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Patterns of anticipatory coarticulation in adults and typically developing children

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PATTERNS OF ANTICIPATORY COARTICULATION IN ADULTS AND

TYPICALLY DEVELOPING CHILDREN

by

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GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

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This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the thesis of (Kurtt R. Bouchér) in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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ABSTRACT

PATTERNS OF ANTICIPATORY COARTICULATION IN ADULTS AND TYPICALLY DEVELOPING CHILDREN

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Master of Science

Coarticulation is the kinematic and spectral overlap between adjacent sounds during speech production. Coarticulation patterns in typical adults have been well established; however, the manner in which coarticulation is developed in children is still unclear. Research has provided conflicting views, showing that children exhibit more, less, or an equal degree of coarticulation when compared to adult speakers. Considering the divergent findings present in the literature regarding coarticulation in children, the purpose of the present study is to further investigate anticipatory coarticulation in typically developing young children between the ages of three and six years. This study focuses on the acoustic characteristics of an unstressed vowel, the schwa, prior to a series of real words. Results indicate that children exhibit adult-like patterns of coarticulation even at a relatively young age. However, the degree of anticipatory coarticulation is

dependent upon the phonemic context, with greater differences being evident in a fricative context and less when followed by a stop consonant.

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Introduction

The phenomenon of coarticulation in adult speakers has been well documented (Katz, Kripke, & Tallal, 1991; Kent & Read, 2002; Nittrouer, Studdert-Kennedy, & McGowan, 1989; Nittrouer & Whalen, 1989; Repp, 1986; Sereno, Baum, Marean, & Lieberman, 1987; Turnbaugh, Hoffman, & Daniloff, 1985), yet many questions concerning coarticulation in children remain unanswered. Although many studies have examined the patterns and degree of coarticulation in younger speakers, previous findings have not established a consistent developmental view. Several studies report that children exhibit a greater degree of anticipatory coarticulation than adults (Nittrouer, Studdert-Kennedy, & McGowan, 1989; Nittrouer & Whalen, 1989; Repp, 1986), while other studies indicate that children initially have less coarticulation than adult speakers (Hodge, 1989; Sereno & Lieberman, 1987). Research has also indicated that adults and children exhibit approximately the same amount of coarticulation, yet the patterns of coarticulation are much more variable in children (Katz, Kripke, & Tallal, 1991; Sereno, Baum, Marean, & Lieberman, 1987; Turnbaugh, Hoffman, & Daniloff, 1985).

Considering the divergent findings in the literature regarding coarticulation in children, the purpose of the present study is to further investigate anticipatory coarticulation in typically developing children between three and six years of age. This study will focus on the acoustic characteristics of an unstressed vowel, the schwa, prior to a series of linguistic context words.

Review of Literature

A speech sound spoken in isolation can be described and classified by a limited set of distinctive articulatory and acoustic features. However, the speech used in everyday communication is much more complex, in that sounds are not typically produced in isolation, but are sequentially combined with other sound productions to form syllables, words, and phrases. During the production of conversational speech, the acoustic signatures of individual sounds are blended together into a type of acoustic *code* that allows the speaker's message to be transmitted to the listener in a highly efficient manner. Although the muscle movement of the individual articulators is relatively slow, the parallel nature of their movement allows information about successive sounds to be encoded simultaneously in the acoustic signal (Liberman, Mattingly, and Turvey, 1972). Thus, each sound we produce often affects those which both follow and precede it (Mullin, Gerace, Mestre, and Velleman, 2003).

This phenomenon of individual speech sounds intermingling with those adjacent to them is known as *coarticulation* (Kent & Read, 2002) and can be described in terms of the direction in which it occurs. *Forward* or *anticipatory coarticulation* occurs when a sound or phoneme is affected by the production characteristics of a subsequent sound. For example, anticipatory coarticulation is evident when the spectrum of the fricative /ʃ/ as followed by /i/, as in the word *she*, is compared to an /ʃ/ followed by an /u/, as in the word *shoe*. The /ʃ/ in *she* will typically exhibit more high frequency energy than the /ʃ/ found in *shoe*. This is due to a smaller front resonating cavity that is created in the vocal tract by the tongue being anteriorly prepositioned to anticipate the muscle movements required for the production of the following high-front /i/ vowel. Conversely, an /ʃ/ production preceding a back vowel (/u/), which requires a more posterior tongue position, will typically exhibit a lower spectral mean. In both linguistic contexts, *she* and *shoe*, the tongue begins to move to the articulatory placement needed for the following vowel (/i/ or /u/) before the production of the /ʃ/ has been completed. This simultaneous movement of the articulators skews the spectral energy of the /ʃ/ toward a higher or lower frequency range than would be evident in the production of an /ʃ/ in isolation. Although changes in formant frequency patterns are often attributed to differences in tongue placement, it is important to acknowledge that the acoustic characteristics of speech can also be affected by other articulatory factors such as lip rounding and jaw movement.

Perseveratory (or *carryover*) *coarticulation* occurs when a latter sound is modified by the speaker due to the production of an earlier sound. Thus, the articulatory characteristics of one sound are carried over to a subsequent sound (Kent & Read, 2002). For example, a comparison of the /æ/ vowel as contained in the words *map* and *cap* will reveal perseveratory nasalization in /æ/ when it is preceded by a nasal plosive such as /m/. Perseveratory nasalization is not evident, however, in the /æ/ vowel when it is preceded by a voiceless stop, such as /k/. This nasalization is the result of the velopharyngeal port not being completely closed until after the production of the vowel is initiated. Meanwhile, the /æ/ from *cap* will also exhibit a spectrum that has been influenced posteriorly by the initial /k/ sound. Perseveratory coarticulation can in part be explained by the inertia of the articulators in motion (Katz, Kripke, & Tallal, 1991; Sereno, Baum, Marean, & Lieberman, 1987; Turnbaugh, Hoffman, & Daniloff, 1985).

Systematic patterns of coarticulation in adult speech have been extensively documented; however, previous research investigating coarticulation in children has failed to establish a consistent developmental view. Some studies have shown that the speech of young children shows more coarticulation than that of adults (Nittrouer et al., 1989; Nittrouer et al., 1996; Nittrouer & Whalen, 1989), while other studies have found that children exhibit less coarticulation than adults (Hodge, 1989; Repp, 1986; Sereno & Lieberman, 1987). A third set of findings indicates that children and adults demonstrate similar patterns of coarticulation in their speech, but that children's coarticulatory patterns exhibit greater variability than those of adults (Goodell & Studdert-Kennedy, 1993; Katz & Bharadwja, 2001; Katz et al. 1991; Nittrouer, 1993; Sereno et al. 1987; Sharkey & Folkins, 1985; Sussman, Duder, Dalston, & Cacciatore, 1999; Turnbaugh et al., 1985).

A 1989 study by Nittrouer et al. indicated that when producing fricative-vowel syllables, children exhibit a greater degree of coarticulation than adults. The authors of the study measured the anticipatory and perseveratory coarticulation of the vowels /i/ and /u/ across two different fricative contexts (/ʃ/ and /s/). The target segments were embedded in a series of nonsense syllables (e.g., /ʃiʃi/, /sisi/, /ʃuʃu/, and /susu/). In addition to measuring the coarticulation of the two monphthongal vowels, the authors also examined the spectral characteristics of the fricatives to determine the extent in which the production of the fricatives changed as a function of the surrounding vowel context.

Nittrouer et al. (1989) found that the children who participated in the study contrasted phonetic segments less clearly than adults and that the surrounding linguistic context had a greater influence on the children's fricative productions when compared to adult speakers. Nittrouer and Whalen (1989) conducted a follow-up perceptual study based on the findings presented by Nittrouer et al. (1989), which found that the enhanced coarticulatory effects seem to provide additional perceptual information that significantly improves the accurate identification of the syllable.

