Spectral analysis of target-appropriate /t/ and /k/ produced by phonologically disordered and normally articulating children

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Abstract

Previous research (Forrest, Weismer, Hodge, Dinnsen and Elbert, 1990) has shown that some phonologically disordered children differentially mark seemingly homophonous phonemes; however, the resulting contrast may be spectrally distinct from that produced by normally articulating children of the same age. In the present investigation possible sources for these differences between normally articulating and phonologically disordered children's productions of target-appropriate phonemes were pursued. Spectral characteristics of seemingly correct productions of /t/ and /k/ in word-initial position were analysed for four normally articulating and seven phonologically disordered children to assess the effect of recency of acquisition, depth of knowledge of the contrast and/or the effect of a phonological disorder on accuracy and variability of production. Results revealed that children who had acquired the velar-alveolar contrast more recently, and who had incomplete knowledge of that contrast, produced target-appropriate /t/ and /k/ differently from their normally articulating peers and other phonologically disordered children with greater knowledge of the contrast. Further, the phonologically disordered children with incomplete knowledge of the velar-alveolar contrast were less variable than the other phonologically disordered or normally articulating children in the spectral characteristics across repeated productions. Analysis of the spectral characteristics of word-initial /t/ and /k/ at a later point in time indicated similarities between all speaker groups in the spectral parameters that distinguished the velar from the alveolar stop. However, the stability of these parameters across repeated productions decreased for the phonologically disordered children with greater knowledge of the contrast. These effects are related to motor skill development and found to be consistent with previously demonstrated patterns of skill acquisition.

Keywords: speech acquisition, phonological disorders, velar-alveolar contrast.

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Introduction

Numerous studies have shown that phonologically disordered children produce acoustic markers to seemingly homophonous phonemes (Weismer, Dinnsen and Elbert, 1981; Maxwell and Weismer, 1982; Hoffman, Stager and Daniloff, 1983; Catts and Jensen, 1983; Gierut and Dinnsen, 1986; Chaney, 1988; Forrest and Rockman, 1988). Further, it has been demonstrated that acoustic markers to phonemes either may foreshadow phonemic acquisition without intervention (Forrest *et al.*, 1990) or may facilitate generalization of a treated phoneme (Tyler, Edwards and Saxman, 1990; Tyler, Figurski and Langsdale, 1993). The majority of investigations have focused on temporal indices of the acoustic signal that differentiate normally articulating from articulation-disordered speakers (Maxwell and Weismer, 1982; Catts and Jensen, 1983; Gierut and Dinnsen, 1986; Forrest and Rockman, 1988; Tyler *et al.*, 1990). However, the examination of spectral characteristics is critical to the understanding of disordered speech, since articulatory postures and distinctions are manifested by changes in the acoustic spectrum (Fant, 1960). Spectral measures of disordered speech, particularly the speech of articulation-disordered children, are made very challenging by methodologies that were designed to analyse normally articulating adults (e.g. sound spectrograph, linear predictive coding). Other procedures based on statistical summaries of fast Fourier transforms (FFT) show promising results when applied to the speech of normally articulating adults (Forrest, Weismer, Milenkovic and Dougall, 1988) and children (Forrest *et al.*, 1990) as well as disordered speakers (Forrest *et al.*, 1990; Thompson, McClean and Summers, 1992). These procedures use the first four spectral moments (i.e. mean, variance, skewness and kurtosis, respectively) to describe the FFT of obstruent consonants. Because these four moments give information about the centre frequency of the FFT (mean), as well as the tilt of the spectrum (skewness) and the diffusion or compactness of the peaks in the spectrum (kurtosis), a good representation of the spectral characteristics of the stop consonants is provided. Forrest *et al.* (1988) demonstrated that stop consonants produced by adults could be classified with a high degree of accuracy using discriminant function analysis with the moments from the first 40 ms of stop consonants as input variables. Application of the moments procedure to the velar and alveolar stop consonants produced by normally articulating children also yielded reliable distinctions between the voiceless phonemes produced at these two places of articulation.

Spectral moment analysis of the speech of phonologically disordered children was used to determine whether phonologically disordered children produce acoustic cues to phonemes that are judged perceptually to be in error (Forrest *et al.*, 1990). Results indicated that some children do produce acoustic markers to seemingly homophonous phonemes, and that these markers may evidence the emergence of phoneme acquisition. For example, one subject within a group of phonologically disordered children produced acoustic differences between perceptually identical productions of target velar and alveolar stops such that 87% of her target /t/s and /k/s were classified correctly by discriminant function analysis of spectral moments. The spectral characteristics that discriminated target velar from alveolar stops were not the same for this phonologically disordered child (K.R.) as those which differentiated /t/ and /k/ when produced by normally articulating children or adults. These spectral results verified auditory-perceptual judgements in that the phonologically disordered speaker was not perceived to make a clear contrast between /t/ and /k/ and the spectral cues marking the contrast were not as distinctive as those produced by normally articulating speakers. That is, all the normally articulating children were perceived to produce the velar-alveolar contrast and the spectra corresponding to these phonemes were distinguished from one another by centre frequency and kurtosis, the same parameters that

