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Acoustic Evidence for the Development of Gestural Coordination in the Speech of 2-Year-Olds: A Longitudinal Study

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Studies of child phonology have often assumed that young children first master a repertoire of phonemes and then build their lexicon by forming combinations of these abstract, contrastive units. However, evidence from children's systematic errors suggests that children first build a repertoire of words as integral sequences of gestures and then gradually differentiate these sequences into their gestural and segmental components. Recently, experimental support for this position has been found in the acoustic records of the speech of 3-, 5-, and 7-year-old children, suggesting that even in older children some phonemes have not yet fully segregated as units of gestural organization and control. The present longitudinal study extends this work to younger children (22- and 32-month-olds). Results demonstrate clear differences in the duration and coordination of gestures between children and adults, and a clear shift toward the patterns of adult speakers during roughly the third year of life. Details of the child-adult differences and developmental changes vary from one aspect of an utterance to another.

KEY WORDS: development, coarticulation, gesture, gestural coordination, speech timing

From a study of word-initial consonants in the early words of three children learning English, Ferguson and Farwell (1975) concluded that the initial unit of linguistic contrast in child phonology was not the phoneme, but the word. Implicit in this proposal was the notion that the word (or phrase) is the domain over which a child initially organizes its articulations (cf. Waterson, 1971). A good deal of evidence has now accumulated to support this view (e.g., Macken, 1979; McCune & Vihman, 1987; Menn, 1983, 1986; Menyuk, Menn, & Silber, 1986; Vihman & Velleman, 1989).

Also implicit in the apparent primacy of the word is the notion that smaller units of articulatory organization, whether consonants and vowels (Davis & MacNeilage, 1990) or the gestures that compose them (Studdert-Kennedy, 1987), gradually emerge as independently controllable units through local differentiation of the CV syllable into its onset and nucleus (cf. Lindblom, MacNeilage, & Studdert-Kennedy, 1983). The process of differentiation, or gestural segregation, may begin with variegated babble (Davis & MacNeilage, 1990) and continues as the child's lexicon grows.

By this account, the early course of phonological development is one in which the child gradually narrows its minimal domain of articulatory organization from the syllable, or syllable string, to the segment (cf. Menn, 1986). If this is so, we might expect spatiotemporal overlap of gestures to diminish as children come to segregate consonantal from vocalic gestures and to coordinate them into the precise temporal patterns typical of adult speech (Browman & Goldstein, 1986, 1989; see also

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Studdert-Kennedy & Goodell, in press). Evidence for such a decline has indeed come from acoustic analyses of fricative-vowel syllables spoken by young children and adults (Goodell, 1991; Goodell & Studdert-Kennedy, 1991; Nittrouer, Studdert-Kennedy, & McGowan, 1989; Siren, 1991), although an attempt to replicate Nittrouer et al. (1989), under slightly different experimental conditions, found no differences between children and adults (Katz, Kripke, & Tallal, 1991).

Before reviewing other relevant studies, we should note a terminological issue of some theoretical importance. The standard term *coarticulation* refers to the interaction and supposed mutual adjustments in articulatory form between nearby phonetic segments (consonants and vowels). Moreover, the commonly used terms *anticipatory coarticulation* and *perseveratory coarticulation* imply (incorrectly, in our view) that the beginnings and ends of these segments are phonetically irrelevant intrusions into a neighboring segment rather than necessary and intrinsic portions of the articulatory act. Such views are inevitable as long as the entities said to be coarticulated—consonants, vowels, and features—are physically undefined elements of abstract linguistic description.

In the present paper we take the segment to be a recurrent pattern of gesture that gradually emerges, as a potential unit of phonetic representation, through differentiation and integration of the gestures that form a child's early words (Studdert-Kennedy, 1987). Following Browman and Goldstein (1986, 1989), we take a gesture to be the formation and release of a constriction within the oral (lip, tongue tip, tongue body), velic, or laryngeal articulatory subsystems. We assume, further, that acoustic vectors commonly attributed to coarticulation arise not from articulatory adjustments between neighboring segments, but from the coproduction, or temporal overlap, of invariant neighboring gestures. Accordingly, we use the term *gestural overlap* to describe our own data, reserving the term *coarticulation* for studies where that word has been used.

Several studies have used acoustic analysis to compare coarticulation in children's and adults' utterances. Here, we briefly review work directly relevant to the present paper, namely, studies of anticipatory vowel-to-schwa gestures (where the effect of the stressed vowel on a preceding schwa in an iambic ə'CV sequence is measured), of anticipatory vowel-to-stop-consonant gestures (where the effect of a vowel on the preceding stop consonant in a CV sequence is measured), and of anticipatory stop consonant-to-vowel gestures (where the effect of a stop consonant on the preceding vowel in a VC sequence is measured). We should note that the studies to be reviewed differ considerably in their numbers of subjects, and so in their statistical power, or probability of correctly rejecting the hypothesis of no difference between children and adults. We leave it to the reader to adjudicate among their findings in light of these differences.

Three studies have examined the development of intersyllabic stressed-vowel-to-schwa effects in iambic disyllables. Repp (1986) analyzed coarticulation in one adult and two children (ages 4:8 and 9:5). Second formant (F2) estimates for the schwa in two-word sequences such as [ə#'CV] (in which # represents a word boundary) showed that the adult and the older child anticipated the front-back tongue position of the stressed vowel transconsonantally, whereas the younger child did not. In addition, first formant (F1) estimates for the schwa showed that only the adult anticipated tongue height. In a far more extensive study of 3-, 5-, and 9-year-olds and adults ($n = 10$ for each group), Hodge (1989) estimated F2 values in bark at the midpoint of the schwa in utterances of [ə#'stV] (where V = i, u); only the 9-year-olds and adults gave significant evidence of anticipating the stressed vowel in the schwa.

Such results suggest that overlap of vocalic gestures in neighboring syllables may develop as speakers mature, with tongue front-back position emerging earlier than overlap of tongue height. However, Repp's results for tongue height are contradicted by those of Flege (1993), who conducted a study with a larger sample of eight adults and 8-year-old children ($n = 8$). Flege used glossometry (a technique in which the vertical distance between tongue and hard palate is measured with an artificial palate or "glossometer") to measure tongue height in /ə'hVp/ utterances. The children showed significantly greater assimilation of stressed vowel tongue height to preceding schwa than did adults. Flege's results therefore suggest that cross-syllabic vowel coarticulation decreases with age.

Five studies have examined intrasyllabic stop-vowel coarticulation in children and adults (Hodge, 1989; Repp, 1986; Sereno, Baum, Marean, & Lieberman, 1987; Sereno & Lieberman, 1987; Turnbaugh, Hoffman, Daniloff, & Absher, 1985). Four of these studies report that children coarticulate virtually the same as adults, and one study suggests that children may coarticulate more than adults. Turnbaugh et al. (1985) investigated within-syllable CV coarticulation in three 3- and 5-year-old children and three adult males who produced repetitions of CVC nonsense monosyllables. They found no differences due to age in the degree or pattern of coarticulation across consonants, and concluded that within-syllable CV stop coarticulation is virtually the same for children and adults. They suggested that within-syllable CV coarticulation may develop before the age of 3.

As described above, Repp (1986) examined lingual coarticulatory effects in [ə#CV] repetitions produced by a 4-year-old, a 9-year-old, and an adult. Estimates of F2 close to consonant release revealed significant consonant-vowel coarticulation in the younger child and adult, but only a marginal degree of coarticulation in the older child. If we assume that the older child's marginal effect would have proved significant on more extensive sampling, these results are consistent with those of Turnbaugh et al., suggesting no difference between 4-year-old children and adults.

Sereno et al. (1987) studied anticipatory lip rounding in consonant-rounded-vowel syllables, spoken by four adults and eight children (3 to 7 years old). The authors excluded "unintelligible tokens" spoken by the children, combined the children's data for statistical analysis, and concluded that coarticulation of lip rounding for the vowel and tongue release for the consonant was virtually the same for the two groups. The lack of child-adult differences may have been due to the selection of adult-like tokens from the children's utterances, and to the averaging of children's data over a 4-year range. However, Sereno et al.'s result is consistent with a similar finding for overlap of lip rounding and tongue constriction by Nittrouer et al. (1989) in larger age-segregated groups (n = 8) of 3-, 4-, 5-, 7-year olds, and adults, uttering fricative rounded-vowel syllables.

Sereno and Lieberman (1987) investigated coarticulation in [ki] and [ka] syllables spoken by 5 adults and 14 children (approximately 2½ to 7 years). The adults consistently exhibited coarticulation of consonant and vowel, but the children were more variable, some displaying adult-like patterns, others quite different patterns from adults. The mean difference between groups was not significant, and the authors concluded that coarticulatory patterns are similar in adults and children. Again, the lack of child-adult differences may have been due to data selection and averaging across a 4- to 5-year age range.

One study has departed from the consensus of the preceding four. Hodge (1989) reported a study of 3-, 5-, 9-year-olds, and adults repeating the monosyllables [di], [dæ], and [du]. Results indicated that variation in F2 onset values, as a function of following vowel, was greatest for the 3-year-olds and declined with age, but the author did not report the statistical significance of these effects.

Finally, Kent (1983) has reported the apparent effect of a final stop on a preceding vowel in a CVC syllable, by inference from formant values over the final portion of the vowel immediately before closure for [k] in the word *box* [bɑks], spoken by three 4-year-olds and three adults. For the adults he found that F2 rose into the closure, whereas for the children F2 was relatively flat throughout the vowel. He interpreted this as evidence of greater coarticulation in the adults than in the children. An alternative interpretation, suggested by Nittrouer et al. (1989), is that the children's lack of a final transition was due to a raised F2 throughout the vowel in anticipation of the /k/ closure, and therefore reflected more rather than less gestural overlap.

In short, four of the six studies of stop-vowel or vowel-stop coarticulation report no differences between children and adults. The two discrepancies, depending on interpretation, either are themselves discrepant or agree in suggesting that children coarticulate more than adults.

Whatever conclusions we draw from the studies reviewed here are limited, however, by the fact that, with the exception of one 32-month-old in Sereno and Lieberman (1987), none of the subjects was younger than 3 years old. By this age a child typically has a sizable receptive and expressive vocabulary (Templin, 1957) and a basic command of syntax (Limber, 1973). Elsewhere it has been argued that consonants and vowels first emerge as integrated patterns of gesture in child speech in response to at least two pressures: one pressure toward economy of storage as the lexicon increases in size, another toward rapid lexical access in the formation of multiword utterances (Studdert-Kennedy, 1987, 1989; cf. Branigan, 1979; Donahue, 1986). If this is so, and if we want to understand the early development of gestural organization in speech, we need to examine the acoustic records of children most of whose utterances are still single words.

Two further cautions emerge from the studies we have reviewed. First, if we are to trace development in any detail, we must use relatively homogeneous groups well defined by age and by an appropriate linguistic measure, such as vocabulary size or mean length of utterance (MLU). Grouping data from 3- through 7-year-olds—as was done by Sereno et al. (1987) and by Sereno and Lieberman (1987)—can be seriously misleading. Second, even within a developmentally homogeneous group, children are likely to differ from one another more than adults do. High variability, combined with the small samples that labor-intensive measurement procedures often necessitate, add up to low statistical power and a high probability of failing to detect true child-adult differences. One way to increase statistical power is to control for individual differences in rate and style of phonological development by conducting longitudinal studies that permit comparison of each child with herself.