In a more recent study, Nittrouer et al. (1996) measured the formant frequency patterns, specifically the second formant (F2), of an unstressed schwa prior to a series of fricative-vowel and stop-vowel syllables. These context syllables were created by combining the consonants /s/, /ʃ/, /t/, /k/, /d/, with the three monophthongal corner vowels of /i/, /ɑ/, and /u/. The target contexts were then embedded into the carrier phrase *It's a ____ Bob*. The findings from this study in part replicated the results of Nittrouer et al. (1989) and supported the earlier conclusion that children actively exhibit a greater degree of anticipatory coarticulation than adults. The target schwa was found to be differentially affected by the production of the subsequent consonant and vowel phoneme in all groups of subjects. However, the coarticulation between the schwa and the subsequent phonemes was more pronounced in the children's speech than in the adult subjects. The authors concluded that the age-related differences in anticipatory coarticulation could not be fully explained by morphological differences in vocal tract anatomy.

Not all research supports the finding that children exhibit more coarticulation than adults. Some researchers have found that children may exhibit less coarticulation than adults (Hodge, 1989; Repp, 1986; Sereno & Lieberman, 1987). A study by Repp (1986) investigated the speech production of several speakers at different stages of development. Similar to Nittrouer et al. (1989, 1996), the coarticulation of an unstressed schwa preceding a consonant-vowel context was examined. The target schwa preceded the syllables /si/, /sɑ/, /su/, /ti/, /tɑ/, and /tu/, while embedded in the carrier phrase *I like the* _______. Repp found that a 4-year-old speaker did not display systematic differences in their schwa production across the different linguistic contexts, whereas a 9-year-old and adult speaker did exhibit such differences. However, in light of the small number of participants involved in the study, any conclusions drawn from these results should be interpreted with caution.

Likewise, Sereno and Lieberman (1987) found less evidence of coarticulation in children. Not wanting to rely solely on acoustic data as had previous researchers, the authors conducted a perceptual study in which ten speakers listened to the initial 25 ms of the syllable as spoken by the test subjects. The study included child speakers ranging from 2 to 7 years of age and a comparison group of adults. This study examined the effect of the vocalic context on a preceding /k/ phoneme in the syllables /ki/ and /kɑ/. Results from the perceptual and acoustic data indicated that the adults exhibited consistent patterns of anticipatory lingual coarticulation. For the children however, the results of the perceptual tests demonstrated significantly more inter- and intra-subject variation in coarticulation. The authors suggest that consistent coarticulatory patterns emerge with the acquisition of the fine-tuned speech motor patterns that accompany maturation.

Other studies have demonstrated that children and adults exhibit approximately the same amount of coarticulation (Katz et al. 1991; Sereno et al. 1987; Sharkey & Folkins, 1985; Turnbaugh et al., 1985). The experiment by Katz et al. was designed to test the claim that young children's speech exhibits more reliance on context, and thus exhibits more coarticulation. The researchers studied both lingual and labial anticipatory coarticulation in a group of 3-, 5-, and 8-year-olds and adults. Results indicated that for an /s/ followed by a vowel (/sV/), acoustic measures did not differ as a function of age, which contradicted earlier research by Nittrouer et al. (1989).

Katz et al. (1991) found that the magnitude of lingual coarticulation was quite similar for all subjects, both children and adults. This study examined the effect of the vocalic context on a preceding /s/ phoneme in the syllables /si/ and /su/, produced in the carrier phrase *I said* ____. Spectral centroid and peak values were extracted from the target fricative segments. The researchers found no evidence that suggested a greater degree of coarticulation in 3-year-old speakers as compared to older speakers, and in fact, acoustic and video data supported the notion that 3-year-old children coarticulate speech sounds in a manner that is very similar to older children and adults. Overall, the results of Katz et al.'s study suggested that while children show a greater degree of variation in their coarticulation, they do not produce a greater or lesser degree of intrasyllabic coarticulation than adults. This conclusion is further supported by the findings of several other researchers (e.g. Sereno et al., 1987; Sharkey & Folkins, 1985; Turnbaugh et al., 1985).

The majority of research in the field of children's coarticulation has commonly involved children 3 years of age or older. However, Goodell and Studdert-Kennedy (1993) designed a study that examined the speech behavior of children as young as 20 months of age. This study also differed from other studies in that it was a longitudinal examination of the maturation of speech production of the child participants across a 10-month time period. The participants of the study were all in the early stages of speech development, ranging in age from 22 to 37 months. The study examined coarticulation of an unstressed schwa in a variety of consonant and vowel contexts. Specifically, the authors investigated the first and second formant frequency patterns of the schwa when embedded in the following nonsense syllables: /bə'bɑ/, /bə'bi/, /bə'dɑ/, /bə'di/, /bə'gɑ/, and /bə'gi/.

The researchers found clear differences in duration and coordination of gestures between adults and these relatively young children, as well as a clear shift toward adult-like patterns at about age 3 years. In addition, Goodell and Studdert-Kennedy found that details regarding child-adult differences and developmental changes vary from one aspect of an utterance to another, indicating that intra-subject variation in children may account for much of the discrepancy among previous researchers' findings.

Sussman et al. (1999) also conducted a longitudinal study of a child speaker, in this case from age 7 months to age 40 months. This study was meant to investigate the earliest developments of coarticulation from babbling through the acquisition of early words, and eventually into segments of running speech. As elicitation of target syllables would prove difficult in infants, the authors extracted (from running speech samples) utterances containing /bV/, /dV/, and /gV/ syllable combinations. The researchers found that for labial sounds in a consonant-vowel context, the participant exhibited a steady increase in coarticulation with chronological maturation. The authors concluded that the child's speech had adult-like patterns of coarticulation by approximately 10 months of age. Results of the study indicate that children develop adult-like patterns of coarticulation for alveolar stops in the prelinguistic babbling stage (7 months of age) and for velar stops by the end of the first year.

Studies have also found that coarticulation in children varies according to consonant type. Due to the relationship between articulatory gestures and the acoustic signal, Katz and Bharadwaj (2001) state that there are many problems associated with measuring articulatory movement patterns using solely acoustic data. Thus, the researchers chose to examine coarticulatory patterns in kinematic and perceptual terms, comparing productions of /sV/ and /ʃV/ in children 4 to 7 years of age. Both kinematic and (preliminary) perceptual data revealed more lingual coarticulation in children for /sV/ than for /ʃV/.

Nittrouer (1993) found that children's tongue gestures are constrained by phonetic context more than those of adults until at least 7 years of age. Similar to the methodology employed by Nittrouer et al. (1996), this study also examined coarticulation by looking at the acoustic characteristics of an unstressed schwa when followed by different consonant-vowel syllables, created by combining the consonants /s/, /ʃ/, /t/, /k/, and /d/ with the vowels /i/, /ɑ/, and /u/. According to the author, the children participating in the study were able to acquire adult-like patterns of jaw movements sooner than they did for tongue movements. In addition, although the children produced gestures similar in shape to those of the adults, many of these speech movements were produced more slowly and with greater temporal variability. In light of these results, the author also concluded that the contradictions in various research findings might arise from differences in test tokens and methods of analysis.

Considering the divergent findings presented in the literature mentioned above, the purpose of the present study is to further investigate anticipatory coarticulation in young children. Speech data collected from a previous study addressing the obstruent productions of typically developing children and adults (Nissen, 2003) will be reanalyzed to investigate age-related differences in anticipatory coarticulation. Specifically, this study will utilize formant frequency measures to address the following three research questions: First, is the articulation of an unstressed and centralized vowel (/ə/) significantly affected by the articulation (place) of the initial obstruent and following vowel located in a subsequent syllable? Second, have the younger speakers in this study acquired patterns of lingual coarticulation similar to the adult speakers? Third, does the degree of anticipatory lingual coarticulation differ significantly as a function of speaker age?

Methods

Participants

Speech recordings were elicited from three groups of children between the ages of 3;0 (years; months) and 5;11 ($N = 42$) and one comparison group of adults ($N = 14$). Speakers in the 3-year-old group were between 3;0 and 3;11 years of age; the 4-year-old group ranged between 4;0 and 4;11 years of age; and the 5-year-old group included children between 5;0 and 5;11 years of age. The adult speakers within the comparison group were between 18 and 40 years of age. Each group was composed of an equal number of male and female subjects. Subjects were recruited from university and community preschool programs, local churches, community activity groups, and an already established database of former research subjects. Adult subjects were paid for their participation in the study, as were the parents or legal guardians of the child participants.