distinguish normal adult productions. The phonologically disordered speaker alone distinguished target velar from alveolar stops, a contrast that was used to classify the normal adult productions. The disordered speaker did appear to make this contrast as evidenced by a systematic difference in knowledge either aided or forced. The target-appropriate /t/ and /k/ were not perceived in this contrast was not addressed in the disordered group, for whom there was inconsistent evidence of the velar-alveolar contrast. The hypothesis that the contrast was acquired by the child is supported by the hypothesis that subphonemic contrasts are not acquired.

One might predict that productions perceived to be accurate would be produced by the child. Acoustic analysis of K.R.'s productions of target-appropriate, provided evidence of discriminating normally articulating children (frequency and kurtosis) did not distinguish phonemes. Instead, indices of spectral moments that distinguished her productions of K.R.'s post-treatment /t/ and /k/ from the velar-alveolar contrast normally produced by those of children in the normal group.

This result raises a number of questions about contrasts by phonologically disordered children produce. Do normally articulating children have temporal cues to phonemes have phonologically disordered speakers? Do normally articulating peers, when produced by a phonologically disordered speaker, differ from normal models. In the present study, word-initial /k/ and /t/ are contrasted in normally ordered children. The goal of the study was to determine if disordered children produce target-appropriate articulating peers. If differences in the phoneme in the child's inventory are not perceived and therefore characterized by lexicographic knowledge to the phoneme? To test the effect of /t/ and /k/, two groups of phonologically disordered children were perceived to produce /t/ and /k/ in word-initial position only (PDI). The results also produced a variety of phonological contrasts in word-initial position only (PDI). The representation of the velar-alveolar contrast is acquired first in word-initial position.

children produce acoustic (Dinnsen and Elbert, 1981; 83; Catts and Jensen, 1983; 1988). Further, it has been argued that the phonological knowledge that children have may foreshadow phonemic generalization of a contrast (Dinnsen and Langsdale, 1993). The acoustic signal that is produced by normally articulating speakers (Maxwell and Dinnsen, 1986; Forrest and Rockman, 1990) has characteristics that are critical to the contrast (e.g. skewness and kurtosis). Spectral measures of the acoustic signal that are made by normally articulating adults are based on statistical measures when applied to the acoustic signal (e.g. Dinnsen and Dougall, 1988). Spectral measures of the acoustic signal that are made by normally articulating speakers (Forrest *et al.*, 1990; Dinnsen *et al.*, 1990) use the first four spectral measures (e.g. skewness, kurtosis, etc.) to describe the FFT of the acoustic signal (e.g. skewness) and the diffusion of the spectral signal (e.g. skewness). (1988) demonstrated that the degree of accuracy using the first four spectral measures of stop consonants (e.g. 40 ms of stop consonants) in the velar and alveolar stop contrast yielded reliable distinctions of articulation.

For normally articulating children, the acoustic signal that is produced by normally articulating speakers (Forrest *et al.*, 1990; Dinnsen *et al.*, 1990) has characteristics that are critical to the contrast (e.g. skewness and kurtosis). Spectral measures of the acoustic signal that are made by normally articulating speakers (Forrest *et al.*, 1990; Dinnsen *et al.*, 1990) use the first four spectral measures (e.g. skewness, kurtosis, etc.) to describe the FFT of the acoustic signal (e.g. skewness) and the diffusion of the spectral signal (e.g. skewness). (1988) demonstrated that the degree of accuracy using the first four spectral measures of stop consonants (e.g. 40 ms of stop consonants) in the velar and alveolar stop contrast yielded reliable distinctions of articulation.

distinguish normal adult productions of these stop consonants (Forrest *et al.*, 1988). For the phonologically disordered speaker, indices of spectral shape (i.e. skewness and kurtosis) alone distinguished target velar from alveolar stops. However, even though the spectral cues used to classify the normal and disordered speakers' productions were different, the disordered speaker did appear to have some knowledge about the velar-alveolar contrast, as evidenced by a systematic distinction between these targeted places of articulation. This knowledge either aided or foreshadowed phonological learning in that, after treatment, target-appropriate /t/ and /k/ were in this child's inventory in all word-positions, even though this contrast was not addressed in treatment. The other children in the phonologically disordered group, for whom no acoustic distinction could be determined, had only inconsistent evidence of the velar-alveolar contrast after treatment. Although it is possible that the contrast was acquired by maturation alone, the results are also consistent with the hypothesis that subphonemic markers to a contrast may indicate some knowledge of that contrast.

