern, which is unusual among hearing children (although more common among paediatric cochlear implant users—M. J. Osberger, personal communication), served to neutralize a variety of ambient places (alveolars, velars) and manners (stops, fricatives) of articulation.

Representations

As mentioned previously, the decision to employ proper nouns as the responses in this task was based upon the assumption that, among possible lexical items, representations for names of familiar people in G.K.'s environment would most likely be already present in G.K.'s lexicon and would moreover be relatively stable. Evidence that this was borne out includes the relatively spontaneous (i.e. unprompted) nature of responses on this task, and the stability of productions across the five elicitation sessions.

Among the 23 names elicited, a number of these appeared to be very nearly correct in their production, and were furthermore relatively stable over time. These included productions of *Amy*, *Debbie*, *Haley*, *Nick*, *Patty*, *Sarah* and *Tara*. In these cases, especially, the phonological distance between target and response appeared to be fairly small. Here may be invoked the two criteria that all consonantal slots were marked, and that the consonants produced were phonetically or phonologically similar to the target segments. A second group of productions showed fairly stable productions across the elicitation sessions but also showed greater phonological distance between target and response than the first group. This second group included *Alfred*, *Alice*, *Cathy*, *Dwayne*, *Josh*, *Kris*, *Kristin*, *Marge* and *William*. Finally, a third group showed either relatively unstable representations or greater phonological distance between target and response than in the first two groups. Names in this last group included *Allyson*, *Carly*, *Diana*, *Kim*, *Sawyer*, *Shanan* and *Yvonne*.

Although it was assumed that proper nouns would be relatively well established in this child's lexicon (as opposed to other open-class items), the range of apparent stability noted above might result from both the specific sound segments involved and differences in the timing of the introduction of items into the lexicon. At early stages of linguistic development, information regarding the second factor (unfortunately not available for this study) might prove helpful in interpreting anomalous data.

Discussion

This report has been a description of a developing phonological system at a relatively early stage of development, concentrating on two basic characteristics of all phonological systems: the sound segment inventory and phonotactic constraints. The relatively small corpus of data and earlier stage of phonological development has to a large extent precluded a more detailed discussion of such phonological attributes as levels of representation, morphophonemic alternations, and phonological rules and constraints. Nevertheless, inventory and phonotactic characteristics, as well as correspondence patterns, can shed some light on the phonological system used by this child.

The emerging phonological system described here is one for a child almost 6 years old; in comparison with hearing children of that age this system was clearly not age-appropriate: several segments were missing from the consonant and vowel inventories, there were several non-English sounds, and some productions were unstable across elicitations. The fact that some segments were missing was due in some cases to their being absent from the probe; however, in other cases, segments that appeared in the probe were nevertheless not produced. Among the consonants, /r/ was probed twice syllable-initially (in *Sarah* and *Tara*), twice syllable-finally (in *Carly* and *Sawyer*), twice in initial clusters (in *Kris* and *Kristin*), and once in a final cluster (in *Marge*). Of these 37 opportunities to produce some type of /r/, G.K. produced none. Ingram (1976) notes that both Templin (1957) and Olmsted (1971) suggested that acquisition of /r/ (singleton in all positions) occurs by age 4;0 in hearing children. Further, according to Templin (1957), the initial consonant cluster /kr/ (as in both *Kris* and *Kristin*) is also acquired by age 4;0. On the other hand, in a number of cases, G.K.'s productions of the /kr/ cluster reflect: (1) correct production of the velar stop /k/ (that is, not fronted to an alveolar) ; and (2) stage 3 cluster development (of four stages; Greenlee, 1974), at which both positions are marked, but one (or perhaps both) constituent segments are realized with correspondents.

