Journal of Phonetics (1987) **15**, 247–257

Developmental aspects of lingual coarticulation

Joan A. Sereno and Philip Lieberman

Box 1978, Department of Cognitive and Linguistic Sciences, Brown University, Providence, RI 02912, U.S.A.

Received 20*th October* 1986, *and in revised form* 16*th February* 1987

The experiment investigated the effects of lingual coarticulation in the speech stimuli of five adults and 14 children. CV syllables ([ki], [ka]) were analysed both acoustically and perceptually to determine the effect of the vocalic environment on the preceding velar stop consonant. In the acoustic analyses, short-time spectra were computed for each consonantal stimulus. Perceptual tests were then conducted by presenting the initial burst portion of the [ki] and [ka] syllables to adult subjects for identification. The acoustic results indicate that the adult stimuli, as expected, show significant coarticulatory effects. In the child data, however, the differences between the velar stops preceding front and back vowels are not always present. Moreover, the perceptual data show that the coarticulatory cues in the adult stimuli are perceptually salient but that these cues are not as perceptible in some of the children's stimuli. The results are discussed in terms of their implications for language learning.

1. Introduction

An important issue in present-day speech research is the analysis of coarticulation. The concept of coarticulation assumes that speech sounds are modified by the influence of contiguous phonemes. These coarticulatory effects are commonly described as anticipatory or forward coarticulation and carryover or backward coarticulation. The most interesting aspect of these coarticulatory influences, especially anticipatory coarticulation, is that an explanation for the results extends beyond simple inertial factors. Anticipatory coarticulation may reflect planning in motor behavior.

Most studies of anticipatory coarticulation have examined the effects of lip-rounding on consonants preceding a rounded vowel, i.e. labial coarticulation (Kent & Minifie, 1977). In this study another type of coarticulation—lingual coarticulation—was examined in which a velar stop consonant is influenced by the subsequent vocalic environment. For example, it is well-known that in English the velar stop consonant has two distinct allophones: one, before front vowels, has a relatively anterior vocal-tract constriction, and the other, before back vowels, has a relatively posterior vocal-tract constriction (Öhman, 1966; Houde, 1967; Kent & Moll, 1969; Amerman & Daniloff, 1977). These articulatory differences have also been documented in other languages such as Swedish (Öhman, 1967) and Danish (Fischer-Jørgensen, 1954).

Such articulatory adjustments have been shown to have distinct acoustic consequences (Fant, 1973; Zue, 1976). Acoustic analyses of short-time spectra at consonantal release

0095–4470/87/030247 + 11 $03.00/0

reveal that a velar stop consonant preceding a front vowel (for example, [ki]) has both a mid-frequency and a high-frequency spectral peak, whereas a velar stop preceding a back vowel (for example, [ka]) has a predominant low-frequency spectral peak and a secondary spectral peak in the high-frequency region.

These acoustic differences have also been shown to involve perceptual consequences (Schatz, 1954; Winitz, Scheib, & Reeds, 1972; Cole & Scott, 1974; LaRiviere, Winitz & Herriman, 1975). For example, LaRiviere *et al.* (1975) found that subjects can reliably identify the following vowel when given only the brief-burst portion of the consonant. In summary, then, many articulatory, acoustic, and perceptual studies demonstrate that robust lingual coarticulatory cues are present in the consonant preceding a vowel.

The present study replicates previous acoustic and perceptual results of anticipatory lingual coarticulation in adult speakers. First, we investigated whether the acoustic characteristics of the consonant varied as a function of vowel context and, then, whether these acoustic effects were perceptible. More importantly, however, we wanted to compare adult data with those of children to see if the same coarticulatory effects are also present in their speech. Relatively few studies have investigated children's speech (Kent, 1983). Most of the acoustic analyses (Eguchi & Hirsh, 1969; Tingley & Allen 1975; Kent & Forner, 1980) and articulatory measurements (Watkin & Fromm, 1984; Sharkey & Folkins, 1985; Smith & McClean-Muse, 1985) of children's speech have shown that there is decreased variability with increasing age, reflecting a general development of speech skills. In general, the speech of children shows less precise productions and more variable speech motor-control patterns. On this basis, one might expect that the speech of children will also show more variable effects of coarticulation compared with adult speech stimuli.