One might predict that productions by a phonologically disordered child that are perceived to be accurate would be acoustically similar to productions by a normal speaker. Acoustic analysis of K.R.'s post-treatment /t/ and /k/, which were judged to be target-appropriate, provided evidence contrary to this prediction. The acoustic variables discriminating normally articulating children's velar from alveolar stops (i.e. centre frequency and kurtosis) did not yield accurate classification of K.R.'s production of these phonemes. Instead, indices of spectral shape (skewness and kurtosis), the same variables that distinguished her productions prior to treatment, yielded higher classification accuracy of K.R.'s post-treatment /t/ and /k/. So, even though K.R. was perceived to produce the velar-alveolar contrast normally, there were still differences between her productions and those of children in the normally articulating group.

This result raises a number of perplexing questions about the production of phonemic contrasts by phonologically disordered speakers. For example, do phonologically disordered children produce target-appropriate phonemes differently from normally articulating children such that the spectral cues to phonemes are different? Differences between normally articulating and phonologically disordered speakers in control of temporal cues to phonemes have been shown to exist (Catts and Jensen, 1983) wherein some phonologically disordered speakers produce an exaggerated VOT, compared to their normally articulating peers, when making a word-initial voicing contrast. For the phonologically disordered speaker, spectral cues to target-appropriate phonemes may also differ from normal models. In the present investigation, spectral cues to perceptually correct, word-initial /k/ and /t/ are compared for normally articulating and phonologically disordered children. The goal of this analysis is to determine whether phonologically disordered children produce target-appropriate phonemes differently from their normally articulating peers. If differences are found, are they related to the recent acquisition of the phoneme in the child's inventory? That is, is the phoneme a new part of the child's system and therefore characterized by less precise articulation which is reflected in the spectral cues to the phoneme? To test the effects of recency of acquisition on the spectral characteristics of /t/ and /k/, two groups of phonologically disordered children were included. One group of phonologically disordered children produced a variety of phonemes in error, but were perceived to produce /t/ and /k/ correctly in all word positions (PDA). The second group also produced a variety of phonemic errors but were perceived to produce /t/ and /k/ in word-initial position only (PDI). The PDI group represents speakers with a less developed representation of the velar-alveolar contrast. Because English stop consonants generally are acquired first in word-initial position (Dinnsen, Chin, Elbert and Powell, 1990;

Stoel-Gammon, 1985), a native speaker of English with /t/ and /k/ in this position, exclusively, would be assumed to have less knowledge about these sounds than a speaker with these sounds in all word positions. Comparison of spectral characteristics of word-initial /t/ and /k/, using spectral moments (Forrest *et al.*, 1988), were made for the three groups of speakers to address the effects of phonological disorder and/or recency of phoneme acquisition on the production of these stop consonants.

A second index of production accuracy, variability, was also investigated. Studies have shown a progressive decrease in variability of acoustic parameters as speech motor control develops (Eguchi and Hirsh, 1969; Kent, 1976). Because acoustic variability is inversely related to articulatory control for 3- to 12-year-old speakers (Kent, 1976), it was hypothesized that children with less knowledge of the velar-alveolar contrast (i.e. children in the PDI group) would exhibit greater variability across repeated productions than children with greater knowledge of the /t/-/k/ distinction (i.e. PDA and NA children).

All analyses were repeated for both groups of PD subjects, approximately 3 months after the initial analysis interval, when the subjects had completed treatment. The purpose of this second analysis interval was to give a longitudinal perspective on the effects of development of the phonological system, in general, and experience with /t/ and /k/, specifically, on the acoustic characteristics of the velar-alveolar contrast. By this second analysis point, children in the PDI group had acquired target-appropriate /t/ and /k/ in all word positions. It was hypothesized that the PDI subjects would present acoustic cues to word-initial /t/ and /k/ that were similar to the cues used by PDA children to mark this phonemic contrast.

Methods

Speech sample

The speech sample, presented in Table 1, was part of a larger sample and was designed to elicit tokens that are commonly in error when produced by phonologically disordered children, rather than to sample a specific child's erroneous productions. Each word was presented by the clinician and the child repeated the word in the carrier 'I can say *word*, again'. Words were presented randomly and each was represented six times within the sample.

Table 1. *Speech Sample*

tot	tea	teen
cot	key	keen

There were a number of reasons that a 'generic' speech sample was implemented. First, the children described in this report were part of a larger project in which the relation between phonological knowledge and learning was addressed. Acoustic markers to a phoneme comprised one aspect of phonological knowledge that was thought to influence learning. The acoustic probe was designed to supplement the phonological analysis. Because repeated stimulation with a phoneme (Forrest, Balash and Belles, 1984) as would occur during administration of the acoustic probe, can be an effective teaching tool (but see Winner and Elbert, 1988) it was necessary to present the acoustic probe prior to the phonological probe so that knowledge of the child's phonological system was accurate at the initiation of treatment. Therefore, a child's phonology was unknown at the time of the acoustic probe and no specific speech sample could be designed.