With these considerations in mind, a 10-month longitudinal study was designed to examine gestural coordination in children who were within a few months of their second birthday at the start of the study, close to the earliest age at which we could expect reliable cooperation from the subjects. The following questions were addressed: Does gestural coordination in the speech of children at this age differ from that of adults? How does gestural organization change over a 10-month interval within roughly the third year of life? Do measurements from the acoustic records of these children support the inference from studies of child phonology that their minimal domain of gestural organization is wider than that of adults?

Method

Subjects

Twelve subjects (6 girls 20 to 27 months old at the start of the study and 6 adult females) participated in the study. All subjects were monolingual English speakers from the southern New England region. One sex (female) was chosen in order to avoid confounding by possible sex differences in development. The time span of the study (10 months, beginning during the one-word stage) was deemed long enough, given the age under study, for a fair amount of developmental change to be observed. Previous studies have shown that for many children at roughly this stage of development MLU increases substantially over a 10-month period (Brown, 1973; Miller & Chapman, 1981).

Table 1 lists the children's ages and MLUs. The girls were roughly matched for age (mean = 22 months) and level of language development at the start of the study, as assessed by estimates of MLU (reported in morphemes, mean = 1.4), taken from a 30-min recording session; 10 months later mean MLU had increased to 4.4. Thus it was expected that changes in the children's phonological skills would also be apparent.

Materials

The test utterances for the present experiment were the following minimal-pair nonsense disyllables, with stress on the second syllable: [bə'bɑ], [bə'bi], [bə'dɑ], [bə'di], [bə'gɑ], [bə'gi]. The intervocalic labial, alveolar, and velar consonants

TABLE 1. Children's ages in months and their corresponding mean lengths of utterance (MLU) at Time 1 and Time 2.

	Time 1		Time 2	
Subject	Age (months)	MLU	Age (months)	MLU
BO	20	1.4	30	4.2
SK	20	1.0	30	3.8
LH	21	1.5	31	4.5
SR	21	1.9	31	4.6
EA	23	1.1	33	4.7
JM	27	1.5	37	4.6
Mean	22	1.4	32	4.4

were chosen in order to compare the effects of consonant place of articulation on vocalic formant transitions; all subjects at both 22 and 32 months of age were able to produce velars. An iambic stress pattern was chosen because adult studies (e.g., Alfonso & Baer, 1982) have found that a neutral schwa is highly susceptible to the effects of a following stressed vowel; a listener, naive to the purposes of the study, spot-checked the experimenter's model utterances in several sessions and confirmed that they were indeed iambic. The vowels [i] and [ɑ] were chosen because the former is the highest front vowel and the latter the lowest back vowel in English, so that any intersyllabic context effects on the preceding schwa should be quite evident.

Instruments

A Marantz PMD 430 portable tape recorder was used to collect all speech samples. The adults were recorded using an Audio Technica AT9300 microphone, whereas the children were recorded wearing a Samson Stage II wireless microphone with an Audio Technica 831 lapel microphone sewn into a vest.

Procedures

The first author recorded each child's utterances in two half-hour sessions in the child's home at both the first and tenth months. Only the first session from each month was fully analyzed; data from the second session were drawn on only when a subject did not produce at least two repetitions of a given utterance type in the first session. Specially designed stuffed animals with names corresponding to the minimal pairs were used to elicit as many productions as possible through games with puppets, puzzles, books, and a dollhouse. The subjects repeated the test utterances after the experimenter, so that all utterances were immediate repetitions, or imitations. Since imitations may be closer to their targets than spontaneous utterances (cf. Leonard, Schwartz, Folger, & Wilcox, 1978), this procedure may lead to an underestimate of the child-adult differences likely to be observed in spontaneous speech. The order of the test utterances differed across children, but the experimenter attempted to elicit the same number of repetitions of each utterance type in each session. The number of acceptable tokens of each utterance type for each child ranged from 1 to 15, with a mean of 7. Data entered into the statistical analyses for individual children were means based on all acceptable utterances. No utterances were rejected on the basis of the perceived quality of the first vowel because this procedure might have biassed the sample toward adult-like forms from which vowel harmony and spondaic stress patterns (precisely the possible effects of interest) had been eliminated. Utterances were rejected only when formants could not be estimated in the Discrete Fourier Transform (DFT) spectra, or when the first author judged a subject's response to differ from the adult target in the second vowel (e.g., [biˈdɑ] instead of [bəˈdi], or in syllable structure (e.g., [ˈbəˈdəˈgə] instead of [bəˈgɑ]). Seven unacceptable responses out of a total of 515 responses from the children's data were excluded from the analysis. The adult subjects recorded the set of disyllables in random order six times. The adult subjects repeated the test words after the experimenter, and no adult responses were excluded.

Data Analysis

Acoustic measurements. All tokens were digitized at a 20-kHz sampling rate on a VAX 780 computer at Haskins Laboratories. The Haskins Waveform Editing and Display system was used to measure utterance durations and to locate the midpoint of each syllable. Durations were measured on the waveform of each utterance for the first syllable (from the onset of the first full period of voicing to the offset of the last full period of voicing before closure), for the medial stop closure (voice offset to voice onset), and for the second syllable (voice onset to voice offset). Estimates of the center frequencies of the first and second formants were made from DFT spectra, computed with a 25.6 msec Hamming window and a 3.2 msec slide between windows, at five locations: onset, midpoint and offset of the schwa, onset and midpoint of the stressed vowel. These formant estimates were made by first locating on the DFT spectral display the highest amplitude harmonic in the region of a given formant at a given point in the utterance, together with its two neighboring harmonics, immediately above and below it. A special purpose program then computed the amplitude-weighted mean of the three harmonics by summing over the corresponding bins of the DFT transform of the frequencies. An informal test of the reliability of the procedure (by having a second judge locate the main harmonic for a given formant in a few randomly chosen tokens) yielded 100% agreement.

Statistical analyses. A set of three separate analyses of variance, in addition to a number of *t*-tests, was carried out on each of a dozen different aspects of the data. These analyses compared (a) the children at Times 1 and 2 (repeated measures), (b) the children at Time 1 with the adults, and (c) the children at Time 2 with the adults. Obviously, these analyses are not independent. However, none of the standard procedures for reducing the risk of a Type I error (false rejection of the null hypothesis) across multiple nonorthogonal comparisons, by adjusting the significance level, is applicable to a set of analyses that combines both repeated and nonrepeated measures. Nor indeed are

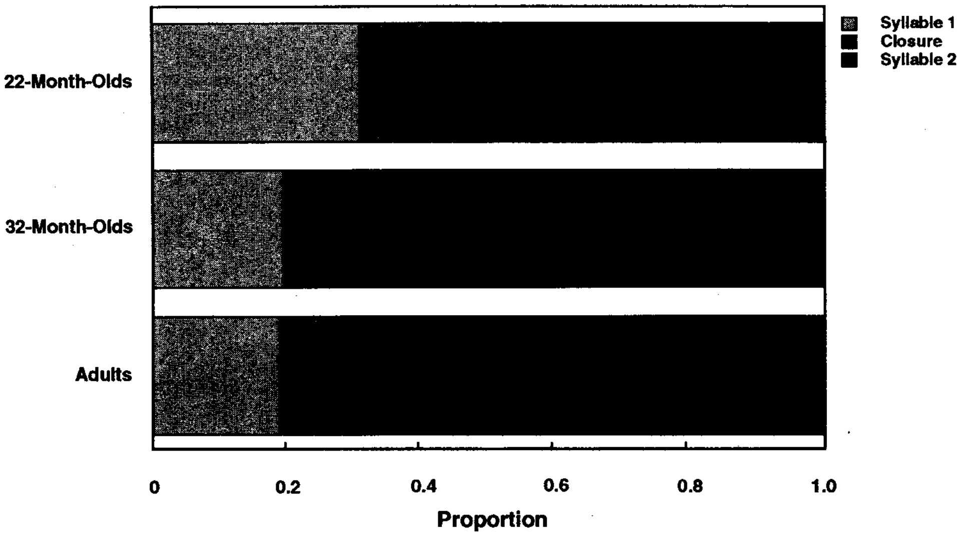

FIGURE 1. Mean syllable and closure durations as a percentage of the mean total duration for 22- and 32-month-olds and for adults.

these procedures designed to apply to sets of comparisons across different, yet correlated, aspects of a body of data, such as (for example) formant patterns at schwa midpoint and formant patterns at schwa offset. In the absence of any generally accepted procedures, we note simply that most of the effects reported below are highly significant. Importantly, they also reveal systematic patterns of change with age that encourage belief in their reliability. Nonetheless, we recommend that readers bear in mind the risks of both Type I and Type II error (false acceptance of the null hypothesis) in interpreting the results.

Results

The results are reported in three separate main sections (Durations, Overlap of Vowel Gestures, Overlap of Consonant and Vowel Gestures), each followed by its own discussion. The paper concludes with a general discussion.

Durations

Table A in the Appendix lists the mean absolute durations and the mean proportions of the utterances accounted for by each syllable and by the closure durations. The mean proportions of the total durations assumed by the first syllable, closure, and second syllable are illustrated in Figure 1. For the 22-month-olds the first syllable accounts for 31% of the total utterance, closure for 19%, and the second syllable for 50%. For the 32-month-olds: first syllable 20%, closure 20%, second syllable 60%. For the adults: first syllable 18%, closure 15%, second syllable 67%. Comparing the children and adults, we find that the proportion of the utterance taken up by the first syllable and closure is greatest for the children at Time 1 (50%) and diminishes with age to 33% in the adults.

As we would expect, overall duration decreases with age: 610 to 546 to 482 msec. For the adults all total duration means were within 3 msec of each other (481 msec, 484 msec, 481 msec for utterances carrying the medial consonants [b], [d], and [g], respectively). By contrast, the 22-month-olds' durational means for tokens with [d] and [g] were roughly the same (631, 640, respectively), but the mean for utterances with labials was 70 to 80 msec shorter (560 msec).

Analyses of variance on the total durations with three factors (Consonant × Stressed Vowel × Age) revealed significant effects of consonant ($F_{2,20} = 6.96$, $p < .005$) and age ($F_{1,10} = 8.31$, $p < .02$) for the 22-month-olds and adults, and of age ($F_{1,10} = 4.79$, $p = .05$) for the 32-month-old children and the adults. A consonant-by-age interaction for the 22-month-olds and adults ($F_{2,20} = 6.37$, $p < .01$) reflected the different pattern of durations for these age groups noted above. Two-tailed *t*-tests on the first syllable ratios revealed significant differences between children at Time 1 and adults ($t(10) = 4.422$, $p < .001$), between the children at Time 1 and Time 2 ($t(5) = 3.932$, $p < .01$), but not between the children at Time 2 and adults. For closure duration ratios two-tailed *t*-tests revealed a significant difference between the 32-month-olds and adults ($t(10) = 2.856$, $p < .02$), but not between the 22-month-olds and adults or between the children at Time 1 and Time 2. Finally, two tailed *t*-tests on the second syllable ratios revealed significant differences between the age groups: 22-month-olds and adults ($t(10) = 6.252$, $p < .0001$), 32-month-olds and adults ($t(10) = 3.028$, $p < .01$), and 22- and 32-month-olds ($t(5) = 3.603$, $p < .02$).

The results agree with previous studies reporting that children's utterances tend to be longer than adults' (DiSimoni, 1974; Eguchi & Hirsh, 1969; Kubaska & Keating, 1981; Smith, Sugarman, & Long, 1983). The shorter total durations for [bə'bV] than for [bə'dV] and [bə'gV], spoken by the younger children, perhaps stem from repetition of the initial consonant, in the manner of canonical babble, facilitating relatively rapid execution.