Table 8 lists all consonants produced on at least one occasion by G.K. across all five sessions. A somewhat more strict criterion for inclusion of a sound segment is at least two occurrences (Stoel-Gammon, 1987;Dyson, 1988). Table 10 displays those consonant segments that occurred at least twice in G.K.'s productions. Using this more strict criterion, G.K.'s consonant inventory appears more English-like. Although, obviously, several segments are still missing, a comparison of the consonant inventories in tables 8 and 10 shows that many of the non-English segments mentioned earlier occurred only once in G.K.'s productions. Singleton non-English segments are all fricatives, and although there are four segments analysed here as non-English affricates, two of these can occur as a word-final cluster ([ts dz]), and all four are composed of English stops and fricatives.

Dinnsen *et al*. (1990) have suggested a typology of phonetic inventories, based on the productions of 40 children with normal hearing with phonological delays. It provides a rough measure of complexity based on the number of phonological distinctions (described in terms of distinctive features from Chomsky and Halle, 1968) present in the inventory. Order in the development of phonetic inventories was demonstrated by the fact that all more complex inventories used all the distinctions used by more simple inventories, but not viceversa; there was therefore an implicational, hierarchical relationship among inventories of varying complexity (complexity being based on the number of distinctions, not the number of sound segments). Common to all inventories examined was a basic distinction among vowels, glides and consonants, so that the simplest inventories (called Level A inventories) used the features syllabic, consonantal, sonorant and coronal to distinguish sound segments. Level B inventories also used these features but added the feature voice. Level C inventories added the features continuant and delayed release, and Level D inventories added nasal (distinguishing nasal and non-nasal sonorant consonants). Finally, Level E inventories distinguished sounds using features used in all more simple inventories and added strident, lateral or both. For the children examined in Dinnsen *et al*. (1990), complexity, as defined here, did not correlate with either number of segments in the inventory or children's ages.

Using the typology suggested by Dinnsen *et al*. (1990), examination of G.K.'s consonant inventory in table 10 shows that it was a relatively complex one. Level A distinctions were all instantiated: syllabic (consonants vs vowels), consonantal (‘true consonants’ vs glides), sonorant (obstruents [e.g. stops] vs sonorants [e.g. nasals]), coronal (e.g. bilabial stop vs alveolar stop). Likewise, there were distinctions between voiced and voiceless consonants (e.g. [t] vs [d]), characteristic of Level B inventories. Stop consonants were distinguished from fricatives by the feature continuant and from affricates by the feature delayed release, indicative of Level C inventories. Further, the Level D feature nasal distinguished, in G.K.'s inventory, [n] and [l]. The distinctive features that characterized the most complex inventories in Dinnsen *et al*.'s (1990) typology were not used in G.K.'s inventory; that is, neither strident nor lateral was used to distinguish consonant segments. The feature strident would distinguish, for instance, [θ] and [s], which have the same voicing and place features. The feature lateral would distinguish [l] and [r]. Thus, although there were several gaps in G.K.'s consonant inventory, it was a relatively complex one in terms of the features used to distinguish segments.

Two types of phonotactic constraints were examined for this study: those on allowable basic syllable structures (general sequences of consonants and vowels), and those on allowable classes of sounds in certain syllable positions. Two specific constraints on the structure of syllables were explored: the constraint that consonants may appear only as singletons (i.e. not in clusters) and the constraint that all syllables are open. In process analyses (e.g. Ingram, 1976), these constraints are satisfied in child language by processes called ‘cluster reduction’ and ‘final consonant deletion’. Although G.K.'s productions showed some singletons where the ambient language has clusters and some open syllables for ambient closed syllables, there did not appear to be absolute constraints against clusters or closed syllables.