A second reason for using 'generic' speech sample was that it permitted the investigation of disordered speakers' correct productions, in addition to error productions. This allowed

an investigation of the depth of the phonological systems compared to normally articulating children. This has the disadvantage of limited ability to sample the diversity of errors produced by disordered children. Contextual effects may also be investigated.

In the present investigation, the phonemes were chosen because they were the most difficult (Forrest 1990) in which spectral differences were most apparent. A group of normal speakers were used to produce the phonemes. Additionally, /k/ and /t/ were included in word-initial position, and /t/ and /k/ were included in all word positions or excluded.

Subjects

Three groups of children were used: normally articulating children (PDA), mean age of subjects in all three groups was 3;10. The PDA group was based on reports of the children's parents by a spontaneous speech sample. The PDI group produced all American-English phonemes but contained phonologically disordered phonemes as determined by a standardized phonological inventory (Fristoe, 1986). A 306-item phonological inventory was used that all the phonologically disordered children had. However, group 3 (PDA), i.e. /t/ and /k/ in word-initial position. Subjects in group 3 ($n = 3$) had phonemes occurred only in word-initial position or both of the target phonemes (/t/ and /k/) at the incorrect place of articulation. The PDI group was phonologically disordered speakers.

All PD subjects received continuous treatment of the target sounds. This treatment occurred over a 6-month period. Treatment methodology was consistent with Swartzlander and Chin (1990).

†The subjects in this report were part of a larger project in which phonological knowledge and learning, which included 40 phonologically disordered children, were investigated. Four of these children, one had to be excluded from analysis because of changes associated with integration of the phonological system. The acoustic probes used for treatment were consistent with those used for the PDI group. ‡The difference in number of target sounds were targeted for treatment. In the PDI group, one sound, some children learned to produce the sound, therefore, received treatment only on the targeted phonemes.

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investigated. Studies have shown that as speech motor control develops, articulatory variability is inversely related to age (Kent, 1976), it was expected that there would be a polar contrast (i.e. children with phonological disorders produced fewer than children with normal language (NA children)).

approximately 3 months after treatment. The purpose of this study was to investigate the effects of development on the production of /t/ and /k/, specifically, on the basis of the second analysis point, to determine if /k/ in all word positions. Acoustic cues to word-initial /t/ and /k/ were used to mark this phonemic contrast.

A sample and was designed for phonologically disordered children. Each word was presented on the carrier 'I can say word', and repeated six times within the

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sample was implemented. First, a subject in which the relation between acoustic markers to a word was thought to influence the phonological analysis. (Kent and Belles, 1984) as would be an effective teaching tool (but not an acoustic probe prior to the treatment). The acoustic system was accurate at the time of the treatment. It was unknown at the time of the treatment.

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an investigation of the depth of phonological differences in the disordered children's systems compared to normally articulating children. However, a 'generic' speech sample has the disadvantage of limited tokens of any phoneme, because many items are needed to sample the diversity of errors found in the population of phonologically disordered children. Contextual effects may not then be fully sampled.

In the present investigation, word-initial, singleton /t/s and /k/s were analysed. These phonemes were chosen because they were used in an earlier investigation (Forrest *et al.*, 1990) in which spectral differences between one phonologically disordered speaker and a group of normal speakers were found, even after the disordered speaker had acquired both phonemes. Additionally, /k/ and /t/ were the only phonemes that some children produced in word-initial position, and not in other word positions. Other phonemes were present in all word positions or excluded from the inventories of the 40 children in the larger study.

Subjects

Three groups of children between the ages of 3;6 and 6;6 participated in this study. The mean age of subjects in all three groups was equivalent. Group 1 was comprised of four normally articulating children (NA) from the Madison, WI region. Normal articulation was based on reports of the children's mothers who all were speech-language pathologists, and by a spontaneous speech sample obtained prior to the experiment. All children in the NA group produced all American-English obstruents in all word positions. Groups 2 and 3 contained phonologically disordered children who had at least six errors in three or more manner categories as determined by the Goldman-Fristoe Test of Articulation (Goldman and Fristoe, 1986). A 306-item probe list which was adapted from Gierut (1985) indicated that all the phonologically disordered children evidenced /t/ and /k/ in their phonetic inventories. However, group two subjects ($n = 4$) produced these phonemes in all word positions (PDA), i.e. /t/ and /k/ were produced correctly by children in the PDA group. Subjects in group 3 ($n = 3$)† had a phonotactic constraint on /t/ and /k/ such that both phonemes occurred only in word-initial position (PDI). For this last group of subjects, one or both of the target phonemes (/k/ or /t/) was omitted, produced as a glottal stop, or produced at the incorrect place of articulation in word-medial and word-final positions. All phonologically disordered speakers came from the Bloomington, IN area.