The purpose of the present study was to investigate the acoustic and perceptual effects of lingual coarticulation in the speech of adults and children in order to determine if anticipatory lingual coarticulatory effects differ in the speech of adults and children.

2. Method

2.1. *Acoustic analysis*

Three tokens of each of the CV syllables ([ki], [ka]) were produced by five adult and 14 child speakers of American English. The adult speakers were college students and the children ranged in age from two years eight months to seven years one month. Each utterance was read from a 3 × 5 card by the adult speakers and repeated from live-voice productions by the children. The adult and children's syllables were recorded with high quality equipment.

For the acoustic analysis, a 25-ms half-Hamming window was placed at the onset of each syllable (see Fig. 1). As we were interested in the frequency location of major energy concentrations and not just local maxima, a spectral smoothing technique was applied using a 10-pole linear prediction algorithm, similar to the procedure used by Zue (1976). Spectra of this initial-burst segment were then derived.

For the adult stimuli, a low frequency spectral peak between 1.0 and 3.6 kHz and a high-frequency spectral peak between 3.6 and 6.5 kHz were identified. A similar procedure was used for the children's stimuli except that spectral values were shifted upwards because of the shorter length of a young child's supralaryngeal vocal tract (Lieberman, 1980). For the children's stimuli, the spectral peaks located between 1.3 and

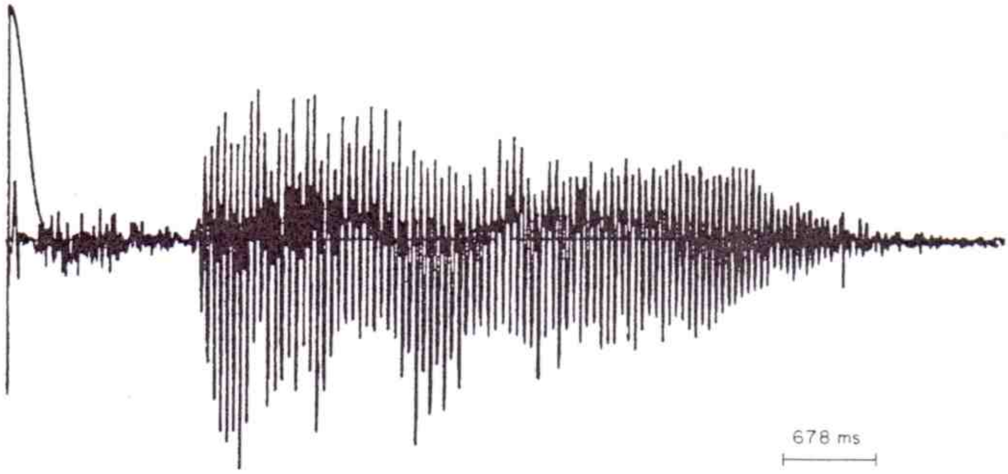

Figure 1. Waveform display of a [ki] stimulus is shown with superimposed half-Hamming window used for sampling the spectrum.

4.0 kHz were identified as low-frequency peaks and the spectral peak located between 4.0 and 7.0 kHz was identified as the high-frequency peak.

2.2. *Perceptual study*

Ten Brown University students, who were native speakers of American English and had no known hearing impairments, served as subjects in the perceptual study. Each subject was presented with the initial 25 ms of the CV syllables. The stimuli were presented binaurally using high quality equipment. The adult and child stimuli were blocked, with the adult stimuli preceding the children's. The subject's task was to identify in a forced-choice paradigm the absent vowel, [i] or [a], given only 25 ms of the brief-burst portion of each syllable.

3. Results

3.1. *Acoustic analysis*

The acoustic analyses showed strong lingual coarticulatory effects for adults, and variable, or sometimes non-existent, lingual coarticulatory effects in the children. For the adult [ki] and [ka] stimuli, mean spectral-peak values were calculated for the lower (1.0–3.6 kHz) and higher (3.6–6.5 kHz) frequency regions. These values are displayed in Table I. For the [ki] stimuli, the overall mean values were 3109 Hz (SD = 297 Hz) for the lower frequency region and 4630 Hz (SD = 588 Hz) for the higher frequency region. The [ka] stimuli, by comparison, show a sizeable lowering of values in the low frequency region (1902 Hz, SD = 454 Hz), but similar values in the higher frequency region (4430 Hz, SD = 430 Hz). On average, then, there was a substantial 1207 Hz lowering of the spectral peak of [k] stimuli followed by [a] compared to [i] and only a 200 Hz difference at the higher frequencies. These differences can be seen clearly in an example of the [ki] and [ka] spectra of an adult speaker (Fig. 2).