Four main correspondence patterns were observed in G.K.'s productions: target aspirated stop = unaspirated stop, target continuant = non-continuant, target lateral sonorant = non-lateral non-sonorant, and target non-labial = voiceless alveopalatal fricative. Although the first three patterns are attested in the phonologies of children with normal hearing (Ingram, 1976; Stoel-Gammon and Dunn, 1985), the last pattern, which appeared to apply to a number of different segments in the ambient language, would be unusual in a hearing child's phonology on two counts. First, according to this pattern target alveolars are realized as alveopalatals, whereas in the developmental phonologies of children with normal hearing it is more common for alveopalatals to be realized as alveolars. This pattern is subsumed by a number of authors (e.g. Ingram, 1976) under a general process called ‘fronting’, whereby target alveopalatals and velars are realized as alveolars. Second, according to this pattern, a number of stops, both alveolar and velar (there are no alveopalatal stops in English), were realized as the alveopalatal fricative. Much more common in phonologies of children with normal hearing is a process of ‘stopping’, by which fricatives or affricates are realized as stops, or fricatives as affricates (Stoel-Gammon and Dunn, 1985: 40). Mary Joe Osberger (personal communication) has indicated that, among paediatric cochlear implant users, acquisition, or at least emergence, of the alveopalatal fricative commonly precedes that of the alveolar fricative. For children with normal hearing, Templin (1957) reports mastery of both of these consonants at the same age, approximately 4;0 to 4;6 years. Sanders (1972) indicates that customary production of the alveolar fricative precedes that of the alveopalatal (3;0 vs 4;0), but that mastery of the alveopalatal precedes that of the alveolar (7;0 vs 8;0). Finally, Smit, Hand, Freilinger, Bernthal and Bird (1990) suggest recommended ages of acquisition of 6;0 for the alveopalatal fricative and 7;0–9;0 for the alveolar. With respect to G.K.'s phonology, certainly neither of the two fricatives could be said to have been ‘mastered’ by this stage, as both sounds were in error at least some of the time.

It would be appropriate at this point to address some of the methodological problems that arose during this study. First, the use of familiar faces as stimuli and the associated names as responses was based on the perceived need to tap into a corpus of words that would be well practised and available for spontaneous production. As might be expected, this rather arbitrarily defined corpus was lacking in a number of sound segments (most notably [z]). As one of the reviewers pointed out, the addition of a small number of additional words would have enabled a more complete analysis. Although we believe the face-naming methodology to be a sound one, especially for younger children, we also believe the reviewer's suggestion to be equally sound.

Second, transcription reliability may not appear particularly high for this study (72% for consonants, 77% for vowels), but at the present time the research literature is not entirely clear regarding acceptable levels of transcription reliability for this particular population. Criteria are not fixed across the field and appear to depend on factors such as task, narrowness of transcription, and analysis procedures. For instance, both Ertmer *et al*. (1997) and Sehgal *et al*. (1998) define reliability for their studies as ‘agreement that a token was or was not an acceptable allophone of the target’; Ertmer *et al*. report 79% inter-judge agreement for vowels, and Sehgal *et al*. report 81% inter-judge agreement for consonants. On the other hand, Tobey *et al*. (1991a) report both intra-judge and inter-judge reliability figures that appear to vary according to both evaluative task and whether transcription was done before or after implantation. In still other studies (e.g. Tobey *et al*., 1994; Kirk *et al*., 1994), transcription reliability is not reported at all. It might be believed that a solution to the transcription reliability problems lies in instrumental analysis; however, this nod to technology must be approached with caution. First, the effort required to conduct instrumental analyses of the large amount of speech material that is inevitably collected for any serious study might turn out to be prohibitive. Second, and perhaps more important, instrumental measures must still be converted to the ‘real’ analytical units, usually a phonetic transcription. It is not clear, for instance, how a phonological analysis, within any current theory, could be performed directly on spectrograms. Likewise, no current assessment of correct or incorrect production of a phoneme is based directly on waveforms.