Interestingly, the children's greater duration is not distributed evenly across the two syllables. The younger children have difficulty producing weak or reduced syllables (as reported also by Allen & Hawkins, 1980), so that they tend to equate the duration of the first syllable and the following closure with the duration of the second syllable. The decline in the proportion of the total duration assigned to the first syllable, and the roughly corresponding increase in the proportion assigned to the second, from 22 months to 32 months, combined with the lack of a significant difference in the first syllable proportion for 32-month-olds and adults, indicate that the children's ability to make a stress contrast has become virtually adult-like over this 10-month interval.

Overlap of Vowel Gestures

Formant paths and vowel plots. Tables B and C in the Appendix list mean formant values for F2 and F1 at the five measurement points for all subjects. Peterson and Barney (1952) report mean first and second formant frequencies for their 28 female speakers of the high front vowel [i] as 310 Hz and 2790 Hz respectively, and for the low back vowel [ɑ] 850 Hz and 1200 Hz, respectively. The mean adult formant values for the midpoint of the stressed vowel in the present study correspond roughly to the above values: 317 and 2513 Hz for [i], 772 and 1399 Hz for [ɑ].

With regard to adult vowel-vowel overlap (Figure 2), early onset of the stressed vowel gesture is evident for the front-back dimension in the second formant paths, estimated from formant values at onset, midpoint, and offset of the first syllable schwa. These paths lie approximately 200 Hz higher in [bə'bi], [bə'di], and [bə'gi] than they do in the corresponding members of the pairs: [bə'bɑ], [bə'dɑ], and [bə'gɑ]. No anticipatory effects appear in the high-low tongue dimension; measurements of F1 in the schwa before stressed [ɑ] and [i] are roughly the same, a finding that accords with a previous adult study (Alfonso & Baer, 1982).

In contrast, mean formant estimates for the six children show clear overlap of the stressed vowel with schwa in both dimensions at both ages (Figures 3 and 4). For the 22-month-olds (Figure 3) in [bə'bV], F2 before stressed [i] is approximately 700 Hz higher than F2 before stressed [ɑ] at schwa onset, midpoint, and offset; in [bə'dV] the corresponding [i]-[ɑ] difference is about 120 Hz at onset, 500 Hz at midpoint, and 350 Hz at offset; in [bə'gV] the difference is 500 to 600 Hz throughout the schwa. For schwa F1, the largest difference between the [i]-[ɑ] formant paths is found in [bə'bV], with a difference of about 300 Hz at vowel midpoint; for [bə'dV] there is a difference of about 100 Hz throughout the schwa; and in [bə'gV] a difference of about 120 Hz at schwa offset. The F1 formant paths indicate that these children anticipate the stressed vowel in tongue height, as well as in the front-back tongue dimension (as indicated by F2).

The mean formant paths for the children at Time 2 are shown in Figure 4. For the stressed vowels mean formant values remain virtually unchanged over the 10-month period, indicating that any differences in spectral structure at other points in the utterance are not a consequence of vocal tract growth. (Two tailed *t*-tests at stressed vowel midpoints revealed a significant difference only for F1 [i] (*t*(5) = 4.017, *p* < .01), none for F1 [ɑ], F2 [i], or F2 [ɑ]).

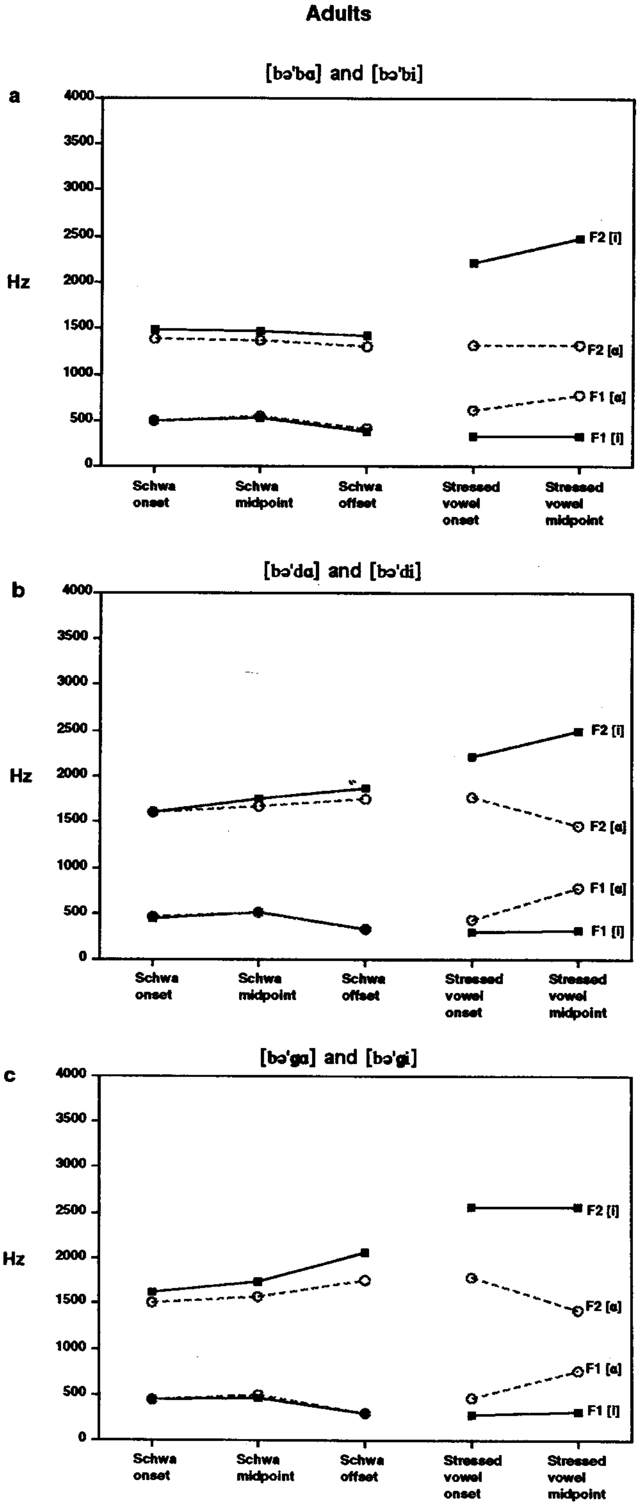

FIGURE 2. Mean formant paths for adults for [bə'bʌ], [bə'dV], [bə'gV].

The most salient differences between the two ages are in the schwa. Consider, for example, the schwa midpoints. For

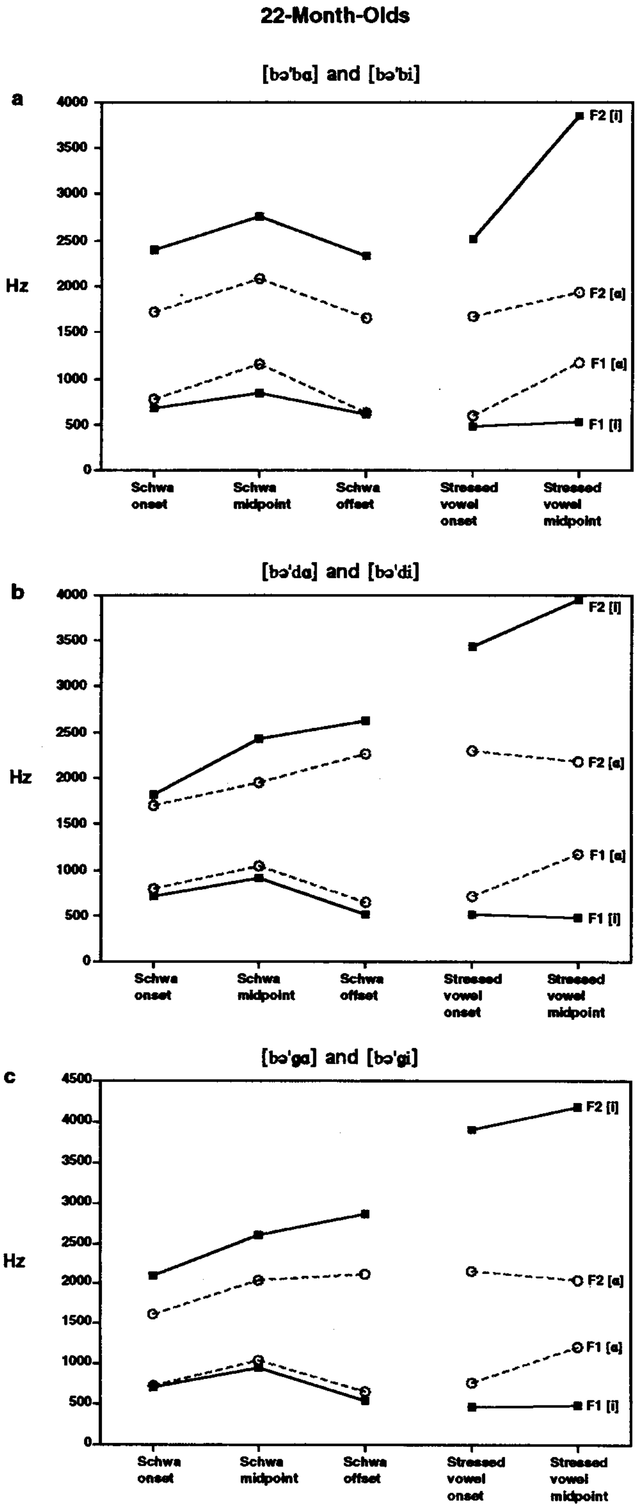

FIGURE 3. Mean formant paths for 22-month-olds for [bəˈbV], [bəˈdV], [bəˈgV].

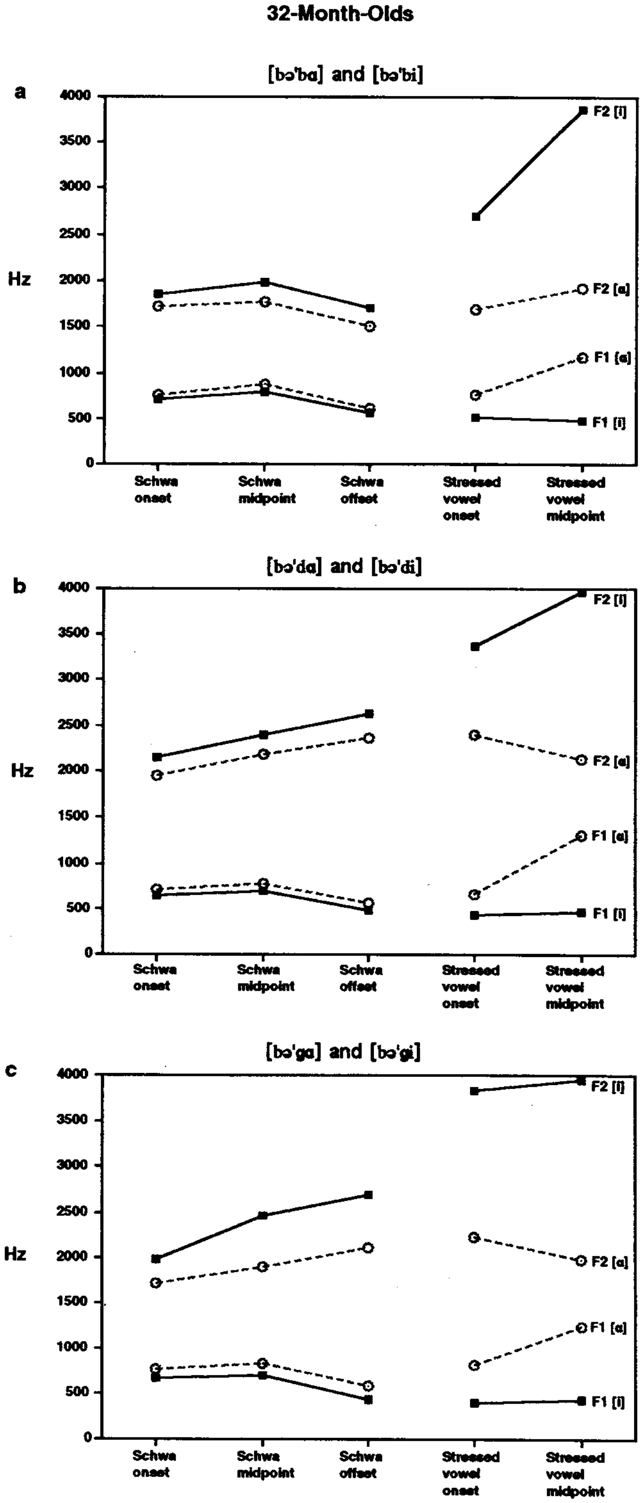

FIGURE 4. Mean formant paths for 32-month-olds for [bəˈbV], [bəˈdV], [bəˈgV].