All child and adult subjects were native speakers of Standard American English. Parental report indicated that no children participating in the study had a diagnosed history of speech, language, or hearing problems. Participants reporting previous episodes of otitis media participated in the study on condition that the otitis media was not currently occurring or chronic in nature. Prior to participation all subjects were required to pass a hearing screening with pure tone air conduction thresholds of 25 dB HL for the frequencies 0.5, 1.0, 2.0, 4.0, and 6.0 kHz in a quiet-room environment. An oral/motor screening was administered to the participants to ensure normal craniofacial structure and musculature. In addition, at the time of their participation in the study all subjects were required to have visible front incisors.

All child speakers were required to pass a phonological screening prior to testing. Screenings were performed using the Goldman-Fristoe Test of Articulation (GFTA) (Goldman & Fristoe, 1986). This screening was conducted to determine if each child exhibited age-appropriate phonological development. Since many of the targeted phonemes are typically acquired between the ages of 3 and 6 years, no subject was excluded from the study based solely on the acquisition or quality of any particular phoneme, but only on the basis of a general standard of age-appropriate phonological development. Thus, the GFTA was used as a screening tool and not for the purpose of a full phonological evaluation. If a subject failed any of these screening protocols, the speaker's legal guardian was notified and given the appropriate referrals regarding follow-up evaluation.

Stimuli

Five voiceless obstruents (/t, k, θ, s, ʃ/) and three monophthongal vowels (/i, ɑ, u/) were combined to form 15 context words. Specifically, the corpus of context words included the following: *teapot, Thomas, toothbrush, key, car, cougar, thief, thought, Thoot, seal, sock, soup, sheep, shark,* and *shoe*. Considering that Standard American English has no words that begin with the consonant /θ/ followed by an /u/ vowel, participants were instructed to produce the proper name *Thoot* in reference to a fictional character. Speakers were familiarized with all tokens prior to recording. Moreover, each phrase was screened post-recording to ensure that the article *a* in the carrier phrase was produced as an identifiable schwa. The target vowel, the schwa, and the 15 different context words were produced while embedded in the carrier phrase, *this is a* ____. Each stimulus phrase was repeated three times; thus, the entire corpus of elicited productions yielded a total of 45 tokens per subject.

Procedures

Recording. Speech samples were recorded directly to a computer in a quiet room. Specifically, a high-quality Shure SM10A-CN low impedance dynamic microphone and a Samson Mixpad-4 preamplifier were used to facilitate the recording of subject productions. The microphone was placed approximately 4 cm from the speaker's lips during recording. Three tokens of each stimulus item were elicited using a computer program written in the Matlab programming language. The speech tokens were sampled at a rate of 44.1 kHz with a quantization of 16-bits by a Sound-blaster compatible sound card and subsequently saved directly to an internal computer disk. Following the recording of each stimulus token, a graphic presentation of the token was viewed to identify inappropriate recording levels (peak-clipping) or an insufficient recording window. If any of these conditions occurred, the token was re-recorded.

The productions in the stimulus set were elicited through picture identification. Full-screen-size pictures representing the target words were presented on a 15-inch computer screen, positioned approximately 2 feet from each subject. All pictures used in the study were age-appropriate for preschool children. If a subject incorrectly identified a picture as a different lexical item during the recording session, a prompt was given and that particular item was re-recorded.

Acoustic analysis. Reanalysis of the data was approved by the Brigham Young University Institutional Review Board for Human Subjects Research (protocol E06-014) on October 27, 2006. Frequency tracks for the first and second formants of the target vowel segments (/ə/) were extracted using Praat acoustic analysis software, version 4.02 (Boersma & Weenink, 2004). Specifically, a linear predictive coding (LPC) based tracking algorithm was used to determine formant calculations for the vocalic segments of interest at 5 ms intervals by means of the Burg method (Kay, 1988; Marple, 1987) with 11 coefficients. The LPC analysis employed a 25 ms Hamming window with 50% overlap and 98% pre-emphasis. Each token was checked to ensure that surrounding speech sounds were not audible in the analyzed segment. In addition, these automatically tracked formants were visually inspected for accuracy, and where necessary, hand-corrected or deleted prior to any statistical analysis.

Using values from the extracted formant tracks, average first formant (F1) and second formant (F2) frequencies were calculated at eight different equidistant measurement points throughout each vowel's overall duration (point 1 = t1, point 8 = t8, etc.). Thus, t1 resulted in an average of the formant values in the initial 12.5% of the vowel's duration. For the target segment, mid-point values for F1 and F2 were determined by averaging t3 through t6 (middle 50%).

Formant values from the middle 50% of each schwa production were then transformed to a perceptually normalized scale, specifically, the equivalent rectangular bandwidth (ERB) scale (Glasberg & Moore, 1990; Moore, 1997). The ERB auditory scale is a psychophysical metric, which employs a *notched-noise* method rather than traditional masking procedures to measure the auditory filter bandwidth of the human auditory system. The ERB metric is somewhat similar to the previously developed Bark scale (Zwicker, 1975; Zwicker & Terhardt, 1980), except that for lower frequencies (below 1500 Hz), the slope of the ERB function decreases with decreasing center-frequency, while the Bark scale remains nearly linear.

Vowel duration measures were automatically computed to the nearest millisecond (ms) based on the initial and ending time points of the extracted formant tracks mentioned above.

Data analysis. Prior to statistical analysis, all data were collapsed across repetitions of a given stimulus item. Repeated measures analyses of variance (ANOVA) were used to determine significant acoustic variation in the schwa productions as a function of the obstruent context, vowel context, and age group. Results of significant *F*-tests included a measure of effect size, in particular partial eta squared or η^2 (the value of η^2 can range from 0.0 to 1.0, and can be considered a measure of the proportion of variance explained by a dependent variable when controlling for other factors). Greenhouse-Geisser adjustments were utilized to adjust *F*-tests with regard to degrees of freedom when significant deviations from sphericity were found. Furthermore, pairwise comparisons for significant within-subject factors were conducted using General Linear Model repeated-measures contrasts, with comparison significance being determined by the appropriate *F*-tests (see SPSS, 1997). Significant between-subject post-hoc results were determined by *t*-tests. Multiple comparisons were accounted for by a Bonferroni adjustment.

Results

Patterns of Coarticulation

Stop-vowel context. Results from the ANOVA indicated a significant difference in F2 patterns as a function of stop context, $F(1, 52) = 63.89$, $p < .001$, $\eta^2 = .55$. This main effect of stop context was due to an increase in F2 values of the neutral schwa when followed by an alveolar stop /t/ (21.08 ERB) as compared with the velar stop /k/ context (20.42 ERB).

A main effect of vowel context was also found to be significant for both F1, $F(2, 104) = 10.39$, $p < .001$, $\eta^2 = .17$, and for F2 measures, $F(2, 104) = 26.55$, $p < .001$, $\eta^2 = .34$. Pairwise tests indicated significant differences ($p = .002$) in formant values between each of the three vowel contexts. F1 ERB values of the neutral schwa were highest when followed by an /i/ context (14.42), second highest in the /ɑ/ context (14.21), and lowest in the /u/ context (14.01). F2 ERB values of the neutral schwa followed a slightly different pattern, with /i/ being the highest (21.03), followed by /u/ (20.77), and /ɑ/ (20.44), respectively. There was also a significant stop by vowel interaction effect for F2, $F(2, 104) = 8.80$, $p < .001$, $\eta^2 = .15$. The difference in the schwa's F2 values for the /t/ and /k/ contexts increased in the context of a more posterior vowel, as is demonstrated in Figure 1.