Thus, if future research on the phonological systems of children who use cochlear implants can be expected to rely on phonetic transcriptions, then mechanisms need to be implemented that will increase both the reliability and validity of these transcriptions. It is not unreasonable to expect that, in the course of acquisition, these children may produce sound segments not in the inventory of the ambient language, and so training for transcribers needs to include recognition of such segments, along with the appropriate symbols for representing those segments. The International Phonetic Alphabet (International Phonetic Association, 1949, 1989, 1993), for instance, is ‘international’ precisely because its repertoire of symbols is not limited to representing the sounds of English. In a truly independent phonological analysis for a child who produces uvular stops, for instance, there can be no good reason not to represent these with the IPA [q], rather than as a [k] with a backing diacritic. Training in phonetic transcription must include recognition of the fact that not all non-English sounds are merely distortions of English ones; some of these sounds fall into categories that are perfectly normal in other languages. A wide variety of transcription training and experience, including English and non-English sounds, as well as the speech of persons with hearing impairment, will thus advance the course of research in this area greatly.

The foregoing has been a preliminary linguistic description of aspects of the phonological system of a child, G.K., after using a cochlear implant for approximately 2 years. Two characteristics of this child's independent phonological system were examined in detail: the sound segment inventory and phonotactic constraints. In addition, patterns of correspondence between target and produced sound segments were considered. Although the segment inventory did not match that of English, it was, given the number of features used to distinguish sound segments, a complex inventory. Productions were not limited to simple syllabic structures; rather, complex sequences of consonants and vowels were produced, including closed syllables and consonant clusters. Correspondence patterns showed some similarities to those present in the developing phonologies and children with normal hearing.

These characteristics of the phonological system were emphasized in this preliminary description, because that system was still at an early stage of development. With more developed phonologies it should be possible to apply similar methodology from both theoretical and clinical linguistics to delve more deeply into the internal patterns of the system. More specific characteristics that would be amenable to such analysis include allophonic variation, neutralization of contrasts, and more specific constraints on phonotactics.

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Appendix: Other test scores

Perception test scores from two regular testing intervals are reported here, one when G.K. was age 65 months (1.5 years postimplant) and the other when she was 71 months (2.0 years postimplant).

Mr Potato Head Task (Robbins, 1994; Kirk *et al*., 1997)

This task assesses open-set auditory comprehension in young deaf children using a Mr Potato Head toy (Hasbro, Inc., Pawtucket, RI). This toy consists of a plastic potato-shaped ‘head’ to which can be affixed plastic ‘accessories’, e.g. articles of clothing, limbs, facial features. The task requires the child to execute 10 instructions requiring manipulation of the toy, for example, ‘Put a hat on Mr Potato Head’. Both a sentence score (indicating complete compliance with the command) and a word score (indicating partial compliance) are generated. G.K.'s scores were as indicated in table A.

Pediatric Speech Intelligibility (PSI) test **(Jerger, Lewis, Hawkins and Jerger, 1980)**

The PSI evaluates both peripheral and central components of auditory disorders. It is a closed-set speech perception test consisting of 20 monosyllabic words and 10 sentences. Word response choices are depicted on four plates of five pictures each and sentences on two plates of five pictures each; children respond to spoken stimuli by pointing to a picture on the plate. In the version of administration used at the Indiana University School of Medicine, stimuli are presented live-voice, and a sixth picture has been added to each response plate so that children cannot select a target simply through a process of elimination. G.K.'s scores were as indicated in table B.

Table C contains information regarding intelligence and language measures taken when G.K. was 65 months and 71 months (1.5 years and 2.0 years after implantation).

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Table 1

Names corresponding to face stimuli

Orthography	Pronunciation	Orthography	Pronunciation
Alfred	[′æl.fɹɨd]	Kris	[k^h ɹɪs]
Alice	[′æ.lɪs]	Kristin	[′k^h ɹɪ.stĩn]
Allyson	[′æ.lɪ.sɨ̃n]	Marge	[maɹdʒ]
Amy	[′eɪ̃.mi]	Nick	[nɪk]
Carly	[′k^{h}aɹ.li]	Patty	[′p^h æ.□i]
Cathy	[′k^{h}æ.θi]	Sarah	[′sɛ.ɹə]
Debbie	[′dɛ.bi]	Sawyer	[′sɒɪ.jɚ]
Diana	[daɪ.æ̃.nə]	Shanan	[′ʃæ.nɨ̃n]
Dwayne	[də.′wẽɪn]	Tara	[′t^{h}ɛ.ɹə]
Haley	[′heɪ.li]	William	[′wɪl.jə̃m]
Josh	[dʒɑʃ]	Yvonne	[jɨ.′vɑ̃n]
Kim	[k^{h}ĩm]		