[bəˈbV] mean F2 at the schwa midpoint of the 32-month-olds has dropped from its value 10 months earlier by about 800 Hz before [i], and by about 300 Hz before [ɑ]; for [bəˈdV] the drop before [i] is 200 Hz, whereas F2 before [ɑ] has risen by over 200 Hz; for [bəˈgV] F2 values at schwa midpoint have dropped by about 150 Hz before both vowels. F1 values at schwa midpoint have dropped roughly 50 Hz before [i], 300 Hz before [ɑ] in [bəˈbV], and by about 200 Hz before both [i] and [ɑ] in [bəˈdV]. In [bəˈgV] F1 values at schwa midpoints are lower by about 150 Hz before both vowels. The difference between F1 values at schwa midpoints before the two vowels has decreased by about 200 Hz in [bəˈgV], but is roughly the same at both ages in [bəˈdV]. The absolute, non-normalized formant values suggest then that the 22-month-olds overlap gestures for the stressed vowel and the schwa more strongly in both dimensions of tongue placement than the older children, and that children at both ages do so more strongly than the adults.

We see the effects of age, and the different effects of the two stressed vowels, quite clearly if we plot the mean formant values at schwa midpoint before [i] and [ɑ] separately for each age group: in Figure 5 F2-F1 is plotted on the abscissae, estimating relative front-back tongue position (Ladefoged, 1984), and F1 on the ordinates, estimating relative tongue height. Due to the reversed axes, the plots of the vowels correspond roughly to vowel position in the oral cavity. For the 22-month-olds the schwa values before [ɑ] lie close to those of the target stressed vowel itself, whereas before [i] they are appropriately more central. For the 32-month-olds, schwa values before [ɑ] have moved forward and upward in the oral cavity and are beginning to cluster with schwa values before [i], much in the fashion of the adults. Notice that, even in the adults, for each place of consonantal closure, schwa before [i] lies closer to [i] than to [ɑ], and schwa before [ɑ] lies closer to [ɑ] than to [i]. Notice too that for both older children and adults schwa before both [i] and [ɑ] is slightly lower and clearly more backed before labial than before alveolar or velar closure.

To determine the statistical significance of the differences between children and adults described above, we must remove the effects of differences in vocal tract size on spectral range. We therefore turn now to our normalization procedures.

Normalization procedures and statistical tests: Tongue front-back position (F2-F1). Ladefoged (1984) has proposed that the difference between F2 and F1 provides a more direct estimate of front-back tongue position across the cardinal vowels within a speaker than simple F2. Accordingly, mean F1 was subtracted from mean F2 for each utterance type for each subject at schwa onset (1), schwa midpoint (2), and stressed-vowel midpoint (5) in order to estimate tongue position in the front-back dimension. The estimates at the midpoint of the stressed vowel represent the subject's "target" formant values for [i] and [ɑ]. In order to get a normalized measure of the stressed vowel effects, F2-F1 values at the other two points were expressed as proportions of this "target" value: $F2_{i1}$-$F1_{i1}$/$F2_{i5}$- $F1_{i5}$, $F2_{\alpha5}$-$F1_{\alpha5}$/$F2_{\alpha1}$, $F1_{\alpha1}$, and so forth. The letters and numbers in the subscripts refer to stressed vowels and measurement points. Thus, $F2_{i1}$-$F1_{i1}$ refers to the tongue position at the onset of the schwa before stressed [i], whereas $F2_{i5}$-$F1_{i5}$ refers to tongue position in stressed [i], and so forth. Note that for [ɑ] utterances mean F2-F1 is expected to be lower in the stressed vowel than at the other measurement points; accordingly, the inverse ratio was formed. If the value of F2-F1 in the schwa is identical to the value of F2-F1 in the stressed vowel (i.e., if the gestures for schwa and stressed vowel maximally overlap, yielding front-back tongue harmony), the ratio will be 1. Conversely, any reduction in the degree of gestural overlap will yield a corresponding reduction in the value of the ratio. This procedure for self-normalization of vowels is analogous to one developed by Gerstman (1968) to normalize Peterson and Barney (1952) vowels within and across speakers.

Table 2 lists the indices for the first two measurement points in the schwa. At the onset and midpoint of the schwa before [ɑ]—the points at which gestural overlap should be apparent—the children at 22 months have values of 1.00 and .99 respectively, indicating complete vowel harmony, but by 32 months the values have dropped to .79 and .75, and the adult values of .63 and .64 are even lower. Thus, for [ɑ] the younger children display the largest effect of the stressed vowel in tongue front-back position, whereas the adults display the least. For [i], by contrast, the values for the adults are somewhat closer to 1 at both these points than are those of the 22- and 32-month-olds.

Separate age-pair analyses of variance (Stressed Vowel × Age) were carried out on the F2-F1 ratios at the first two measurement points. See Table 3 for all significant effects and interactions for the three groups. For the 22-month-olds and adults there were significant main effects of both age and stressed vowel as well as a significant stressed-vowel-by-age interaction at both onset and midpoint of the schwa. A simple effects analysis on the ratios for [i] revealed no significant differences between the groups at schwa onset or midpoint. The interactions therefore reflect the fact that the children's ratios are closer to 1 than the adults' before [ɑ], whereas before [i] they do not differ significantly.

For the 32-month-olds and the adults there were significant stressed vowel effects and stressed-vowel-by-age interactions at schwa onset and midpoint, but no main effects of age. The interactions at both points reflect the fact that before [ɑ], the children's ratios are closer to 1, whereas before [i] the adult values are closer to 1. A simple effects analysis on values before [i] revealed a significant difference at schwa onset, indicating earlier anticipation of front-back tongue position of the stressed vowels by the adults (cf. Alfonso & Baer, 1982).

Finally, repeated measures analyses of variance on the 22- and 32-month-olds' ratios at schwa onset and midpoint revealed significant effects of age and stressed vowel at both points, but no significant interactions. Thus, averaged across vowels, the children's ratios in the first half of the schwa were closer to 1 at Time 1 than at Time 2, indicating a decrease in gestural overlap with age. At the same time, children at both ages tended to anticipate front-back tongue position more extensively in schwa before [ɑ] than in schwa before [i].

Tongue height (F1). Ratios were also formed to normalize estimates of tongue height. For [ɑ], mean F1 values in the schwa were placed over mean F1 values at the midpoint of the stressed vowel; for [i], because its F1 at midpoint is typically the lowest F1 in the utterance, an inverse ratio was formed: $F1_{\alpha1}$/$F1_{\alpha5}$ and $F1_{i5}$/$F1_{i1}$, and so forth. Once again, the closer the ratio is to 1, the more the gestural overlap between schwa and stressed vowel.

Table 4 lists the F1 indices at schwa onset and midpoint. At schwa onset, the indices reveal little difference among groups in the anticipation of tongue height for either vowel,

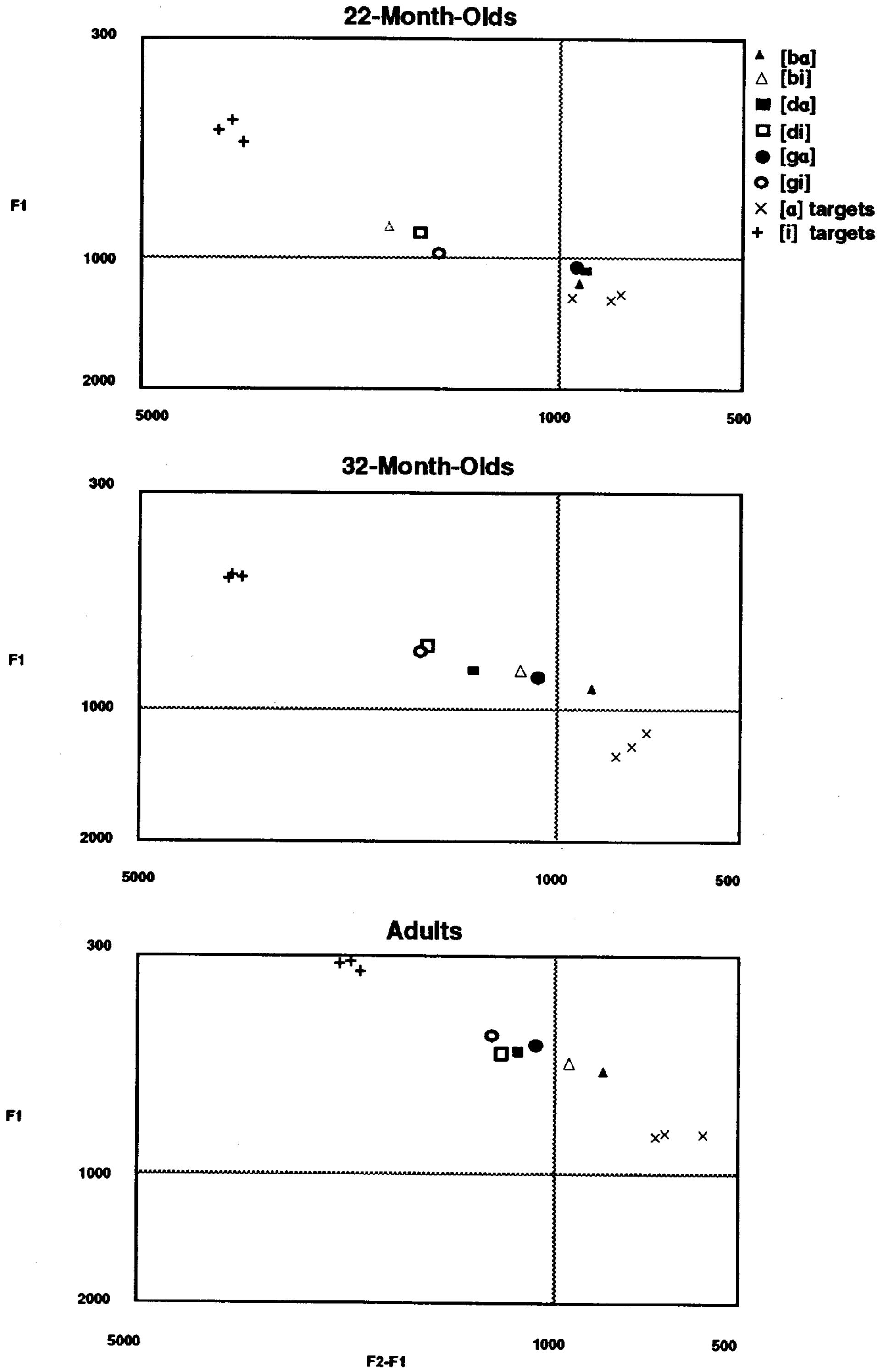

FIGURE 5. Mean F2-F1 plotted against mean F1 for schwa midpoints and stressed vowel midpoints for 22- and 32-month-olds and adults.

and these indices were not further analyzed. But for [ɑ] at schwa midpoint the younger children display almost complete harmony in tongue height between schwa and stressed vowel with a ratio of .99.