All PD subjects received conventional minimal pair contrast treatment on one to three sounds.‡ This treatment occurred after the initial acoustic analysis was completed. Treatment methodology was consistent with the procedures detailed in Elbert, Dinnsen, Swartzlander and Chin (1990). Subjects in the PDA and PDI groups received treatment

†The subjects in this report were part of a larger study of the relation between phonological knowledge and learning, which included 40 phonologically disordered children. Of these 40 children, only five evidenced /t/ and /k/ exclusively in word-initial position. Although acoustic data were collected for four of these children, one had to be excluded because she did not generalize these phonemes to other word positions within the 6-month period that she was studied. Because we were interested in spectral changes associated with integration of phonemes into the child's system, this fourth subject was excluded from analysis. The acoustic characteristics of this subject's /t/ and /k/ productions prior to treatment were consistent with those from the other children in the PDI group.

‡The difference in number of treatment sounds is explained by the differences in learning. Three sounds were targeted for treatment for all PD subjects. However, during the course of treatment on one sound, some children learned other sounds that had been targeted for treatment. Some children, therefore, received treatment only on one sound, whereas other children needed exposure to all three targeted phonemes.

twice a week until a generalization criterion of 90% correct production of probe words was reached (see Elbert *et al.*, 1990). This level of generalization was obtained in about 3 months. No subject received treatment on velar consonants or any sound that was implicational more complex than velars (Dinnsen *et al.*, 1990).

Data collection

Each child was seated in a sound-treated booth along with his/her clinician or experimenter and a head-mounted microphone was positioned approximately 6 cm from the child's mouth. The child was instructed to repeat the test word within the carrier sentence after the word was spoken by the clinician. The transduced speech signal was recorded on a Marantz (PMD360) tape recorder/reproducer. Children were rewarded with stickers five times during the session, and with a small toy at the conclusion of data collection.

Data analysis

Test utterances were low pass filtered at 9 kHz and digitized with a 22 kHz sampling rate using CSpeech, a PC-based waveform editing and analysis package. Test words were extracted from the carrier sentence, high-pass filtered at 70 Hz to remove noise, and edited to include the interval from burst to the third cycle of the vowel. The edited portion of the signal was pre-emphasized by 6 db/octave and 512 point FFTs were performed with a 20 ms Hamming window at successive 10 ms intervals (see Forrest *et al.* (1988) for a more complete description of the procedure).

Each FFT was treated as a random probability distribution from which the first four spectral moments (i.e. mean, variance, skewness, and kurtosis) were calculated. As in our previous work (Forrest *et al.*, 1988, 1990), the mean and coefficients of skewness (skewness/variance^{3/2}) and kurtosis (kurtosis/variance²) calculated at 10 ms intervals from the first 40 ms of the VOT interval, were used to classify all productions of target /t/ and /k/. Moments were grouped for each 10 ms section across all repetitions of each target phoneme independent of vowel context. This yielded 12 variables (i.e. mean, skewness and kurtosis for the first 10 ms interval; mean, skewness and kurtosis for the second 10 ms interval, etc.) that were entered into a discriminant analysis (BMDP7M) for each production of the target phoneme. Each set of the 12 variables calculated for each production defined a case.

Discriminant analysis linearly combines the n input variables for all cases, such as the moments from the first 40 ms of the VOT interval, to derive functions that define the members of each category, where category is the targeted phoneme (/t/ or /k/). Each case was assigned to one of the two categories in this analysis based on the distance of that case from the centre of the category, where the centre of the category was determined from the discriminant function (Klečka, 1980). Members of the same category are minimally distanced from one another, whereas the distance between members of different categories is maximized. In this way the target phonemes, /t/ and /k/, could be categorized on the basis of similarity or difference of the moments that described their spectra. Discriminant analyses were computed independently for each subject group.

In addition to categorization accuracy, an index of variability of the spectra across repeated productions and/or across subjects within groups was determined. The index that was used was mean Mahalanobis D^2 , a measure of the distance of any case from the centre of that category. A small D^2 indicates that the classification variables associated with a given production are consistent with the general group profile, whereas a large D^2 indicates

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Figure 1. LPC smoothed spectra for /t/ (top) and /k/ (bottom) produced by a speaker in the NA group. As these spectra indicate, NA children distinguish /t/ and /k/ on the basis of mean frequency and kurtosis. A higher mean frequency and greater dispersion of spectral peaks was found for /t/ than was noted for /k/ produced by normally articulating children.

disparity between a repetition and the group average. Because the cases were distributed randomly with respect to direction around the mean (i.e. there was no systematic clustering of cases to one side or the other of the category centres), the mean of all D^2 values within each category captures the overall variability of repeated productions relative to the prototype of the category. A large mean D^2 would indicate a lot of variability in the way that the target phoneme was repeated; conversely a small D^2 would be found if the repeated productions were very similar to one another.