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Table 2

Target consonant inventory

Stops	p b			t d		k []	
Fricatives		f v	θ []	s []	ʃ []		
Affricates					[]dʒ		
Nasals	m			n		[]	
Liquids				l	ɹ		
Glides	w				j		h

Note: Phonetic symbol indicates that a segment was contained at least once in the name elicitation probe. Empty brackets indicate that the English segment at that position was absent from the probe.

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Table 3

Number of target segments in nine word positions

	#_V	#_C	#C_	X_CX	V_V	XC_X	_C#	C_#	V_#
p	1								
b					1				
t	1				1	1			
d	3								1
k	2	2							
g									
f				1		1			
v					1				
θ					1				
ð									
s	2			1	1				1
z									
ʃ	1								1
ʒ									
tʃ									
dʒ	1							1	
m	1				1				2
n	1				2				4
ŋ									
l				2	3	1			
ɹ			2	1	2	1	1		
w	1				1				
j	1				1	1			
h	1								

Note: C = consonant, V = vowel, # = word boundary, X = any segment not a word boundary.

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Table 4

Target vowel inventory

	Front	Central	Back	Diphthongs	Rhotacized
High	i ɪ	ɨ			
Mid	ɛ	ə		eɪ	ɚ
Low	æ	ɑ		aɪ ɒɪ	

Table 5

Number of target vowels

	Front		Central			Diphthongs			Rhotacized
i	6	ɨ	4						
ɪ	7								
ɛ	3	ə	4	eɪ	3			ɚ	1
æ	7	ɑ	4	aɪ	1	ɒ ɪ	1		

Note: No high or mid back vowels were contained in the elicitation probe.

Table 6

Target syllable-structures

Syllable structure type	Example
Open	
V	[æ] in ‘Allyson’
CV	[dɛ] in ‘Debbie’
CCV	[kʰ ɹɪ] in ‘Kristin’
CVV	[daɪ] in ‘Diana’
Closed	
CVC	[wɪl] in ‘William’
CCVC	[kɹɪs] in ‘Kristin’
CVVC	[wẽ̃ɪn] in ‘Dwayne’
CVCC	[maɹdʒ] ‘Marge’