Analyses of variance (Stressed Vowel × Age) were carried out for each age-pair on the F1 ratios at schwa onset and midpoint. There were no significant main effects or interactions at schwa onset. At schwa midpoint for the 22-month-olds and the adults, a main effect of age ($F_{1,10} = 7.01$, $p < .02$), was almost entirely due to the ratios in the [ɑ] context,

TABLE 2. Mean ratios of individual mean F2-F1 values at indicated points to individual mean F2-F1 values at stressed-vowel midpoint, listed by stressed syllable and vowel.

	Schwa onset	Schwa midpoint
Children		
22 months		
Stressed Syllable		
bi	0.53	0.60
di	0.32	0.45
gi	0.39	0.46
bɑ	0.82	0.86
dɑ	1.19	1.21
gɑ	1.00	0.90
Stressed Vowel		
i	0.42	0.51
ɑ	1.00	0.99
32 months		
Stressed Syllable		
bi	0.35	0.35
di	0.44	0.49
gi	0.38	0.51
bɑ	0.85	0.88
dɑ	0.72	0.63
gɑ	0.80	0.74
Stressed Vowel		
i	0.39	0.45
ɑ	0.79	0.75
Adults		
Stressed Syllable		
bi	0.51	0.46
di	0.57	0.58
gi	0.52	0.57
bɑ	0.64	0.69
dɑ	0.60	0.61
gɑ	0.63	0.62
Stressed Vowel		
i	0.54	0.54
ɑ	0.63	0.64

with means of .99 and .70 for the children and adults, respectively; a significant effect of stressed vowel ($F_{1,10} = 6.27$, $p < .03$) indicated less extensive anticipation of [i] than of [ɑ] by both groups; a Stressed-Vowel-by-Age interaction was only marginally significant ($F_{1,10} = 3.76$, $p < .08$), but the value of the ratio in the [ɑ] context for the 22-month-olds (.99) indicates that the vowel harmony observed for F2 at schwa midpoint was also present for F1. The corresponding analysis for the 32-month-olds and adults yielded no significant effects or interactions. Finally, repeated measures analyses of variance on the 22- and 32-month-olds' ratios at midpoint revealed significant effects of stressed vowel ($F_{1,5} = 6.68$, $p < .05$) and age ($F_{1,5} = 7.67$, $p < .04$), but no significant interactions. The means for the 22-month-olds and 32-month-olds (averaged across vowels) are .82 and .71, respectively, indicating that schwa and stressed vowel tongue heights are better differentiated at the older age.

Individual differences. Up to this point we have been discussing general trends across the six children. Let us now consider some of the individual differences. Figures 6 and 7 show how two children's vowel plots at schwa midpoint before the two stressed vowels changed over the 10-month interval. In Figure 6 (top) for subject EA overlap of schwa and stressed vowel gestures has resulted in very similar formant values for the midpoints of the schwas and the midpoints of the stressed vowels, a case of near vowel harmony. By 32 months (Figure 6, bottom) the schwa values have assumed a more central position, approaching the pattern of the adults (cf. Figure 5, bottom). Notice however that schwa before labial closure is appreciably lower and more backed than before alveolar or velar closure. The backing pattern is similar to, but more extreme than, that noted above for the adults.

For subject SR (Figure 7, top), a very different pattern is evident. At 22 months schwa measures for all tokens are

TABLE 3. Summary of significant effects in analyses of variance for F2-F1 ratios at schwa onset and schwa midpoint.

Measurement point	Independent variable	Degrees of freedom	F	*p*
22-month-olds and adults				
Schwa onset	Stressed Vowel	1,10	38.93	<.001
	Age	1,10	7.63	<.02
	Stressed Vowel × Age	1,10	20.65	<.001
Schwa midpoint	Stressed Vowel	1,10	27.44	<.001
	Age	1,10	7.95	<.02
	Stressed Vowel × Age	1,10	11.07	<.007
32-month-olds and adults				
Schwa onset	Stressed Vowel	1,10	34.45	<.001
	Stressed Vowel × Age	1,10	13.64	<.004
Schwa midpoint	Stressed Vowel	1,10	22.24	<.001
	Stressed Vowel × Age	1,10	5.26	<.04
22- and 32-month-olds				
Schwa onset	Stressed Vowel	1,5	117.47	<.001
	Age	1,5	8.05	<.04
Schwa midpoint	Stressed Vowel	1,5	41.55	<.001
	Age	1,5	12.73	<.02

TABLE 4. Mean ratios of individual mean F1 values at indicated points to individual mean F1 values at stressed vowel, listed by stressed syllable and vowel.

	Schwa onset	Schwa midpoint
Children		
22 months		
Stressed Syllable		
bi	0.87	0.74
di	0.78	0.60
gi	0.81	0.58
bɑ	0.69	1.02
dɑ	0.75	1.03
gɑ	0.66	0.90
Stressed Vowel		
i	0.82	0.64
ɑ	0.70	0.99
32 months		
Stressed Syllable		
bi	0.76	0.64
di	0.80	0.72
gi	0.71	0.70
bɑ	0.74	0.84
dɑ	0.62	0.68
gɑ	0.63	0.68
Stressed Vowel		
i	0.76	0.68
ɑ	0.66	0.73
Adults		
Stressed Syllable		
bi	0.73	0.63
di	0.75	0.65
gi	0.73	0.69
bɑ	0.68	0.75
dɑ	0.61	0.67
gɑ	0.61	0.67
Stressed Vowel		
i	0.73	0.66
ɑ	0.63	0.70

closer to [ɑ] than to [i]. This subject completely eschews vowel harmony before [i], executing an [ɑ]-like schwa before both [i] and [ɑ]. The data at 32 months (Figure 7, bottom) reveal a more centralized schwa, higher and more forward in the oral cavity. Once again, as in the adults and in EA at 32 months, schwa is more backed before labial than before alveolar or velar closures (cf. Figures 5, bottom, and 6, bottom).

The formant estimates for the subjects as illustrated in the formant path figures prompted two questions: one concerning child-adult differences in gestural overlap; the other concerning differences in the effects of the target stressed vowels, [i] and [ɑ]. The results show that the younger children anticipated the stressed vowel [ɑ] in the schwa in both tongue front-back position and tongue height significantly more than did the older children and adults. The lack of significant effects for the older children and adults indicates that over this 10-month period the children's control of tongue position and height in the schwa had become virtually adult-like. For schwa before [i], all three groups displayed roughly the same amount of gestural overlap in tongue position and tongue height.

We can perhaps gain insight into the differential effects of [ɑ] and [i] on the preceding schwa in the children's data if we consider in more detail the differences between subjects EA and SR, described above. The almost complete harmony between target schwa and its following stressed vowel displayed by subject EA at 22 months before both [i] and [ɑ] demonstrates that she could not segregate schwa from its following vowel in either tongue front-back position or tongue height. As may be judged by comparing the more or less central position of schwa values before [i] in the 22-month-old group data (Figure 5, top) with their harmonized pattern for EA (Figure 6, top), and their [ɑ]-like values for SR (Figure 7, top), EA was alone in this tendency to harmonize schwa with the color of its following vowel. Ten months later she still could not control tongue height before a labial consonant followed by [ɑ], but was well on the way to controlling both tongue front-back position and tongue height in all other contexts.

By contrast, subject SR at 22 months showed no tendency to anticipate either tongue front-back position or tongue height before [i]; instead, she lowered and backed her tongue in target schwa almost as far before [i] as before [ɑ]—in fact, even further if the following closure was labial (see Figure 7, top). The greater lowering and backing of the tongue before [b] than before [d] or [g] (evident in both children and adults, as remarked above) may reflect the lower jaw position at closure for labials than for linguals (cf. Sussman, MacNeilage, & Hanson, 1973), implicating jaw rather than tongue action in the acoustic effect. If this is so, SR's difficulty with schwa at 22 months was perhaps not so much in positioning the tongue to achieve a neutral vowel, as in a tendency to anticipate the jaw lowering of the following stressed vowel, whatever its color. SR's difficulties with schwa would then have arisen from a general tendency to harmonize the jaw height of the two syllables, whereas EA's difficulty, at least with schwa before [i], if not also with schwa before [ɑ], would have arisen from a tendency to harmonize their tongue positions.

In their difficulties with schwa before [i] these two children are unlike the 22-month-olds as a group, each in her different way. But in their difficulties with schwa before [ɑ] they are typical (see Figure 5, top). We may therefore suspect that the older children's difficulty with schwa before [ɑ] also arose, as it did for SR, from a tendency to harmonize jaw height, that is, to anticipate in schwa the jaw lowering of the following stressed vowel. Their ability to block jaw lowering before [i] would then be due to the relatively little jaw movement that stressed [i] entails, as compared with the extensive movement for stressed [ɑ] (cf. Farnetani & Faber, in press). (The effect evidently does not arise from a tendency to anticipate phonetic stress more strongly before [ɑ] than before [i], because the durations of schwa before [i] and [ɑ] are roughly equal—see Table A in the Appendix.) Imprecise control of the jaw, once extensive jaw-lowering has been initiated, may indeed be characteristic of young children's speech. Several authors have reported that children's tongue height for [i] is remarkably accurate, whereas tongue height for [ɑ] and schwa is more variable (Hare, 1983; Otomo & Stoel-Gammon, 1992; Paschall, 1983).

Finally, we may note that subject EA, who alone tended to harmonize schwa with the color of its following vowel, was less phonologically advanced at the start of the study than