Results

Categorization accuracy of the NA subjects' /k/ and /t/ is presented in Table 2. The categorization is fairly good, though worse than is found with adults (Forrest *et al.*, 1988). Further, there is no difference in the categorization accuracy of /k/ and /t/. *Post-hoc* inspection of the canonical weights assigned to the input variables during the calculation of the discriminant function for this group indicate that phoneme discrimination was based primarily on the mean, and secondarily on kurtosis. That is, /k/ was distinguished from /t/ on the basis of mean frequency of the spectra and diffusion of spectral peaks. Previous studies suggest that these are the indices that distinguish stop consonants produced by normally articulating adults (Forrest *et al.*, 1988). Examples of spectra from an NA speaker are presented in Figure 1 with /t/ represented in the top frame and the onset spectrum for /k/ in the bottom portion of the figure.

Table 3 indicates that the discrimination of the velar-alveolar contrast produced by children in the PDA group was comparable to the accuracy found in the normally articulating children. As with the NA children, PDA children distinguished /k/ from /t/ on

Figure 2. LPC smoothed spectra for /t/ (top) and /k/ (bottom) produced by a speaker in the PDA group. Like the children in the NA group (Figure 1), /t/ and /k/ produced by PDA children were distinguished on the basis of mean frequency and kurtosis.

Table 2. Classification of /t/ and /k/ produced by normally articulating subjects

Phoneme	Percentage correct	Number of cases	
		t	k
t	83.6	61	12
k	82.1	12	55
Total	82.9		

the basis of mean frequency, primarily and kurtosis, secondarily. Figure 2 presents representative spectra for subjects in this group.

Table 3. Classification of /t/ and /k/ produced by phonologically disordered children who produced the velar-alveolar contrast in all word positions (PDA)

Phoneme	Percentage correct	Number of cases	
		t	k
t	78.7	57	15
k	86	10	62
Total	82.4		

Categorization of /k/ and /t/ on the basis of the spectra was not very accurate for the PDI children, as shown in Table 4. Although /t/ was categorized correctly for 85% of the tokens, correct categorization of /k/ occurred only at a chance level. Recall that all children in this group were perceived to produce target-appropriate /t/ and /k/ in word-initial position,

Figure 3. LPC smoothed spectra for the PDI subjects

i.e. the data reported here are for the PDI group. Further, there was no evidence of the alveolar compared to the children discrimination of /t/ from /k/ on the variables of mean frequency and kurtosis. The alveolar phoneme in the NA group was distinguished on the basis of mean frequency and kurtosis (Forrest et al., 1998).

Table 4. Classification of /t/ and /k/ produced by PDI subjects on the basis of the velar-alveolar contrast

Phoneme
t
k
Total

By way of example, Figure 3 shows the LPC smoothed spectra for one of the subjects in the PDI group. The spectra for /t/ and /k/ are both comparable to the spectra for the NA group, and are therefore not significantly different.

Variability of repeated productions was also measured using Mahalanobis D^2 . We hypothesized that the variability of the three subject groups would be different, which showed that children with PDI showed more variability between phonemes than children with NA. This result is in line with the theoretical, inverse relationship between the degree of phonemic contrast and the degree of variability (Forrest et al., 1998).

Figure 3. LPC smoothed spectra for /t/ (top) and /k/ (bottom) produced by a subject in the PDI group. For the PDI subjects as a group, only skewness differentiated word-initial /t/ and /k/.

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vel. Recall that all children
/k/ in word-initial position,

i.e. the data reported here are from perceptually correct productions of the target sounds. Further, there was no evidence, perceptually, that these subjects had any greater knowledge of the alveolar compared to the velar stop. Last, for this group of phonologically disordered children discrimination of /t/ from /k/ was based solely on skewness of the spectra, rather than on the variables of mean frequency and kurtosis that distinguished the velar from the alveolar phoneme in the NA and PDA subjects in this study and adults used in previous investigations (Forrest *et al.*, 1988).

Table 4. Classification of /t/ and /k/ produced by phonologically disordered children who produced the velar-alveolar contrast in word-initial position only (PDI)

Phoneme	Percentage correct	Number of cases	
		t	k
t	85	46	8
k	53	25	29
Total	69		

By way of example, Figure 3 shows spectra for /t/ (top) and /k/ (bottom) produced by one of the subjects in the PDI group. Note that the centre frequencies are the same for both spectra and both are comparably diffuse. However, the skewness of these two spectra is different.

Variability of repeated productions was assessed for each subject group using Mahalanobis D^2 . We hypothesized that the PDI children would demonstrate the greatest variability of the three subject groups. This hypothesis was based on empirical evidence which showed that children who produced acoustic, but not perceptible, distinctions between phonemes were more variable than children who were perceived to produce the phonemic contrast correctly (Forrest *et al.*, 1990). Our expectations were also based on a theoretical, inverse relationship between motor maturity and variability (Bruner, 1973). If

Figure 4. Mean Mahalanobis D^2 , an index of the variability of repeated productions from the ideal model which represents the spectral characteristics of the phoneme, for each subject group. Error bars represent one standard deviation.

we can assume that the children who knew the velar-alveolar contrast only in word-initial position had minimal skill in producing the motor patterns associated with /k/ and /t/, then one would expect that this group would evidence the greatest variability.