Table 7

Production of names

	Session number				
Name	**Session 1**	**Session 2**	**Session 3**	**Session 4**	**Session 5**
Alfred	abvi	abvi	abvə	abvɪ	ɑbvɪ
Alice	ˀade	ɑʹlə	ɑlə	ɑl	ɑʂɪ
Allyson	ɑli	ɑː^{h}də	ɑ ʂ ə	ɑ ɬ ɪ	ɑ ɬ ɪ
Amy	hɑw̃i	ˀaʹmi	ˀɑmi	hɑmˀi	ɑːmɪ
Carly	ədəɪ	pfɑli	tɑji	tɔːi	dɑɪ
Cathy	ɑti	ati	ɑti	atiç	ɑti
Debbie	dəʹbi	D̪əbi	ʃːdəbi	dəʹbi	daʹbi
Diana	nːɑ	da^{h}nə	nɑdɑ	ʂɑːnɑ	ʃəbəwə
Dwayne	fwɪm	fɪʃ	fəɪʃ	fɪʐ̥	vẽ
Haley	adɪm	ɑʹdi	ɑdi	ɑʹdi	ɑdi
Josh	dɑʃ	dʒəbə	pvɑʃ	dɑtʃ	dzɑt
Kim	ʃɛ̃m	ɑːdi	ɑ̃mʃɪ̃m, æ̃dʒɛm	ɑhi	əmkɪb̥
Kris	fwɪʂ̥	fɪ	fəˀ	hɪˀ	bəˀ
Kristin	k^{w}ɪdɪn	wətsɪ	ʃeɪb, k^{w}ɪʃɪ	k^{w} ɪtʂɪ	kwɪsɪˀ
Marge	məʒʃ	mə	bɑʃ	məʒʃ	mɑo
Nick	niç	nɪ^{h}	nɪç	nɪˀ	ni
Patty	badɪm	baɪdi	bɑʹti	paçiˀ	pəçiˀ
Sarah	ʃːtɛwə	tʃɛwə	ʃɛwə	ʂ̥əwə	çɛw
Sawyer	təwə	tʂəː	təjə	dzəː	dzəː
Shanan	tɑnɑ	tsəjɛm	pfeɪʃ	θ ɬ ɪ	ç ɬ ɪ
Tara	ʃɛwə	ʃɪw	tsɛwə	dɛwə	tɛwə
William	hiːjYm	mɪmə̃m, mɪnəm	nə̃, mɪnɛm	mɛm	mələm
Yvonne	dadœ	ɛbvə	bvəbvə	bvəbvə	bvɑbvɑ

Table 8

Production consonant inventory across all sessions (one occurrence minimum)

Stops	p b b̥			d̪	t d				k	ʾ
Fricatives		f v	θ	s̪	s z̥	ʂ	ʃ ʒ	ç		
Lateral fricative					ɬ					
Affricatives		pf bv pv		t̪s̪	ts dz	ʈʂ	tʃ dʒ			
Nasals	m				n					
Liquids					l					
Glides	w w̃						j			h

Table 9

Production vowel inventory across all sessions

	Front	Central	Back	Diphthongs
High	i ɪ			
Mid	e ẽ ɛ œ	ə ə ˜	ɔ	eɪ əɪ
Low	a	ɑ		aɪ ao

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Table 10

Production consonant inventory across all sessions (two occurrences minimum)

Stops	b			t d				ˀ
Fricatives		f v	s̪		ɕ	ʃ ʒ	ç	
Lateral fricative				ɬ				
Affricates		pf bv		ts dz		tʃ dʒ		
Nasals	m			n				
Liquids				l				
Glides	w					j		h

Table A

Scores for G.K. on the Mr Potato Head Task at age 65 months (1.5 years after implantation) and age 71 months (2.0 years after implantation)

	Age 65 months	Age 71 months
Sentence	4/10=40%	5/10=50%
Word	12/20=60%	13/20=65%

Table B

Scores for G.K. on the Pediatric Speech Intelligibility Test at age 65 months (1.5 years after implantation) and age 71 months (2.0 years after implantation)

	Modality	Age 65 months	Age 71 months
Word	Auditory only	14/20=70%	16/20=80%
	Visual only	9/20=45%	20/20=100%
	Auditory+visual	17/20=85%	20/20=100%
Sentence	Auditory only	3/10=30%	10/10=100%
	Visual only	2/10=20%	6/10=60%
	Auditory+visual	3/10=30%	10/10=100%

Table C

Scores for G.K. from intelligence and language measures at 65 months (1.5 years after implantation) and 71 months (2.0 years after implantation)

	Age 65 months	Age 71 months
WPPSI-R (Wechsler, 1989)		
Performance IQ	80	n/a
WISC-III (Wechsler, 1991)		
Performance IQ	n/a	96
PPVT (Dunn and Dunn, 1965)		
Age Equivalent (Language Quotient)	57 (88%)	73 (103%)
Reynell Receptive (Reynell and Huntley, 1985)		
Age Equivalent (Language Quotient)	46 (71%)	49 (69%)
Reynell Expressive (Reynell and Huntley, 1985)		
Age Equivalent (Language Quotient)	38 (58%)	44 (62%)