As expected, there was a significant main effect of age for F1 ERB, $F(3, 52) = 11.16$, $p < .001$, $\eta^2 = .39$, and F2 ERB measures, $F(3, 52) = 19.47$, $p < .001$, $\eta^2 = .53$. Post-hoc analysis found that the F1 ERB values for the adult speakers differed from those of the 3-, 4-, and 5-year-old speakers ($p < .002$). Significant differences for F2 ERB values were also found between the adult speakers and each group of child speakers

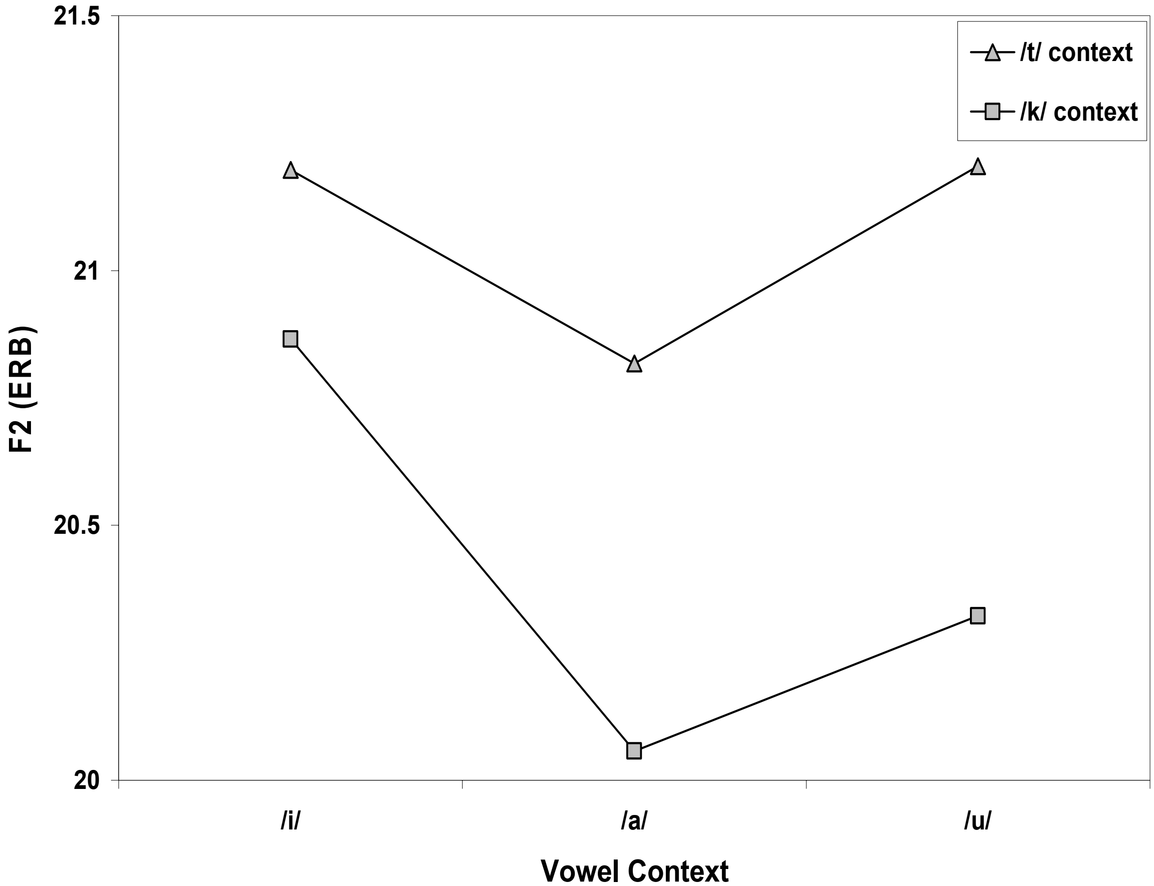

Figure 1. F2 values (in ERB) for /ə/ in stop-vowel contexts.

($p < .001$). However, there were no significant differences between the child groups for F1 or F2 measures.

The F1 and F2 values across stop context are shown in Figures 2 and 3, with the F1 and F2 values for vowel context being shown in Figures 4 and 5, respectively. Results from the ANOVA showed no age interaction effects, indicating similar patterns of coarticulation across the different speaker groups for the production of the target schwa when followed by a real word with an initial stop-vowel sound sequence. See Table 1 for F1 and F2 schwa values in the stop-vowel context.

Fricative-vowel context. Results from the ANOVA indicated a significant difference in F1, $F(2, 104) = 14.69$, $p < .001$, $\eta^2 = .22$, and F2 measures, $F(2, 104) = 7.55$, $p = .003$, $\eta^2 = .13$, as a function of fricative context. For F1, pairwise comparisons indicated significant differences ($p < .001$) only between the /s/ and /ʃ/ contexts (14.34 for /θ/, 14.12 for /s/, and 14.51 for /ʃ/). For F2 measures, significant differences ($p = .009$) were found between the /θ/ and /ʃ/ contexts (20.91 for / θ/, 20.77 for /s/, and 20.60 for /ʃ/).

In addition, a significant effect of vowel context, $F(2, 104) = 40.79$, $p < .001$, $\eta^2 = .44$, indicated that the F2 values for the target schwa were different depending on the articulation of a following vowel. Pairwise comparisons indicated significant differences ($p < .001$) between /i/ and /ɑ/, as well as /ɑ/ and /u/. F2 ERB values of the target schwa were highest in the /i/ context (20.90), followed by the /u/ context (20.86), and lowest for the /ɑ/ context (20.52). No significant fricative-by-vowel interactions were found.

There was also a significant main effect of age for both F1, $F(3, 52) = 14.53$, $p < .001$, $\eta^2 = .46$, and F2, $F(3, 52) = 22.77$, $p < .001$, $\eta^2 = .57$, values of the target schwa. Post-hoc

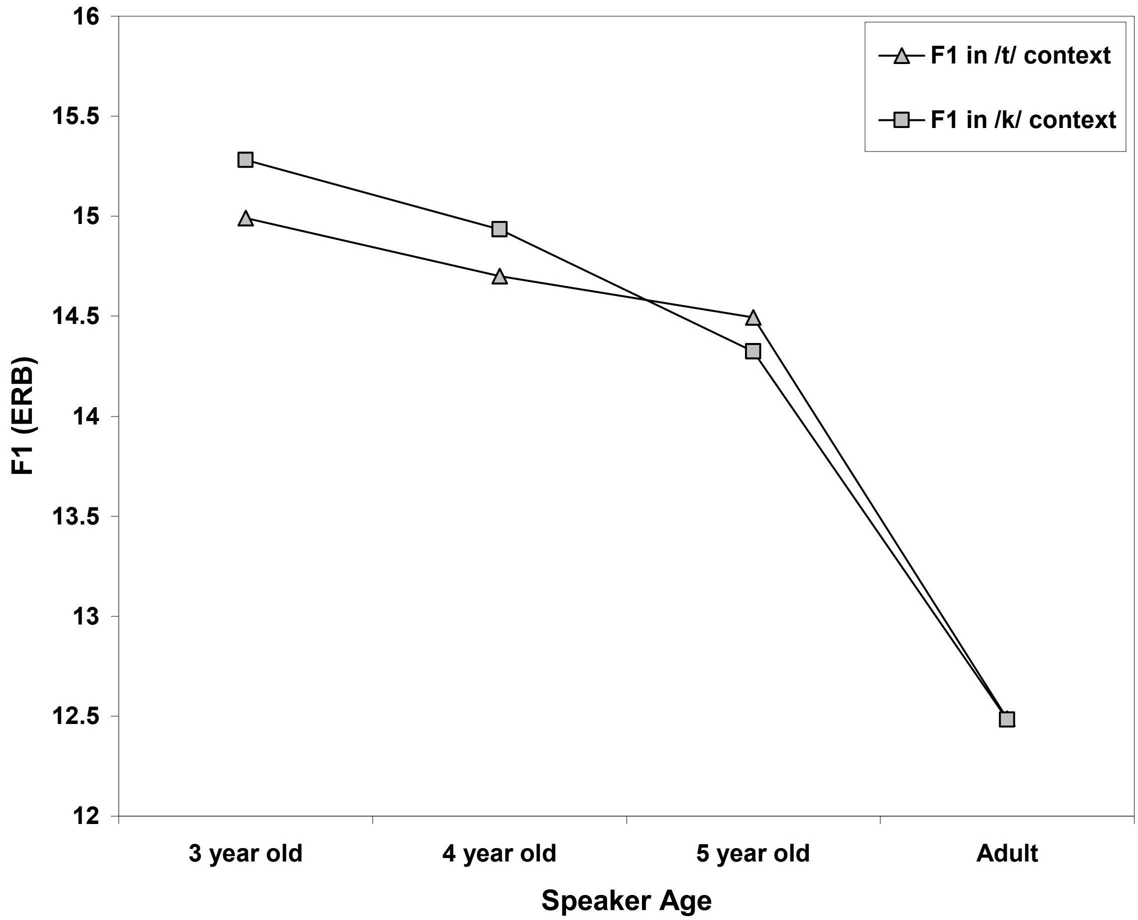

Figure 2. F1 values (in ERB) for /ə/ in stop contexts as a function of speaker age.