It should be noted that the slightly higher frequency of both the [ki] and [ka] stimuli

TABLE I. Mean spectral-peak values measured between 1.0 and 3.6 kHz (the low-frequency region) and between 3.6 and 6.5 kHz (the high-frequency region) for adult stimuli

	[ki]		[ka]	
Speaker	Low-frequency region	High-frequency region	Low-frequency region	High-frequency region
A1	3472	5362	2770	5001
A2	2630	3753	1580	3783
A3	3089	4155	1653	4115
A4	3366	4879	1937	4656
A5	2990	4999	1568	4597
$\bar{X}$	3109	4630	1902	4430

for A1 and A4 can be attributed to the fact that these speakers were female and that, in general, women's overall frequency values are elevated relative to those of males (Peterson & Barney, 1952; Goldstein, 1980).

For the children's [ki] and [ka] stimuli, mean spectral-peak values were also calculated for the lower (1.3–4.0 kHz) and higher (4.0–7.0 kHz) frequency regions. These values are shown in Table II. For the [ki] stimuli, the overall mean values were 3492 Hz (SD = 246 Hz) for the lower frequency region and 5282 Hz (SD = 466 Hz) for the higher frequency region. For the [ka] stimuli, the overall mean frequency values were 2295 Hz (SD = 582 Hz) in the lower frequency region and 5515 Hz (SD = 391 Hz) at the higher frequencies. Overall, then, there was also a sizeable 1197 Hz downward shift of the lower spectral peak of [ka] stimuli and a 233 Hz rise at the higher frequencies.

However, upon closer examination, not all of the children's spectra display the same pattern. In fact, three distinct groups emerge based on an analysis of their [ka] stimuli. The first group consists of the stimuli of the children (C1, C2, C4–C7, C9, C11, C12) whose short-time onset spectra for [ka] display both a high and a low frequency peak,

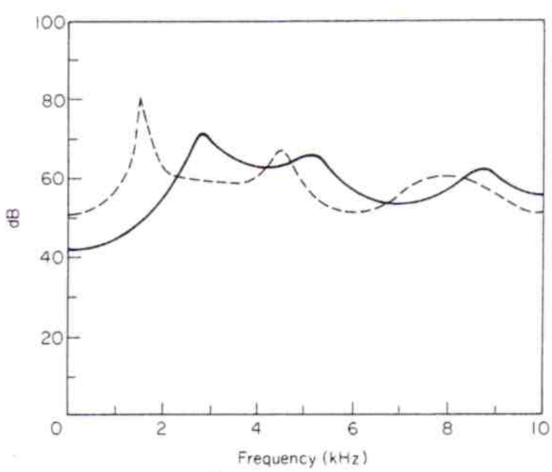

Figure 2. LPC spectra of the burst of [k] for an adult speaker preceding [i] (——) and [a] (- - -).

TABLE II. Mean spectral-peak values measured between 1.3 and 4.0 kHz (the low-frequency region) and between 4.0 and 7.0 kHz (the high-frequency region) for children's stimuli

	[ki]		[ka]	
Speaker (age in months)	Mid-frequency region	High-frequency region	Low-frequency region	High-frequency region
C1 (32)	3593	5362	1465	5074
C2 (36)	3623	5486	2568	6063
C3 (42)	3671	5923	3468	5525
C4 (47)	3562	5214	2067	5704
C5 (48)	3016	4936	2209	5606
C6 (61)	3742	5165	1743	5429
C7 (62)	3688	5260	2107	4853
C8 (66)	3648	4797	3597	5253
C9 (67)	3398	5308	2066	5487
C10 (68)	3064	6246	1764/3715	5878
C11 (72)	3686	5381	2449	6324
C12 (79)	3432	4338	2405	5076
C13 (81)	3675	4838	2364/3348	5247
C14 (85)	3090	5699	1879/3797	5692
$\bar{X}$	3492	5282	2295/3620	5515

similar to adult spectra. These children's spectra are shown in Fig. 3(a). For the children in this first group, there is a substantial 1407 Hz lowering of the lower spectral peak of [ka] stimuli as compared to [ki] stimuli, and a 353 Hz elevation at the higher frequencies.