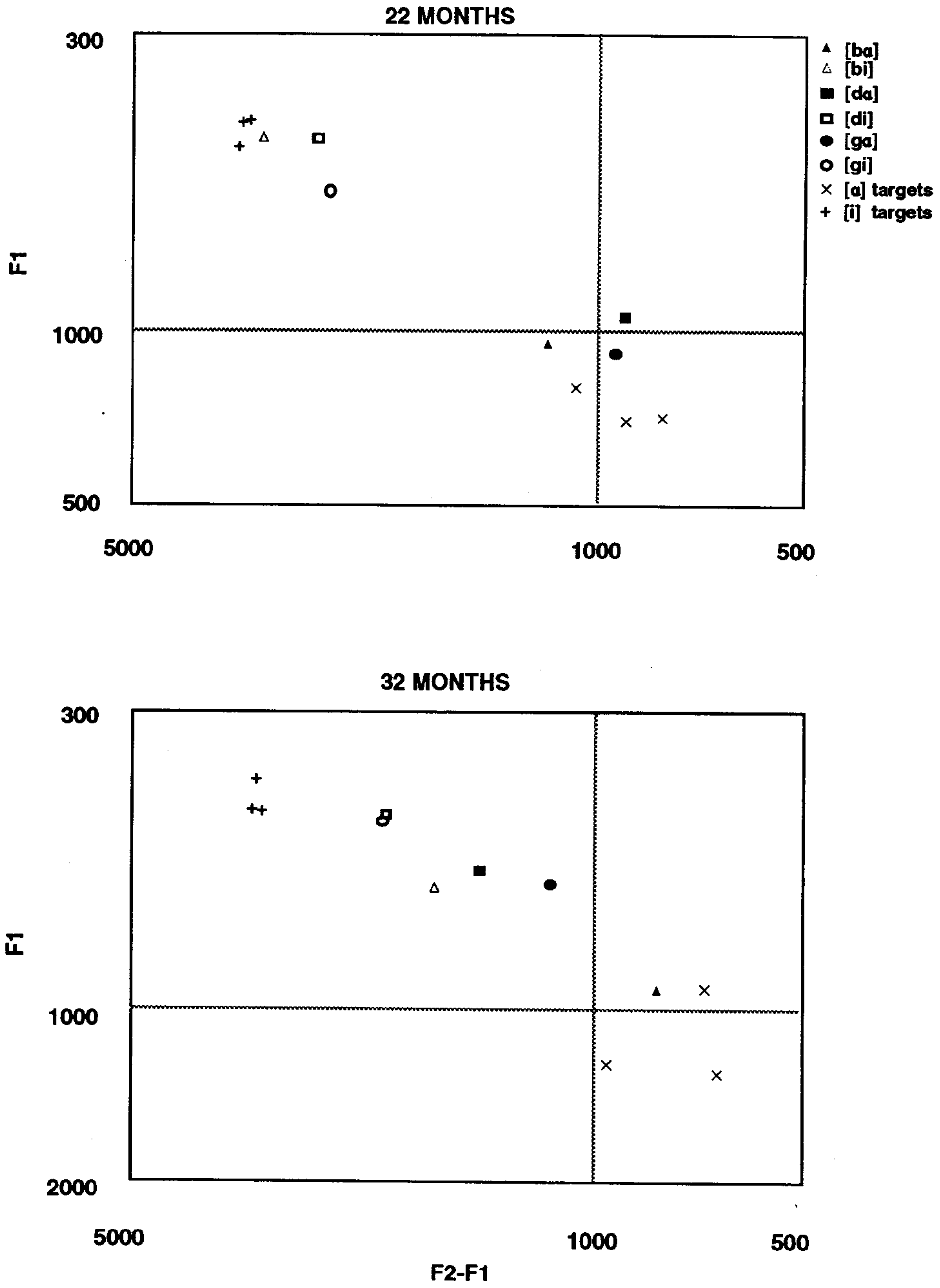

FIGURE 6. Mean F2-F1 plotted against mean F1 for schwa midpoints and stressed vowel midpoints for subject EA at 22 and 32 months of age.

most of the other children, as indicated by MLU and vocabulary estimates, whereas subject SR who displayed no general tendency to harmonize vowel color was the most phonologically advanced. This result is consistent with the hypothesis that less phonologically advanced subjects display greater vowel-to-vowel gestural overlap.

Overlap of Consonant and Vowel Gestures

For normalized estimates of the effect of the stressed vowel gesture on the preceding schwa we had a reference point within the same utterance type, namely, mean formant values at the midpoint of the stressed vowel itself. For normalized estimates of the interaction between vowels and medial consonant gestures, we have no appropriate reference points within an utterance. (As noted above, the extent of formant transitions into or out of a consonant closure, proposed by Kent, 1983, as a measure of consonant-vowel coarticulation, is ambiguous precisely because variations in vowel formant values across subjects cannot be normalized against a reference point within the same utterance.) Accordingly, we had recourse to two across-utterance measures by

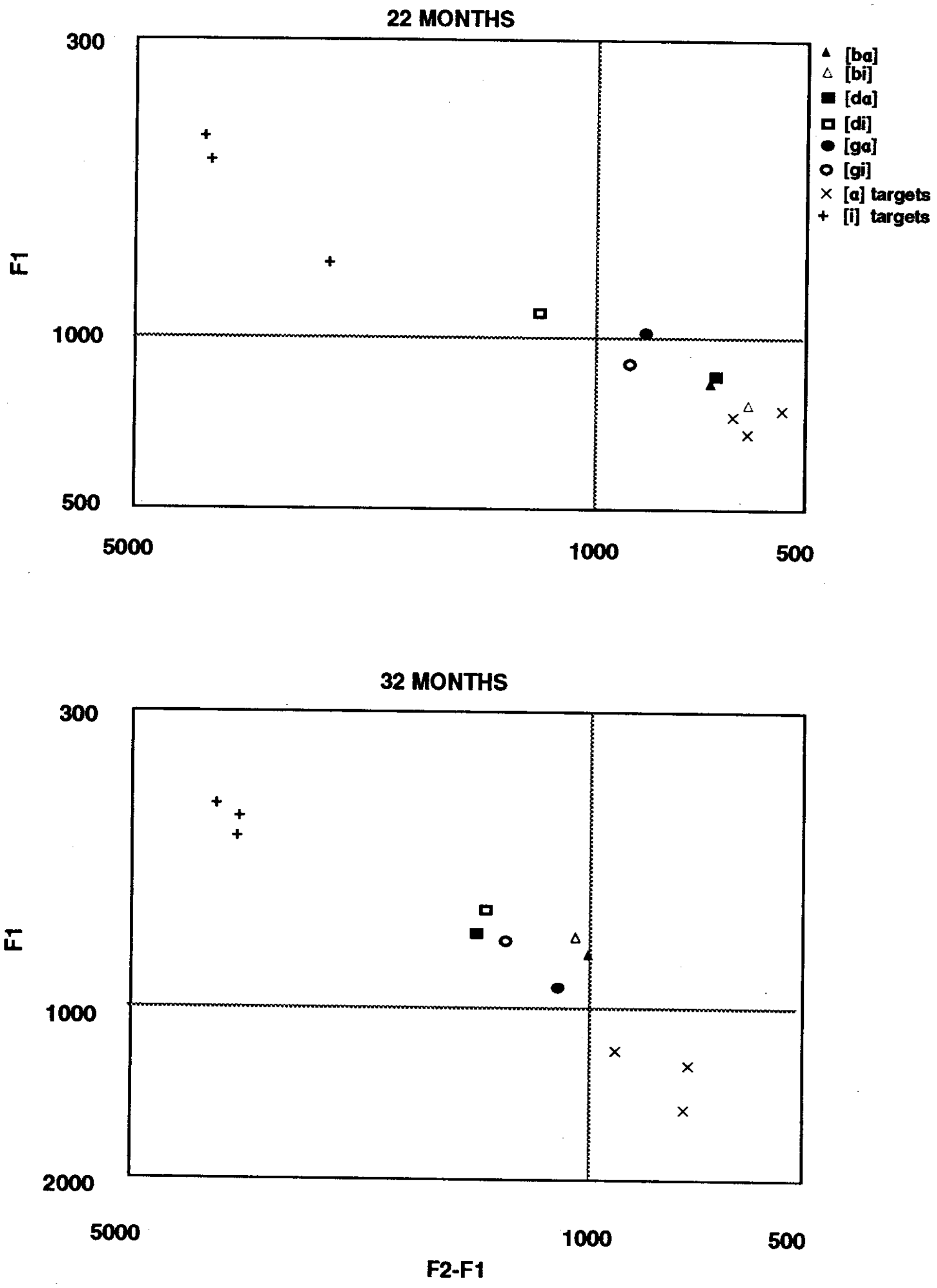

FIGURE 7. Mean F2-F1 plotted against mean F1 for schwa midpoints and stressed vowel midpoints for subject SR at 22 and 32 months of age.

which a change in F2 at a given point in the utterance, as a function of a change in either the medial consonant or the following stressed vowel, served as a normalized index of the influence of the changed gesture on tongue position at that point.

Following Nittrouer et al. (1989), we computed F2 ratios for corresponding points in different utterances. To assess the effect of the medial consonant at schwa midpoint, schwa offset (consonant closure), and stressed vowel onset (consonant release), ratios were formed across consonant contexts with following stressed vowel fixed (bV/dV,bV/gV,dV/gV). (For example, at schwa midpoint for one 32-month-old subject, the mean F2 values for [bi] (1758) and [di] (2300), gave a ratio of .76 and a consonant index of (1-0.76) = .24; for [bɑ] (1701) and [dɑ] (2060) the ratio was 0.83, and the consonant index, (1-0.83) = 0.17. The corresponding group mean indices in Table 5 are 0.27 and 0.18.) The classification of utterances according to stressed vowel was necessary because of the demonstrated effect of the stressed vowel on schwa formant values. To assess the effect of the stressed vowel at consonant closure, consonant release and stressed vowel midpoint, ratios were formed across vowels with

TABLE 5. Mean F2 consonant indices (1-[C_1V/C_2V]) estimating relative F2 shift for three consonant contrasts at schwa midpoint, schwa offset (consonant closure), and stressed-vowel onset (consonant release) before each stressed vowel.

	Age								
	22 months			32 months			Adults		
Consonant ratio	Midpoint	Offset	Onset	Midpoint	Offset	Onset	Midpoint	Offset	Onset
bi/di	−0.18	0.11	0.27	0.27	0.34	0.20	0.15	0.24	0.01
ba/da	−0.05	0.26	0.26	0.18	0.36	0.30	0.17	0.25	0.26
Mean b/d	−0.11	0.19	0.26	0.23	0.35	0.25	0.16	0.24	0.13
bi/gi	−0.13	0.29	0.36	0.19	0.37	0.29	0.15	0.35	0.14
ba/ga	−0.03	0.21	0.20	0.06	0.29	0.33	0.13	0.25	0.26
Mean b/g	−0.08	0.25	0.28	0.13	0.33	0.31	0.14	0.30	0.20
di/gi	0	0.08	0.12	0.03	0.01	0.12	−0.01	0.09	0.13
da/ga	0.04	0.06	−0.10	−0.15	−0.12	−0.10	−0.06	0.01	0
Mean d/g	0.02	0.07	0.01	−0.06	−0.06	0.01	−0.03	0.05	0.07

consonant fixed (Ca/Ci). If there were no effects of varied context on such ratios (indicating complete absence of gestural overlap), their values would be equal to 1. To bring them into conformity with the within-utterance measures described above (and so make for easier reading), indices of gestural overlap were formed by subtracting each ratio from 1; complete gestural overlap would then give an index of 1, complete lack of overlap an index of 0 (cf. Turnbaugh et al., 1985).

The effect of consonant on vowel gestures. Table 5 lists the consonant indices by age, measurement point, and vowel. We note first that the d/g indices are uniformly low, oscillating around zero for all groups at all measurement points. Evidently, differences in F2 alone do not suffice to make this lingual contrast; in fact, the importance of F3 in distinguishing between alveolar and velar stops is well known. Accordingly, we confine our analysis to the labial-lingual contrasts (b/d,b/g).

The expected effect of a labial relative to a lingual constriction is to lower F2, giving rise to a positive index between 0 and 1. At consonant closure and release all indices are indeed positive for all groups and for both vowels; with the exception of the low index (.01) for bi/di at stressed vowel onset in the adults, all indices at these points are significantly different from zero by standard *t*-tests, indicating a substantial effect of the consonant gestures at all ages. At schwa midpoint, by contrast, the indices are positive and significant only for the 32-month-olds and adults; for the 22-month-olds at this point indices are negative (significantly so before [i]).

Table 6 summarizes the significant results of each age-pair analysis of variance (Consonant Ratio × Vowel × Age) on the labial-lingual indices at the three measurement points. There are no systematic main effects of consonant ratio or vowel, although there are several significant interactions (consonant-by-vowel, consonant-by-age, vowel-by-age). None of the interactions lends itself to ready interpretation,

TABLE 6. Summary of significant effects in analyses of variance for consonant indices at schwa midpoint, schwa offset, and stressed-vowel onset.