Mean values of Mahalanobis D^2 are plotted for each subject group in Figure 4. Error bars represent one standard deviation around the mean D^2 for each phoneme and group. As can be seen, PDI had the least variability across repeated productions.

The acoustic analysis completed 3 months later (i.e. after treatment was completed), when all speakers in the PDA and PDI groups evidenced /t/ and /k/ in all word-positions, indicated some improvement in classification accuracy for the PDI children. As Table 5 indicates, the change in classification accuracy is due mostly to improved classification of /k/.

Table 5. Classification of /t/ and /k/ produced by PDI subjects after treatment

Phoneme	Percentage correct	Number of cases	
		t	k
t	85	46	8
k	64.8	19	35
Total	74.9		

By contrast, classification of /k/ for PDA children decreased slightly post-treatment, as noted in Table 6. *Post hoc* inspection of the canonical weights from which the discriminant functions were computed indicated that /k/ and /t/ were discriminated by indices of spectral shape, i.e. skewness and kurtosis, for both groups of phonologically disordered speakers.

As shown in Figure 5, mean D^2 computed from the post-treatment function increased significantly ($t = 3.76$; $p = 0.0005$) for PDI subjects, relative to pretreatment variability estimates. Additionally, greater variability as indexed by higher mean D^2 was noted in /k/ spectra compared to /t/ ($t = 4.14$; $p = 0.0002$) in the PDI group. There was no difference in mean D^2 for the PDA subjects between the pre- and post-treatment analyses ($t = 2.26$; $p = 0.028$), nor in the variability (mean D^2) of /k/ vs /t/ ($t = 1.75$; $p = 0.083$). In these analyses an error rate of 0.01 was chosen because of the number of *t*-tests undertaken.

Figure 5. Mean Mahalanobis D^2 for each subject group pre-treatment (left) and af

Table 6. Classification

Phoneme

t

k

Total

In summary, prior to treatment on the basis of mean frequency NA speakers' velar and alveolar productions by PDA speakers were across repeated productions were to treatment, had less accurate subjects, and the distinction between speakers demonstrated significant phonemes, as mirrored in small

After treatment, accuracy improved for the PDI children phonologically disordered children variables of spectral shape, skewness increased for the PDI children change in variability for the P

Discussion

This investigation was undertaken are similar to their normally articulated /t/ and /k/. Results indicate that in a phonologically disordered

Figure 5. Mean Mahalanobis D^2 , a metric of variability across repeated productions of /t/ and /k/ for each subject group. Comparisons are made for the PDI and PDA groups before treatment (left) and after treatment (right). Error bars represent one standard deviation.

Table 6. Classification of /t/ and /k/ produced by PDA subjects after treatment

Phoneme	Percentage correct	Number of cases	
		t	k
t	80.6	58	14
k	69.6	22	50
Total	75.1		

In summary, prior to treatment /t/ and /k/ produced by PDA subjects were distinguished on the basis of mean frequency and kurtosis, the same spectral characteristics differentiating NA speakers' velar and alveolar stops. Further, classification accuracy of /t/ and /k/ produced by PDA speakers was comparable to that of the NA children, and the variability across repeated productions was similar for these two subject groups. PDI children, prior to treatment, had less accurate classification of perceptually correct /k/ than PDA or NA subjects, and the distinction between /t/ and /k/ was based on spectral skewness alone. PDI speakers demonstrated significantly less variability across repeated productions of both phonemes, as mirrored in smaller mean values of D^2 , compared to either of the other groups.

After treatment, accuracy of classification of /t/ and /k/ on the basis of spectral moments improved for the PDI children and decreased for the PDA children. For both groups of phonologically disordered children, after treatment, classification was based on the variables of spectral shape, skewness and kurtosis. Variability across repeated productions increased for the PDI children after treatment, particularly for target /k/, but there was no change in variability for the PDA subjects.

Discussion

This investigation was undertaken to determine whether phonologically disordered children are similar to their normally articulating peers in the production of perceptually acceptable /t/ and /k/. Results indicate that if the velar-alveolar contrast is evident in all word positions in a phonologically disordered child's system, the spectral characterization of these

d productions from the ideal phoneme, for each subject

contrast only in word-initial positions, then /k/ and /t/, then variability.

t group in Figure 4. Error bars represent one standard deviation for each phoneme and group. Error bars represent one standard deviation.

treatment was completed), /k/ in all word-positions, PDI children. As Table 5 shows, there was an improved classification of

cts after treatment

Number of cases	
t	k
46	8
19	35

slightly post-treatment, as in which the discriminant function was based on the variables of spectral shape, skewness and kurtosis. Variability across repeated productions increased for the PDI children after treatment, particularly for target /k/, but there was no change in variability for the PDA subjects.