The second group consists of the stimuli of children (C3 and C8) whose short-time onset spectra for [ki] and [ka] are almost identical. Examples of these spectra are shown in Fig. 3(b). These children's [ka] spectra are not substantially lowered relative to their [ki] spectra. Instead, the [ka] onset spectra seem more like the [ki] onset spectra, with a mid-frequency and a high-frequency peak. In the low frequency region, there was a 136 Hz lowering of [K] spectra followed by [a] compared to [i] while, at the high frequencies, there was only a very small shift of 29 Hz.

The third group consists of the stimuli of children (C10, C13, C14) whose onset spectra for [ka] display three prominent peaks as shown in Fig. 3(c). For these children, there is a high-frequency and a low-frequency peak, similar to adult stimuli, but in addition, there is an "extra" mid-frequency spectral peak.

In summary then, the children's [ki] and [ka] spectra do not all show the same pattern as the adult stimuli.

3.2. *Perceptual data*

The perceptual results for the adult speech stimuli are shown in Table III. Obviously, there are robust coarticulatory cues present. Subjects are capable of correctly identifying the vowel with approximately 97% accuracy, when given only 25 ms of the preceding consonantal segment. It is interesting to note that these results are comparable to perceptual results for consonant identification. Both LaRiviere *et al.* (1975)

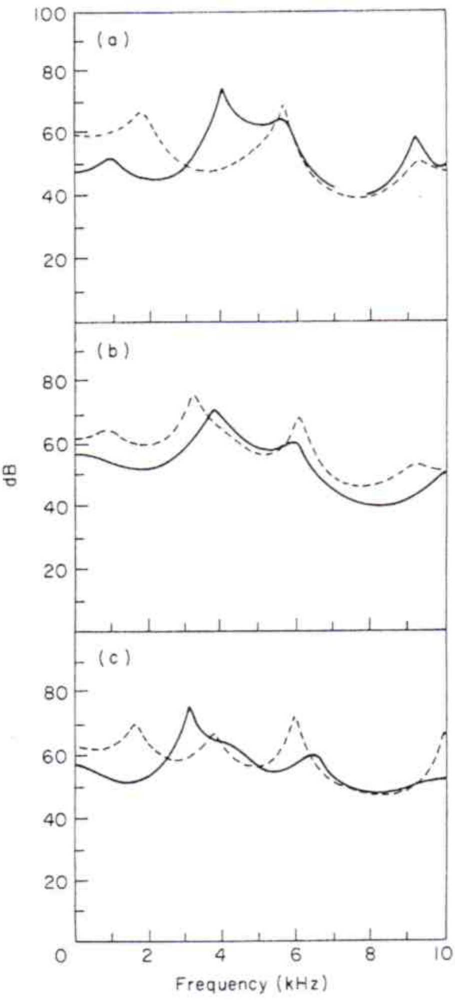

Figure 3. LPC spectra of the burst of [k] for the children's stimuli preceding [i] (——), and [a] (– – –). (a) Examples of a child's stimuli that have distinct [ki] and [ka] spectra; (b) examples of a child's stimuli that have very similar [ki] and [ka] spectra; (c) examples of a child's stimuli that have three peaks in their [ka] spectra.

TABLE III. Percentage corrrect identification of the absent vowel [i] and [a] for the adult stimuli

Speaker	Number of tokens correctly identified	Correct identification of the vowel (%)
A1	168	93
A2	171	95
A3	180	100
A4	174	97
A5	179	99
$\bar{X}$	174	97

TABLE IV. Percentage correct identification of the absent vowel [I] and [a] for the children's stimuli

Speaker (age in months)	Number of tokens correctly identified	Correct identification of the vowel (%)
C1 (32)	171	95
C2 (36)	177	98
C3 (42)	124	69
C4 (47)	170	94
C5 (48)	149	83
C6 (61)	168	93
C7 (62)	176	98
C8 (66)	146	81
C9 (67)	161	89
C10 (68)	170	94
C11 (72)	166	92
C12 (79)	159	88
C13 (81)	158	88
C14 (85)	171	95
$\bar{X}$	162	90

(using natural stimuli) and Blumstein & Stevens (1980) (using synthetic stimuli) found that subjects showed very high consonantal identification scores when given only brief-burst information.