Measurement point	Independent variable	Degrees of freedom	F	*p*
22-month-olds and adults				
Schwa midpoint	Age	1,5	24.42	.0043
Schwa offset	Consonant × Vowel	1,5	6.95	.0462
Stressed-vowel onset	Age	1,5	13.65	.0141
	Consonant × Vowel	1,5	35.10	.0020
	Vowel × Age	1,5	82.10	.0003
32-month-olds and adults				
Schwa midpoint	Consonant × Vowel	1,5	38.69	.0016
Schwa offset	Consonant × Vowel	1,5	15.10	.0116
	Consonant × Age	1,5	7.32	.0425
Stressed-vowel onset	Consonant × Vowel	1,5	28.09	.0032
	Vowel × Age	1,5	8.25	.0349
22- and 32-month-olds				
Schwa midpoint	Age	1,10	18.49	.0016
Schwa offset	Age	1,10	4.77	.0538
	Consonant × Vowel	1,10	6.41	.0298
Stressed-vowel onset	Consonant × Vowel	1,10	12.77	.0051

TABLE 7. Mean F2 vowel indices (1-[Cɑ/Ci]) estimating F2 shift due to the vowel contrast at schwa offset, stressed vowel onset, and stressed vowel midpoint, in three consonant contexts.

Age	Schwa offset			Stressed-vowel onset			Stressed-vowel midpoint		
	bɑ/bi	dɑ/di	gɑ/gi	bɑ/bi	dɑ/di	gɑ/gi	bɑ/bi	dɑ/di	gɑ/gi
22 months	.25	.12	.25	.33	.33	.45	.50	.45	.51
32 months	.11	.09	.20	.37	.29	.41	.50	.46	.49
Adults	.08	.06	.15	.40	.19	.30	.42	.42	.44

because the pattern of interaction tends to vary from one analysis to another (see Table 5). Similarly, the significant effect of age in the analysis at schwa offset of 22- versus 32-month-olds is anomalous, because neither 22- nor 32-month-olds differ from the adults at this point.

In fact, the most striking results are the effects of age at schwa midpoint, where the children's indices at Time 1 are significantly less than those at Time 2 or of the adults. Evidently, consonant closure began relatively earlier in the schwa for the adults and older children than for the 22-month-olds. Yet by the time closure was more-or-less complete (at schwa offset) the difference between the younger children and the adults had disappeared, and at consonant release before [i] it was even reversed (see the Vowel × Age interaction), indicating a stronger effect of the consonant contrast in the children (cf. Figures 2 and 3).

The effect of vowel on consonant gestures. Table 7 lists the vowel indices by age, measurement point, and consonant. Table 8 summarizes the significant results of each age-pair analysis of variance (Vowel Ratio × Consonant × Age) on these indices at schwa offset and stressed-vowel onset; there were no significant effects or interactions at stressed-vowel midpoint.

The expected effect of the low back vowel [ɑ] with respect to the high front vowel [i] is to lower F2, giving rise to a positive index. All indices are indeed positive and, with the exception of those for the adults in the [d] context at schwa offset, significantly different from zero by standard *t*-tests. Notice further that, for the most part and as expected, the indices increase (that is, the vowels are increasingly differentiated) for all groups in all consonant contexts, as we move from schwa offset to stressed vowel midpoint.

Figure 8 displays the pattern of results across ages at schwa offset and stressed-vowel onset. At schwa offset (Figure 8, top) there is a clear tendency for the indices to decrease with age, and the differences between the 22-month-olds and adults are significant (Table 8). All three analyses also yielded a significant effect of consonant. In each age group the indices are lowest for [d], presumably due to the tight constraints exerted by alveolar constrictions on consonant-vowel coarticulation (Recasens, 1991; Stevens, House, & Paul, 1966). For the 22-month-olds, labial and velar indices are equal; for the adults and 32-month-olds velar indices are higher than labials. However, these differences were not reliable enough to induce significant consonant-by-age interactions.

At stressed-vowel onset (Figure 8, bottom), the moment of consonant release into the vowel, the indices are appropriately higher for all groups in all contexts than at the moment of consonant constriction; and indices for lingual consonants again decrease with age, as indicated by a significant effect of age for the 22-month-olds and adults and a marginally significant effect of age for the 32-month-olds and adults. As at schwa offset, all analyses give a significant effect of

TABLE 8. Summary of significant effects in analyses of variance for vowel indices at schwa offset and stressed-vowel onset.

Measurement point	Independent variable	Degrees of freedom	F	*p*
22-month-olds and adults				
Schwa offset	Consonant	2,20	3.33	<.056
	Age	1,10	7.01	<.024
Stressed-vowel onset	Consonant	2,20	9.90	<.001
	Age	1,10	7.42	<.021
	Consonant × Age	2,20	8.76	<.002
32-month-olds and adults				
Schwa offset	Consonant	2,20	6.03	<.009
Stressed-vowel onset	Consonant	2,20	12.53	<.001
	Age (marginal)	1,10	3.33	<.098
	Consonant × Age (marginal)	2,20	3.29	<.058
22- and 32-month-olds				
Schwa offset	No significant effects			
Stressed-vowel onset	Consonant	2,10	6.15	<.02

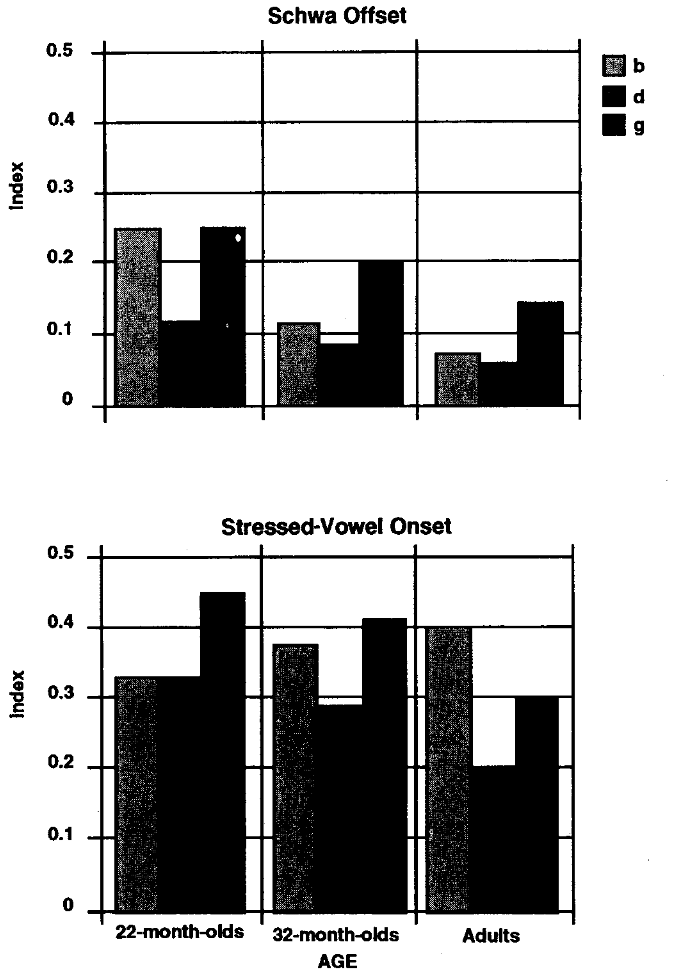

FIGURE 8. Mean vowel indices ([1-Ca/Ci)], estimating relative F2 lowering at schwa offset (top, a) and stressed-vowel onset (bottom, b) for 22- and 32-month-olds and adults.

consonant, with a similar pattern for the linguals ([d] lower than [g]) at all ages. For the labial, by contrast, the pattern reverses: Gestural overlap is least at Time 1, larger at Time 2, and largest for the adults, giving rise to a significant consonant-by-age interaction for the younger children and adults and a marginally significant interaction for the older children and adults. Separate analyses revealed no effects of age for the labials, but significantly greater overlap in the children at Time 1 than in the adults for [d] and [g] [alveolars $F(_{1,10}) = 9.18$, $p < .01$; velars $F(_{1,10}) = 9.41$, $p < .01$], and for [g] to the children at Time 2 [$F(_{1,10}) = 5.72$, $p < .04$]. Comparison of the indices for [b] and [g] by *t*-tests within groups revealed significant differences only for the adults [$t(5) = 2.63$, $p < .05$], indicating greater overlap for labials.

The consonant indices showed that, at the midpoint of the schwa, the children at Time 1, unlike Time 2 and the adults, had not yet begun to move toward closure for the medial consonant. Yet, at the time of consonant closure, the effect of the consonant contrast was not significantly different across ages. This result (paradoxical, if we assume that articulatory movements are slower in younger children) makes sense when we recall that schwa midpoint was (on average) 95 msec before consonant closure in the 22-month-olds, but only 55 msec and 43 msec, respectively, before consonant closure for the 32-month-olds and adults (see Table A in the Appendix). Thus, all three age groups may have begun to close for the consonant roughly the same number of milliseconds before complete closure. It may even be that, in absolute time measured from consonant closure, the children at Time 1 began the movement *before* they did at Time 2. But we do not have the data to test this. All we can conclude from the data we do have is that the absolute extent of gestural overlap in an intersyllabic vowel-stop sequence may be no different in 2-year-old children than in adults. Certainly, we have no evidence for a decline in overlap with age.

Turning to the vowel indices, we recall first that Turnbaugh et al. (1985) found no overall age-related differences in intrasyllabic CV coarticulation for CVC syllables spoken by 3- and 5-year-old children and adults. They suggested that adult-like coarticulation may develop at an earlier age. The results of the present study support this hypothesis for the lingual consonants [d] and [g]; overlap of consonant release with the following vowel gesture decreases from 22-months-olds to 32-months-olds to adults. For the labials, by contrast, there is no significant decrease; on the contrary, there is a nonsignificant trend toward an increase in CV overlap with age, culminating in significantly greater overlap for [b] than for [g] in the adults, a finding in accord with the results of Turnbaugh et al. (1985).

In this difference between lingual and labial consonants, we have another clear counter-example to the general hypothesis that gestural overlap decreases after two years of age. Evidently, an age-related decrease may occur when consonant and vowel gestures engage the same articulatory subsystem (the tongue), but an increase may occur when they engage different subsystems (tongue and lips). The former observation is consistent with the results of another experiment with the same subjects as the present one, in which the adults began the vowel gesture later in the fricative of an alveolar/palatal fricative-vowel syllable than did the children at Time 1 and at Time 2 (Goodell, 1991; Goodell & Studdert-Kennedy, 1991). The same result with fricatives has been reported for 3-year-olds by Nittrouer et al. (1989) and by Siren (1991). This interpretation is also consistent with the finding of Stevens et al. (1966), confirmed by Recasens (1991) electropalatographically, by Turnbaugh et al. (1985) and by the present study acoustically, that consonant-vowel overlap is lowest in a stop-vowel syllable when demands for precision of tongue placement are greatest, namely, in the execution of closure by the tongue-tip at the alveolar ridge.

Discussion

Three questions were posed at the outset: Does gestural coordination in the speech of 2- to 3-year-old children differ from that of adults? How does gestural organization change over a 10-month interval within roughly the third year of life? Do measurements from the acoustic records of young children support the inference from studies of child phonology that children around this age organize their gestures over a wider domain than adults?

The results demonstrate clear differences in speech gestural coordination between 2- and 3-year-old children and adults. They also demonstrate a clear shift in gestural coordination toward that of adult speakers during roughly the third year of life. Generally, we may say that 2- to 3-year-old children do not organize their utterances over a wider domain than adults, but do tend to produce longer utterances with different degrees of overlap between neighboring gestures than adults. Details of the child-adult differences and developmental changes vary from one aspect of an utterance to another, as reviewed below.