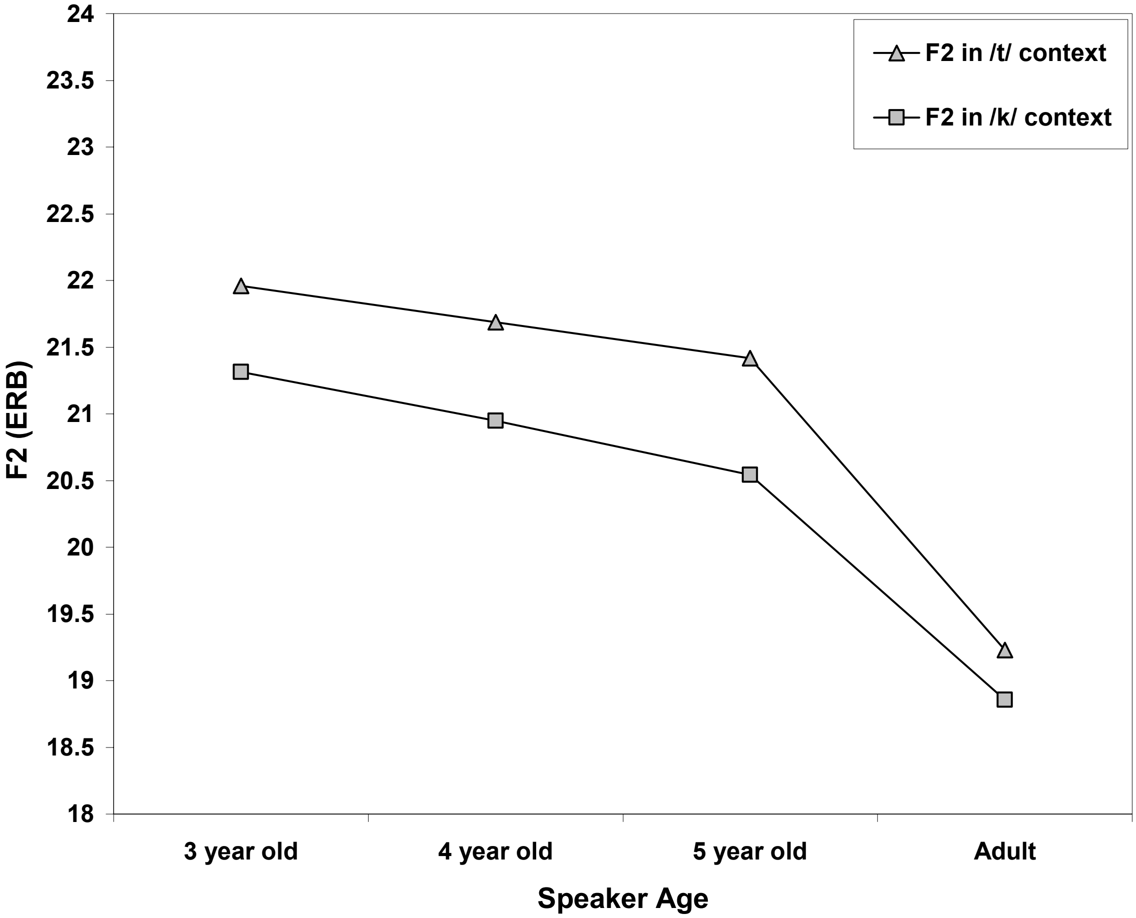

Figure 3. F2 values (in ERB) for /ə/ in stop contexts as a function of speaker age.

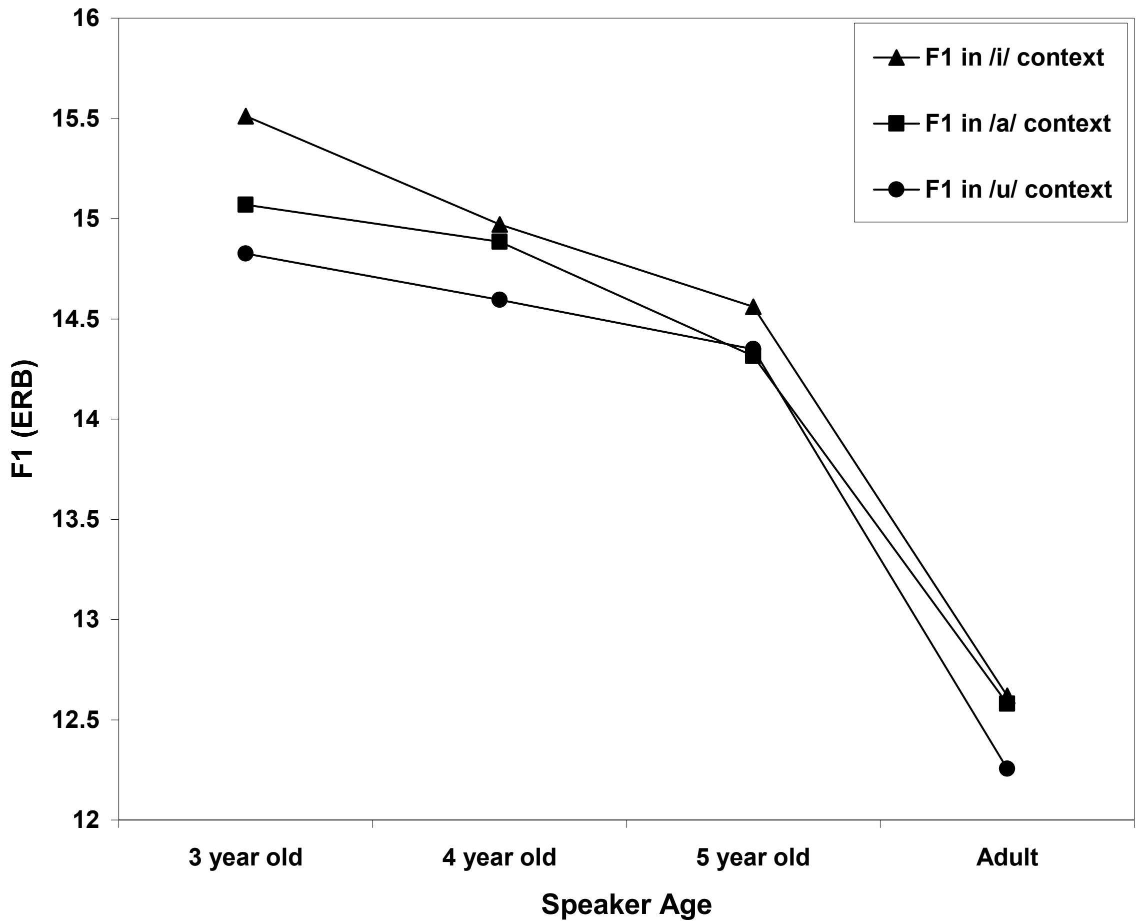

Figure 4. F1 values (in ERB) for /ə/ in stop-vowel contexts as a function of speaker age.