The perceptual results for the children's speech stimuli are shown in Table IV. On average, listeners were capable of identifying the vowel with approximately 90% correct identification. Although the perceptual scores for the children's stimuli, overall, were lower than scores for the adult stimuli, this trend did not reach significance ($t = 1.92$; $P > 0.05$; ns; $df = 17$).

3.3. *Comparison of acoustic and perceptual results*

Summaries of the acoustic and perceptual results of the adult speakers are shown in Table V. For this comparison, a difference score was utilized. This value represents a measure of the average difference between the low-frequency spectral peaks of the [ki] and [ka] stimuli for a single speaker. These results were then compared to the perceptual

TABLE V. A comparison of the acoustic and perceptual data for the adult stimuli

Speaker	Difference (Hz) between low-frequency regions of [ki] and [ka]	$\bar{X}$	Perceptual results	$\bar{X}$
A1	702	876	93	94
A2	1050		95	
A5	1422	1429	99	99
A4	1429		97	
A3	1436		100	

data. Those adult speech stimuli that do not have maximally distinct [ki] and [ka] low-frequency locations (such as A1 and A2 with an average 876 Hz difference) present more difficulty for subjects (average 94% correct identification). Those adult stimuli that have more distinct [ki] and [ka] low-frequency spectral peaks (such as A3–A5 with an average 1429 Hz difference) are more accurately identified (average 99% correct identification).

An analysis of the children's results reveals similar results (see Table VI). The two lowest perceptual scores (average 75% correct identification) were obtained for those children's stimuli (C3 and C8) with the least distinct [ki] and [ka] spectra (an average 136 Hz difference), whereas those children's stimuli such as C1, C2, C4–C7, C9, C11, and C12, with distinct [ki] and [ka] spectra (an average 1407 Hz difference) are better identified (average 92% correct identification).

This comparison of the children's acoustic and perceptual results, however, does not include those children's data (C10, C13, C14) that consistently showed three, rather than two, prominent spectral peaks for their [ka] spectra. As shown in Table VII, these children's stimuli still show a sizeable difference (1274 Hz) between the lowest-frequency regions of [ki] and [ka] stimuli and this difference is matched by a relatively high correct perceptual identification score of 92%.

TABLE VI. A comparison of the acoustic and perceptual data for the children's stimuli

Speaker	Difference (Hz) between low-frequency regions of [ki] and [ka]	$\bar{X}$	Perceptual results (percentage correct identification)	$\bar{X}$
C8	69	136	81	75
C3	203		69	
C5	807	1407	83	92
C12	1027		88	
C2	1055		98	
C11	1237		92	
C9	1332		89	
C4	1495		94	
C7	1581		98	
C6	1999		93	
C1	2128		95	

TABLE VII. A comparison of acoustic and perceptual data for those children's stimuli that showed three prominent spectral peaks for their [ka] spectra

Speaker	Difference (Hz) between low-frequency regions of [ki] and [ka]	$\bar{X}$	Perceptual results (percentage correct identification)	$\bar{X}$
C14	1211	1274	95	92
C10	1300		94	
C13	1311		88	

4. Discussion

In this work the lingual anticipatory coarticulation in adult and child speakers was investigated. The acoustic analysis revealed that adult stimuli do display consistent effects of anticipatory lingual coarticulation. Short-time spectra sampled at consonantal release show a systematic difference between [k] spectra preceding [i] compared to [a]. Specifically, the spectra of [k] preceding [a] have a predominant peak in the low-frequency region compared to spectra of [k] preceding [i]. However, the acoustic analysis of the children's stimuli showed more variable lingual coarticulatory effects. Whilst some of the children's spectra displayed the same pattern as the adults', a few of the children's spectra did not show these systematic differences between [k] spectra preceding [i] compared to [a].

The perceptual study showed that subjects were highly sensitive to the acoustic differences in the adult [ki] and [ka] stimuli. That is, given only 25 ms of consonant onset, subjects could accurately identify the following vowel sound. The perceptual results for the children's stimuli showed less accurate vowel perception scores, especially for the stimuli of those children that did not show substantial spectral shifts in the acoustic analyses of the [ki] and [ka] stimuli.