Gestural Organization Across Ages

The effect of stressed vowel on preceding schwa. In the vowel-to-vowel comparison, the 22-month-olds displayed stronger effects of the stressed vowel on the preceding schwa than did the 32-month-olds or adults for both tongue front-back position and tongue height when this vowel was low back [ɑ]; for schwa before [i] the pattern of results was the same in all three age groups. There were also no differences between the 32-month-olds and the adults in front-back tongue position or tongue height before either [ɑ] or [i], indicating that older children were executing the schwa in much the same way as the adults. We attributed the differential effects of stressed [ɑ] or [i] on preceding schwa in the younger children to anticipation of the more extensive jaw-lowering characteristic of [ɑ], and to poor control of the jaw once extensive jaw-lowering had been initiated.

At the same time, we found extensive gestural overlap in the schwa before both vowels, [ɑ] and [i], for one of the less phonologically advanced subjects at 22 months, but not at 32 months, suggesting that gestural overlap might be found in [i] tokens for other less phonologically advanced subjects. Certainly, at the onset of speech, young children learning English display a bias toward vowel harmony that is absent from the surrounding language: Kent and Bauer (1985) reported that 44% of vowel pairs in the disyllabic babbling of five 13-month-olds were reduplications. Perhaps development of vowel-to-vowel effects in iambic disyllables proceeds from schwa being assimilated with the stressed vowel (vowel harmony) in younger children to schwa assuming a more central vowel position in older children. Harmony might then break earlier before [i] than before [ɑ] because the former's greater acoustic-articulatory distance from schwa facilitates its perceptual and articulatory segregation.

Yet there are discrepancies with previous studies of vowel-to-vowel overlap in older children: studies of two girls, 4 and 9 years of age, by Repp (1986) and eight 8-year-old children by Flege (in preparation). Repp, analyzing [ə#CV] utterances where V was [i,æ,u], found anticipatory effects of front-back tongue position only for the older child and no effects of tongue height in either child. Flege found that 8-year-olds showed greater anticipation of tongue height in a schwa-stressed vowel context, [əˈhVp], (where V was [i,ɪ,o,u,ɑ]) than did adults. If anticipatory effects for tongue position are found in 22- and 32-month-olds (as reported in the present study), why are such effects absent in a 4-year-old, but present in a 9-year-old (as reported by Repp)? If vowel-to-vowel gestural overlap in tongue height has diminished to adult levels by 32 months of age (as reported in the present study), why is it more salient in 8-year-olds than in adults (as reported by Flege)? Here, utterance type is a likely factor; medial stops probably block gestural overlap between flanking vowels more effectively than medial [h]. Of course, discrepancies may also arise from differences in measurement technique, cross-sectional sampling bias, statistical test power, and so on. Systematic longitudinal studies hold the best promise of resolving these issues.

The effect of medial stop consonant on preceding schwa. Indices of the effects of the medial consonant on preceding schwa at midpoint and offset revealed that the adults and older children had already initiated consonant closure at schwa midpoint, where the younger children had not, but that by schwa offset the age difference had disappeared. Since the duration of the schwa was nearly twice as long in the younger children than in the older children and adults, this result tells us nothing about age differences in the absolute temporal extent of overlap. The uncertainty arises because we made our schwa measurements at the same relative point in each utterance (schwa midpoint) rather than at a fixed point, such as a certain number of milliseconds before consonant closure.

However, since the younger children's utterances were longer than those of their elders, their gestures were probably slower, so that movement toward consonant closure must have begun earlier in the vowel in order for it to be completed at the same time. The observed result is therefore consistent with (although it provides no direct support for) the hypothesis of an earlier absolute onset time of the consonant gesture in the children at Time 1, and perhaps in the children at Time 2, than in the adults. Such a result would also be consistent with the interpretation offered by Nittrouer et al. (1989), as noted above, of the data from Kent (1983).

The effect of stressed vowel on preceding medial consonant. For the lingual consonants at closure and release, the pattern of overlap with the stressed vowel was the same at all ages (greater for [g] than for [d]), but its extent decreased with age. For the labial, by contrast, overlap decreased significantly with age at closure, but tended to increase with age at release. The similar patterns for the lingual consonants reflect the fact that initiation of the vowel gesture is more tightly constrained by alveolar than by velar gestures at every age. The age-related changes, though opposite in their effects on labial and lingual consonants, evidently reflect the same developmental process, namely, a growing capacity to segregate, or differentiate, successive gestures. Adults have learned to take advantage of the independence of tongue and lips to execute a more extensive portion of the vowel gesture while their lips are closed than have the children. By the same token, they have learned to delay the onset of the vowel gesture, when closure is executed by the tongue.

As already noted, several cross-sectional studies of so-called "anticipatory coarticulation" have been carried out on older children and adults (Hodge, 1989; Sereno et al., 1987; Sereno & Lieberman, 1987; Turnbaugh et al., 1985). The last three of these studies found no age differences. Hodge (1989), comparing F2 trajectories at vowel onset in /di/, /dæ/,

/du/, found more coarticulation in 3-year-olds than in older children and adults, a result consistent with our own for children close to 3 years of age. However, the lack of age effects in cross-sectional studies of older children, suggests once again that, if we are to understand the development of gestural organization, we must study children longitudinally over their first 2 to 3 years of life.

The Domain of Gestural Organization

The results of this study do not support the general hypothesis that the temporal domain of gestural organization is wider in 2- to 3-year-olds than in adults. The durations of the children's utterances were certainly greater, and the younger children, particularly, tended to assimilate the duration of the unstressed to the duration of the following stressed syllable. Yet at whatever point in an utterance we found evidence of gestural overlap in the children, we also found corresponding evidence in the adults. Nor do the results support the general hypothesis that the degree of overlap at any given point in an utterance is greater in 2- to 3-year olds than in adults. The extent may be equal (as in the overlap of the stressed vowel [i] with the schwa), greater (as in the overlap of the stressed vowel [ɑ] with the schwa, and of the stressed vowel with lingual stop gestures at consonant closure and release), or less (as in the overlap of the stressed vowel with the labial stop gesture). Whether gestural overlap is greater or less, the differences seem largely to arise from the children's difficulties in timing both the precise duration of a gesture and its onset or offset with respect to other gestures. Learning to talk evidently entails (among other things) learning to differentiate, and to bring under independent control, the several gestures that compose the sequence of syllables in an utterance.

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Appendix

TABLE A. Group mean durations for the whole utterance, for each syllable and for closure in milliseconds, listed by medial consonant and stressed vowel. Proportions of the total duration for syllables and closure are given in parentheses, and standard deviations are given in italics.

	Duration			
	Whole utterance	**Syllable 1**	**Closure**	**Syllable 2**
Children				
22 months				
Consonant				
b	560 *134*	183 (.32) *61*	96 (.18) *46*	280 (.49) *86*
d	631 *114*	195 (.30) *55*	110 (.18) *42*	326 (.52) *95*
g	640 *95*	192 (.30) *50*	140 (.21) *55*	307 (.48) *72*
Stressed vowel				
i	633 *113*	199 (.30) *60*	126 (.20) *54*	310 (.48) *82*
ɑ	587 *120*	181 (.31) *47*	105 (.17) *44*	305 (.51) *89*
Mean	**610**	**190**	**116**	**308**
32 months				
Consonant				
b	522 *87*	125 (.22) *21*	104 (.21) *20*	293 (.56) *79*
d	539 *110*	100 (.19) *23*	104 (.19) *31*	334 (.62) *88*
g	573 *73*	109 (.19) *27*	109 (.20) *23*	359 (.61) *59*
Stressed vowel				
i	554 *103*	119 (.20) *26*	116 (.22) *26*	319 (.57) *90*
ɑ	538 *80*	102 (.19) *23*	96 (.18) *19*	339 (.62) *67*
Mean	**546**	**111**	**106**	**329**
Adults				
Consonant				
b	481 *52*	90 (.19) *14*	81 (.17) *14*	310 (.64) *50*
d	484 *52*	90 (.19) *21*	72 (.15) *14*	321 (.66) *51*
g	481 *53*	89 (.18) *18*	65 (.14) *12*	328 (.68) *51*
Stressed Vowel				
i	484 *53*	94 (.19) *14*	75 (.16) *14*	314 (.65) *54*
ɑ	480 *51*	85 (.17) *20*	70 (.15) *14*	325 (.67) *47*
Mean	**482**	**90**	**73**	**320**

TABLE B. Group mean F2 values at the five measurement points, listed by medial consonant and stressed vowel. Standard deviations are given in parentheses.

	Schwa onset	Schwa midpoint	Schwa offset	Stressed vowel onset	Stressed vowel midpoint
Children					
Mean age: 22 months					
Consonant					
b	2063 (556)	2224 (614)	1997 (582)	2097 (485)	2887 (1036)
d	1761 (230)	2194 (471)	2449 (394)	2944 (747)	3068 (948)
g	1857 (327)	2325 (466)	2500 (629)	3028 (970)	3111 (1145)
Stressed Vowel					
i	2108 (473)	2471 (615)	2611 (584)	3336 (686)	3995 (288)
ɑ	1679 (127)	2023 (225)	2019 (458)	2043 (376)	2043 (235)
Mean age: 32 months					
Consonant					
b	1783 (281)	1875 (252)	1600 (244)	2194 (609)	2897 (1042)
d	2051 (213)	2287 (184)	2490 (285)	2889 (562)	3043 (980)
g	1856 (232)	2180 (371)	2402 (429)	3037 (900)	2971 (1052)
Stressed Vowel					
i	1994 (300)	2277 (332)	2337 (559)	3306 (582)	3930 (236)
ɑ	1799 (179)	1950 (223)	1990 (416)	2107 (392)	2010 (229)
Adults					
Consonant					
b	1438 (165)	1424 (157)	1361 (203)	1767 (484)	1904 (637)
d	1606 (93)	1705 (179)	1805 (117)	1996 (258)	1973 (584)
g	1561 (144)	1658 (240)	1907 (244)	2175 (443)	1991 (593)
Stressed Vowel					
i	1573 (163)	1655 (235)	1783 (318)	2331 (248)	2513 (252)
ɑ	1497 (136)	1536 (208)	1599 (267)	1631 (274)	1399 (203)

TABLE C. Group mean F1 values at five measurement points, listed by medial consonant and stressed vowel. Standard deviations are given in parentheses.

	Schwa onset	Schwa midpoint	Schwa offset	Stressed vowel onset	Stressed vowel midpoint
Children					
Mean age: 22 months					
Consonant					
b	725 (170)	999 (299)	622 (173)	537 (154)	856 (358)
d	755 (147)	970 (208)	584 (137)	612 (133)	832 (401)
g	710 (157)	994 (225)	596 (174)	611 (181)	849 (407)
Stressed Vowel					
i	694 (175)	894 (251)	556 (145)	486 (90)	504 (93)
ɑ	765 (127)	1081 (193)	645 (163)	687 (145)	1187 (195)
Mean age: 32 Months					
Consonant					
b	736 (163)	833 (106)	588 (127)	638 (166)	823 (383)
d	679 (121)	739 (138)	520 (82)	547 (144)	884 (449)
g	711 (124)	760 (173)	509 (128)	605 (260)	841 (429)
Stressed Vowel					
i	673 (138)	726 (154)	493 (118)	450 (78)	457 (70)
ɑ	744 (127)	829 (115)	585 (98)	743 (162)	1241 (123)
Adults					
Consonant					
b	495 (144)	543 (84)	395 (123)	471 (156)	549 (241)
d	454 (117)	510 (83)	330 (90)	370 (93)	545 (252)
g	448 (121)	479 (84)	301 (84)	373 (119)	540 (251)
Stressed Vowel					
i	463 (127)	504 (101)	335 (107)	303 (46)	317 (43)
ɑ	467 (132)	517 (71)	349 (107)	506 (113)	772 (127)