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framework. Recall that PDI children were defined as phonologically disordered children who produced /t/ and /k/ only in word-initial position. This constraint on word position could be explained by the children's stereotypical production of the gestures for /t/ and/or /k/ such that generalization of articulatory patterns to other word positions could not be implemented. Stereotypical patterns for these consonants, much like the ballistic arm movements described by Hay (1984), would be characterized by low variability but also low accuracy. Again, the spectra of /t/ and /k/ produced by PDI children in this study were characterized by reduced variability and lower classification accuracy.

Application of Hay's proposals about motor development to phoneme acquisition is supported by the post-treatment analyses of the PDI and PDA groups, and is consistent with the findings of Tyler and Saxman (1991) on VOT acquisition. After treatment, when the PDI subjects produced /t/ and /k/ in all word positions, the classification accuracy of word-initial /t/ and /k/ improved compared to the pretreatment measures. Additionally, the variability across repeated productions increased, indicative of greater flexibility in the implementation of the velar and alveolar consonants. Surprisingly, classification of these stops still was based on indices of spectral shape alone, rather than the interaction of shape and centre frequency characteristic of normal articulation. So, although velar and alveolar stops were integrated more fully into the system, the spectral cues distinguishing them may not be comparable to the productions by a normally articulating child.

Changes in the post-treatment classification of /t/ and /k/ were noted for the PDA children also. For these children, classification accuracy decreased, although variability remained constant relative to the pretreatment measurements. The indices on which the classification was made at the post-treatment interval were reflective of spectral shape alone. This would imply that PDA children's productions of /t/ and /k/, phonemes which were perceptually correct in all word positions prior to treatment, were less like normal /t/ and /k/ after treatment. These types of decrements in phoneme production during and after treatment are not uncommon in the clinical setting (Elbert and McReynolds, 1979). It is reasonable to assume that treatment has an effect on the entire phonological system. When some aspects of a child's system undergo change as a result of treatment, known elements of the phonology may also shift.

Regressions in consonant production have been noted in normal (Smit, Hand, Freilinger, Bernthal and Bird, 1990) as well as phonologically disordered (Dinsnen *et al.*, 1992) processes of speech acquisition. These apparent regressions are often ascribed to variability in the performance of the listener (Smit *et al.*, 1990), attributable to changes in listener criteria or problems with reliability of transcriptions of children's speech. The present results, coupled with data on acquisition of other motor behaviours (e.g. handwriting and arm movement), suggest that regression is a normal phase in the development of skilled movement (Bruner and Bruner, 1968; Hay, 1979, 1984; Wann, 1987).

Discontinuities or transitory decrements in performance (Hay, 1984) may result when the child is refining a skill such that the behaviour is becoming a more complete component of the system. For example, changes in monitoring strategies from exteroceptive (e.g. visual guidance in handwriting (Wann, 1987); auditory guidance in speech) to interoceptive information (e.g. kinaesthetic/proprioceptive information) may result in performance decrements until the new strategy is mastered. Children in the PDA group of the present investigation may be developing more efficient strategies for the correct production of phonemes, in general. These strategic changes result in decreases in performance accuracy. Once the new strategy is mastered the gestures may be characterized by more efficient production, i.e. greater precision with less energy expended.

The data presented in this report are based on a small number of subjects in each group. Differences seen from one time of analysis (e.g. pretreatment) to a later analysis (e.g. post-treatment) may represent random variation. A larger database of normally articulating children, recorded at 6-month intervals within a 2-year period, is being collected and analysed to determine a more stable model of children's stop consonant productions. Additionally, data from 40 phonologically disordered children are being investigated to determine the acoustic characteristics of positional constraints across phonemes and manners of production. The present data suggest, however, that children's acquisition of phonemes follows patterns described in other motor behaviours. Specifically, when a phoneme first appears in a child's system it may be represented by a fixed, invariant model which cannot be generalized across word position. For the phoneme to be generalized across word positions the child must gain flexibility with the phonemic production. Flexibility may be evidenced by greater variability across repeated productions of the phoneme, a stage of speech development that has been noted by previous investigators (e.g. Kent, 1976) and in the present data by the normally articulating and PDA children. This stage of phoneme acquisition may be marked by regressions as the child expands his/her phonetic repertoire, sometimes at the expense of accurate production of known phonemes. Last, an adult-like production of the phoneme develops wherein the speaker provides mature forms of the phoneme across word positions with little variability (Kent, 1976). Within this model, phonologically disordered children may differ in their abilities to produce known contrasts, dependent on the stage of acquisition of the distinction.

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