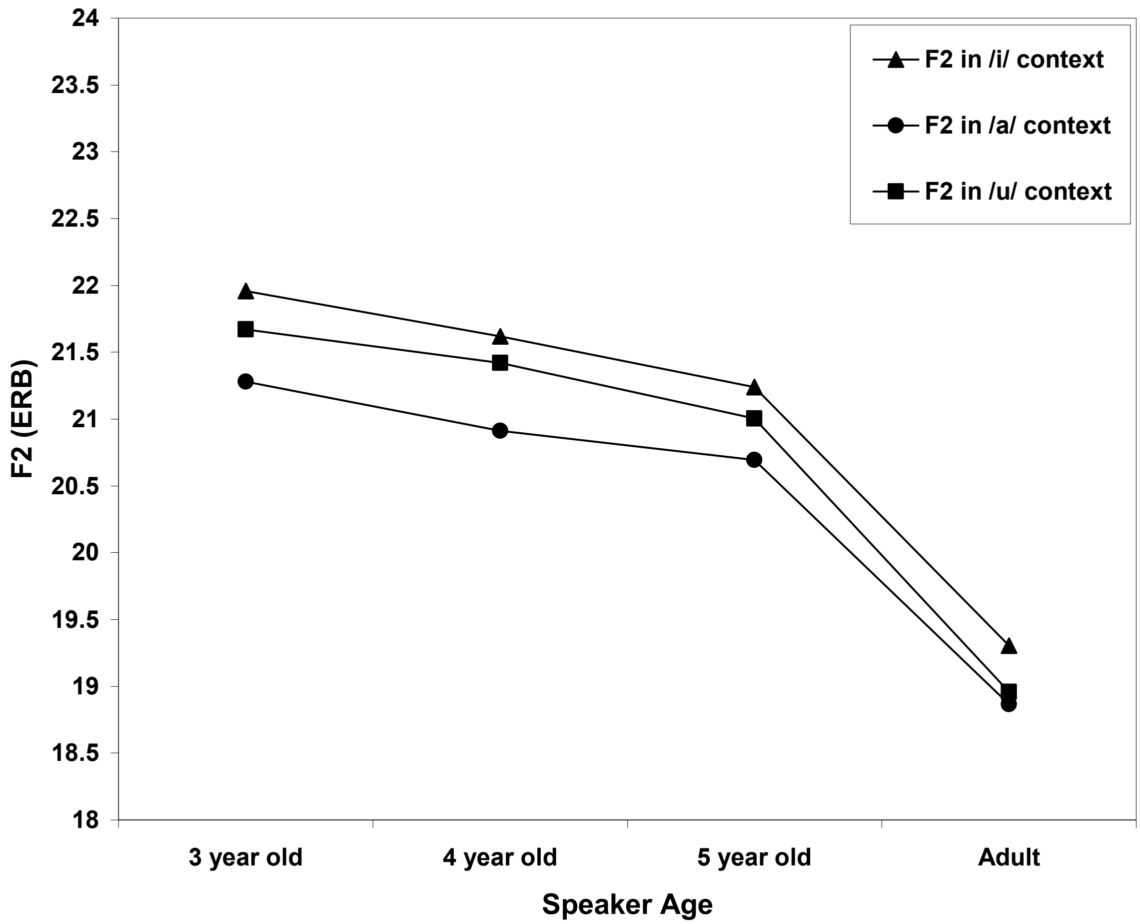

Figure 5. F2 values (in ERB) for /ə/ in stop-vowel contexts as a function of speaker age.

Table 1

Formant Values for /ə/ in the Stop/Vowel Context by Age Group

Schwa context			F1		F2	
Age	Stop	Vowel	F1 linear	F1 ERB	F2 linear	F2 ERB
Adult	/t/	/i/	679.76	12.70	1614.05	19.33
		/ɑ/	659.00	12.53	1562.64	19.06
		/u/	630.81	12.23	1608.69	19.30
	/k/	/i/	662.50	12.54	1603.93	19.28
		/ɑ/	668.82	12.63	1486.61	18.67
		/u/	635.38	12.28	1473.83	18.62
3	/t/	/i/	989.48	15.42	2242.07	22.01
		/ɑ/	914.52	14.83	2139.79	21.64
		/u/	897.52	14.72	2289.91	22.23
	/k/	/i/	1023.50	15.60	2211.91	21.91
		/ɑ/	979.52	15.31	1961.12	20.92
		/u/	933.05	14.93	2004.50	21.11
4	/t/	/i/	914.95	14.87	2194.62	21.87
		/ɑ/	905.48	14.82	2058.05	21.36
		/u/	860.67	14.41	2178.43	21.83
	/k/	/i/	941.00	15.07	2065.27	21.37
		/ɑ/	926.43	14.95	1845.50	20.46
		/u/	904.10	14.78	1986.33	21.01
5	/t/	/i/	866.04	14.45	2122.00	21.58
		/ɑ/	848.41	14.32	2025.43	21.21
		/u/	895.19	14.71	2090.93	21.46
	/k/	/i/	893.02	14.67	1962.48	20.90
		/ɑ/	849.14	14.31	1789.93	20.18
		/u/	818.95	13.99	1880.00	20.55

analysis demonstrated that the F1 ERB values for the adult speakers (12.49) differed ($p < .001$) from those of the 3-, 4-, and 5-year-old speakers (15.34, 14.91, and14.55). Significant differences ($p < .001$) for F2 ERB values were also found between the adult speakers (18.99) and the 3-, 4-, and 5-year-old speakers (21.70, 21.35, and 21.00). However, there were no significant differences between the child groups. The F1 and F2 values across fricative context are shown in Figures 6 and 7, with the F1 and F2 values for vowel context being shown in Figures 8 and 9, respectively. Results from the ANOVA showed no age interaction effects, indicating similar patterns of coarticulation across the different speaker groups for the production of the target schwa when followed by a context word with an initial fricative-vowel sound sequence. See Table 2 for F1 and F2 schwa values in the fricative-vowel context.

Degree of Coarticulation

The degree of coarticulation was measured by calculating the mean absolute differences in formant ERB values for the target schwa across the various linguistic contexts. These data were computed for each speaker prior to statistical analysis. A listing of these values across age groups can be found in Table 3.

Stop-vowel context. A between-subjects ANOVA (age groups) conducted on the mean absolute difference measures revealed a significant main effect of age for F2 values across stop context, $F(3, 52) = 2.80$, $p = .049$. Post-hoc tests revealed that the significant effect of age was primarily due to differences between adult and the 5-year-old speakers ($p = .045$), but no significant differences were found when comparing all other age groups.

The degree of coarticulation across vowel context also varied as a function of speaker age for both F1, $F(3, 52) = 3.58$, $p = .020$, and F2 measures, $F(3, 52) = 5.65$,