The present research supports two main conclusions. First, the analyses of the acoustic effects of lingual coarticulation in velar stop consonants are congruent with the perceptual tests for both the adult and child data. In those cases where the low-frequency spectral peaks for [ka] stimuli were maximally distinct from the low-frequency peaks for the [ki] stimuli, identification of the vowel from brief onset segments was extremely accurate.

Second, the present results illustrate differences between the speech stimuli of the adults and some of the children. The adult data, as well as the data for a majority of the children, show very robust acoustic and perceptual cues for anticipatory lingual coarticulation. However, the stimuli for some of the children (e.g. C3 and C8) lack strong low-frequency peaks in [ka] spectra and, further, these stimuli have relatively poor vowel-identification scores. These children's [ka] spectra show peaks at approximately the same frequency locations as their [ki] spectra, and it seems that listeners are sensitive to these shifts because almost all errors are [ka]'s misidentified as [ki]'s.

The experiment thus demonstrates that the speech of some children does not show the acoustic or perceptual effects of lingual coarticulation. It should be noted that in this experiment, the differences among the child speakers did not correlate with age because the children (e.g. C3, C8) whose [ki] and [ka] spectra showed the most similar patterns were not the youngest children in the study. These preliminary findings are supported by studies showing idiosyncratic patterns in the rate of development of speech articulation skills (e.g. Garnica, 1973). However, additional speech samples from more children should be analysed to corroborate the present results.

The differences between adult and children's speech stimuli that were found in the present experiment are supported by recent studies of anticipatory labial coarticulation (Sereno, Baum, Marean, and Lieberman, 1985; Sereno, Baum, Marean, and Lieberman, 1987). As in the present study, Sereno *et al.* (1987) found that, whilst adult speech stimuli showed strong acoustic and perceptual cues, children's stimuli showed less consistent acoustic and perceptual cues to anticipatory labial coarticulation (cf. Nittrouer 1985; Turnbaugh, Hoffman, Daniloff & Absher, 1985).

The present research can be understood in terms of recent work on speech motor activity. Several investigators (Abbs & Gracco, 1984; Lieberman, 1984, 1985; Abbs, 1986; Gracco & Abbs, in press) found that normal speech muscle activity can be interpreted as complex goal-directed maneuvers that are acquired and not the consequence of specific innate mechanisms. These claims are supported by developmental data on the acquisition of articulatory skills (Watkin & Fromm, 1984; Sharkey & Folkins, 1985). Both of these studies showed that children's utterances were significantly more variable than adult utterances, suggesting different age levels for the acquisition of individual motor processes for speech.

The present research fits comfortably with these conclusions. Both the acoustic and perceptual results suggest that anticipatory lingual coarticulatory cues are not present in the speech stimuli of some children because of individual differences in the development of automatized speech motor control patterns. The present results are consistent with a developmental process involving gradual acquisition and fine-tuning of speech motor patterns.

This research was supported by funds from the John D. and Catherine T. MacArthur Foundation Research Network on the Transition from Infancy to Early Childhood. We would like to express our appreciation to the Harvard Infant Study Center for assistance in data collection.

References

Abbs, J. (1986) Invariance and variability in speech production: a distinction between linguistic intent and its neuromotor implementation, in *The Proceedings of the Symposium on Invariance and Variability of Speech Processes* (J. Perkell & D. Klatt, editors), pp. 202–225. Boston: Lawrence Erlbaum Associates.

Abbs, J. & Gracco, V. (1984) Control of complex motor gestures: orofacial muscle responses to load perturbations of lips during speech, *Journal of Neurophysiology*, **51**, 705–723.

Amerman, J. & Daniloff, R. (1977) Aspects of lingual coarticulation, *Journal of Phonetics*, **5**, 107–113.

Blumstein, S. & Stevens, K. (1980) Perceptual invariance and onset spectra for stop consonants in different vowel environments, *Journal of the Acoustical Society of America*, **67**, 648–662.

Cole, R. & Scott, B. (1974) The phantom in the phoneme: invariant cues for stop consonants, *Perception and Psychophysics*, **15**, 101–107.

Eguchi, S. & Hirsh, I. (1969) Development of speech sounds in children, *Acta Otolaryngologica*, **257** (supplement).

Fant, G. (1973) *Speech Sounds and Features*. Cambridge: MIT Press.

Fischer-Jørgensen, E. (1954) Acoustic analysis of stop consonants, *Miscellanea Phonetica*, **2**, 42–59.