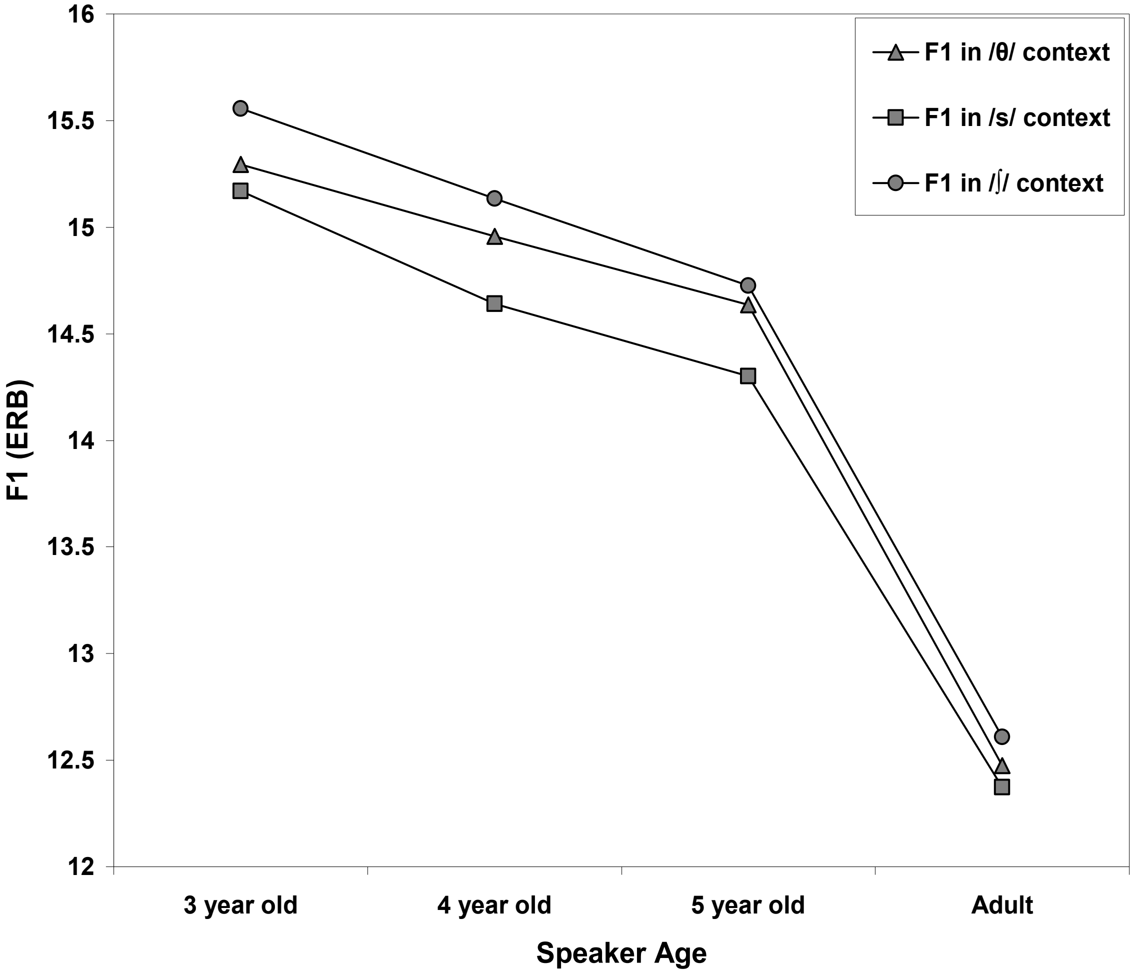

Figure 6. F1 values (in ERB) for /ə/ in fricative contexts as a function of age.

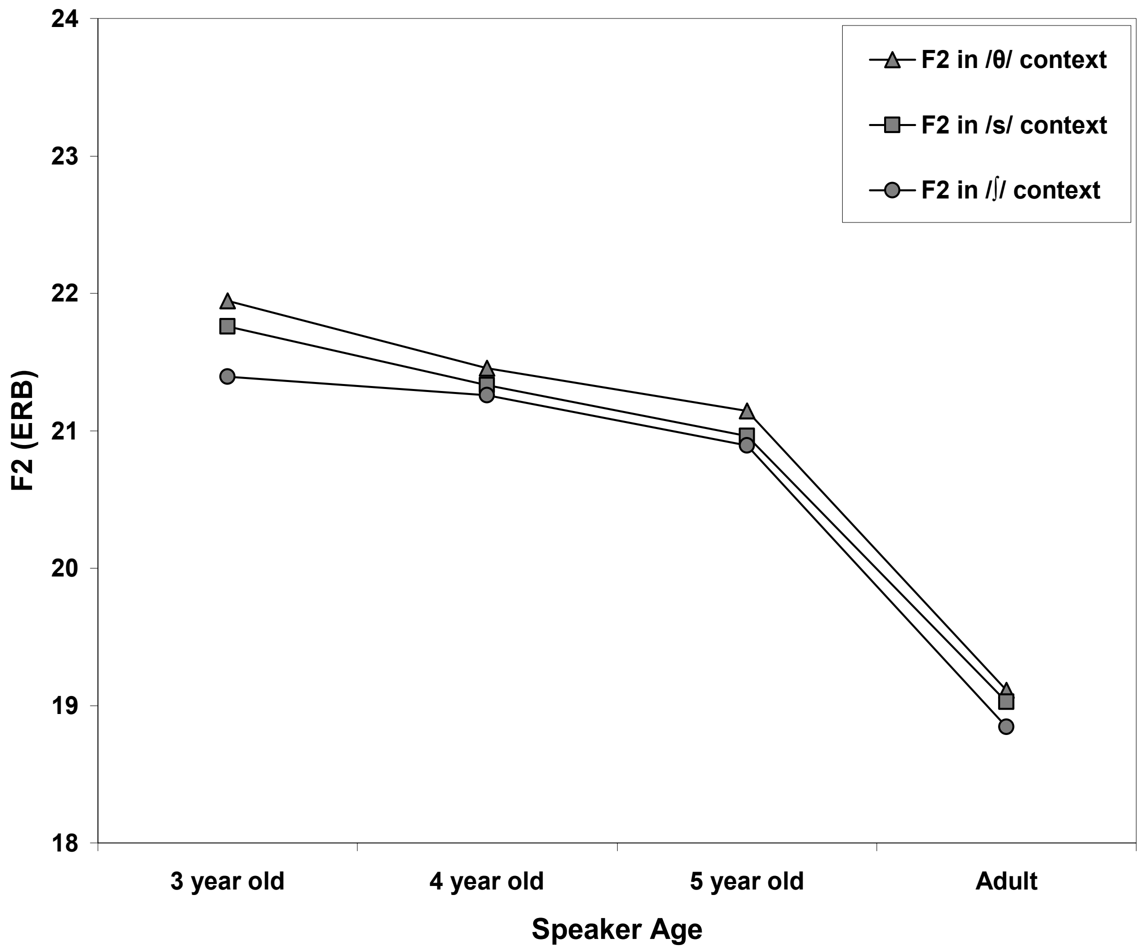

Figure 7. F2 values (in ERB) for /ə/ in fricative contexts as a function of age.