Garnica, O. (1973) The development of phonemic speech perception, in *Cognitive development and the acquisition of language*, (T. Moore, editor). New York: Academic Press.

Goldstein, U. (1980) An articulatory model for the vocal tracts of growing children. Sc.D. Dissertation, M.I.T. (unpublished).

Gracco, V. & Abbs, J. (in press) Dynamic control of the perioral system during speech: kinematic analyses of autogenic and nonautogenic sensorimotor processes, *Journal of Neurophysiology*.

Houde, R. (1967) A study of tongue body movement during selected speech sounds. Ph.D. dissertation, University of Michigan (unpublished).

Kent, R. (1983) The segmental organization of speech, In *The production of Speech* (P. MacNeilage, editor), pp. 57–90. New York: Springer-Verlag.

Kent, R. & Forner, L. (1980) Speech segment durations in sentence recitations by children and adults, *Journal of Phonetics*, **8**, 157–168.

Kent, R. & Minifie, F. (1977) Coarticulation in recent speech production models, *Journal of Phonetics*, **5**, 115–133.

Kent, R. & Moll, K. (1972) Cinefluorographic analyses of selected lingual consonants, *Journal of Speech and Hearing Research*, **15**, 453–473.

LaRiviere, C., Winitz, H. & Herriman, E. (1975) Vocalic transitions in the perception of voiceless initial stops, *Journal of the Acoustical Society of America*, **57**, 470–475.

Lieberman, P. (1980) On the development of vowel production in young children, In *Child Phonology: Perception and Production*, (G. Yeni-Komshian & J. Kavanagh, editors), pp. 113–142. New York: Academic Press.

Lieberman, P. (1984) *The Biology and Evolution of Language*. Cambridge: Harvard University Press.

Lieberman, P. (1985) On the evolution of human syntactic ability. Its preadaptive bases—motor control and speech, *Journal of Human Evolution*, **14**, 657–668.

Nittrouer, S. *The role of coarticulation in the perception and production of speech by young children (3 to 7 years)*. Ph.D. dissertation, The City University of New York (unpublished).

Öhman, S. (1966) Coarticulation in VCV utterances: spectrographic measurements, *Journal of the Acoustical Society of America*, **39**, 151–168.

Öhman, S. (1967) Numerical model of coarticulation, *Journal of the Acoustical Society of America*, **41**, 310–320.

Peterson, G. & Barney, H. (1952) Control methods used in a study of the vowels, *Journal of the Acoustical Society of America*, **24**, 175–184.

Schatz, C. (1954) The role of context in the perception of stops, *Language*, **30**, 47–56.

Sereno, J., Baum, S., Marean, G. & Lieberman, P. (1985) Acoustic analyses and perception data on anticipatory labial coarticulation in adults and children. Paper presented at the 109th meeting of the Acoustical Society of America, Austin, Texas, April 1985.

Sereno, J., Baum, S., Marean, G. & Lieberman, P. (1987) Acoustic analyses and perceptual data on anticipatory labial coarticulation in adults and children, *Journal of the Acoustical Society of America*, **81**, 512–519.

Sharkey, S. & Folkins, J. (1985) Variability of lip and jaw movements in children and adults: implications for the development of speech motor control, *Journal of Speech and Hearing Research*, **28**, 3–15.

Smith, B. & McClean-Muse, A. (1985) Development of lip and jaw control in the speech of children. Paper presented at the 109th meeting of the Acoustical Society of America, Austin, Texas, April 1985.

Tingley, B. & Allen, G. (1975) Development of speech timing in children, *Child Development*, **46**, 186–194.

Turnbaugh, K., Hoffman, P., Daniloff, R. & Absher, R. (1985) Stop-vowel coarticulation in 3-year-old, 5-year-old, and adult speakers, *Journal of the Acoustical Society of America*, **77**, 1256–1257.

Watkin, K. & Fromm, D. (1984) Labial co-ordination in children: preliminary considerations, *Journal of the Acoustical Society of America*, **75**, 629–32.

Winitz, H., Scheib, M. & Reeds, J. (1972) Identification of stops and vowels for the burst portion of /p, t, k/ isolated from conversational speech, *Journal of the Acoustical Society of America*, **51**, 1309–1317.

Zue, V. (1976) Acoustic characteristics of stop consonants: a controlled study. Ph.D. dissertation, M.I.T. (unpublished).