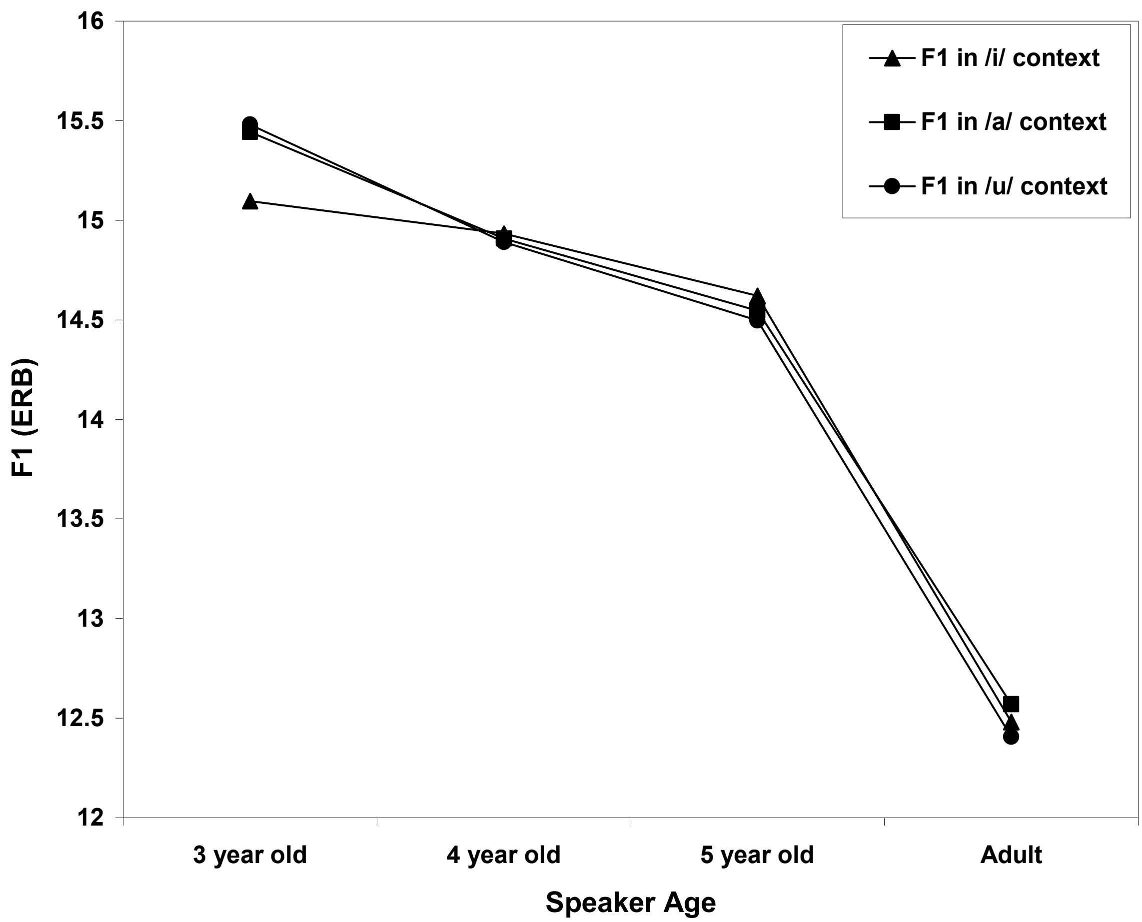

Figure 8. F1 values (in ERB) for /ə/ in fricative-vowel contexts as a function of age.

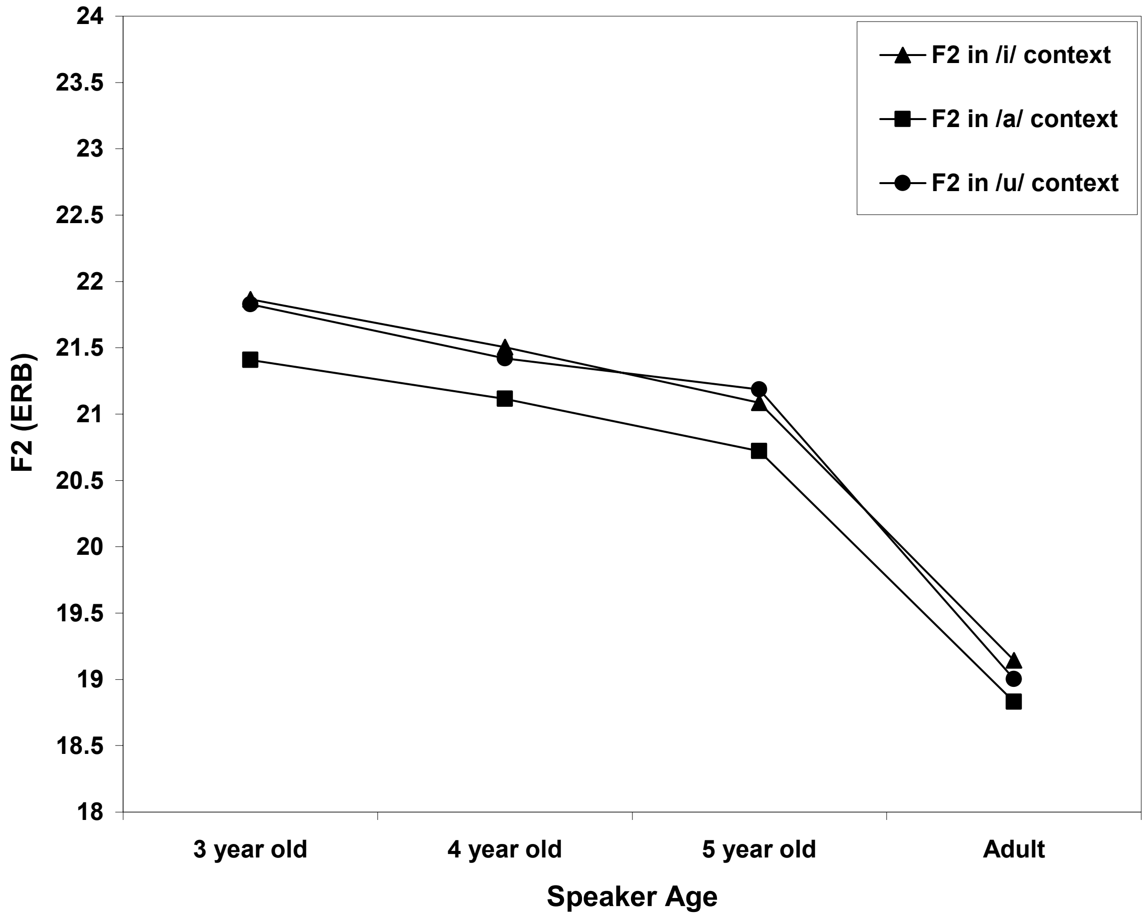

Figure 9. F2 values (in ERB) for /ə/ in fricative-vowel contexts as a function of age.

Table 2

Formant Values for /ə/ in the Fricative/Vowel Context by Age Group

Context			F1		F2	
Age	Fricative	Vowel	F1 linear	F1 ERB	F2 linear	F2 ERB
Adult	/θ/	/i/	648.95	12.43	1595.21	19.24
		/ɑ/	664.76	12.62	1543.45	18.96
		/u/	642.26	12.37	1573.71	19.13
	/s/	/i/	642.86	12.32	1584.55	19.18
		/ɑ/	652.62	12.46	1523.57	18.86
		/u/	641.14	12.34	1557.76	19.04
	/ʃ/	/i/	676.29	12.69	1550.14	19.01
		/ɑ/	669.48	12.63	1489.64	18.68
		/u/	658.14	12.51	1518.83	18.84
3	/θ/	/i/	925.17	14.94	2259.52	22.07
		/ɑ/	979.19	15.39	2161.31	21.73
		/u/	1007.91	15.55	2245.07	22.03
	/s/	/i/	928.05	14.99	2209.55	21.92
		/ɑ/	962.88	15.17	2096.91	21.48
		/u/	978.55	15.35	2196.55	21.88
	/ʃ/	/i/	988.24	15.36	2133.64	21.60
		/ɑ/	1034.71	15.77	1978.41	21.01
		/u/	1010.52	15.54	2117.81	21.57
4	/θ/	/i/	926.31	14.98	2178.57	21.84
		/ɑ/	917.81	14.89	1998.05	21.11
		/u/	927.69	15.00	2070.48	21.42
	/s/	/i/	886.60	14.60	2060.76	21.37
		/ɑ/	878.62	14.59	2007.79	21.17
		/u/	899.50	14.73	2079.86	21.45
	/ʃ/	/i/	960.38	15.22	2049.62	21.31
		/ɑ/	962.64	15.24	1992.88	21.07
		/u/	926.12	14.94	2068.67	21.39
5	/θ/	/i/	906.88	14.82	2037.79	21.27
		/ɑ/	876.21	14.56	1930.57	20.78
		/u/	871.50	14.53	2065.17	21.38
	/s/	/i/	839.45	14.21	1982.95	21.02
		/ɑ/	849.02	14.31	1889.24	20.64
		/u/	859.17	14.38	2032.29	21.22
	/ʃ/	/i/	907.27	14.83	1970.17	20.97
		/ɑ/	902.21	14.77	1918.95	20.75
		/u/	880.05	14.58	1967.98	20.96

Table 3

Absolute Mean Differences for /ə/ as a Function of Linguistic Context and Age Group

	Age Group			
Linguistic Context	3	4	5	Adult
F1 as followed by stop	0.808	0.741	0.669	0.437
F2 as followed by stop	0.955	0.934	1.080	0.624
F1 as followed by stop/vowel	0.993	0.812	0.710	0.499
F2 as followed by stop/vowel	0.648	0.819	0.521	0.348
F1 as followed by fricative	0.871	0.738	0.664	0.407
F2 as followed by fricative	0.777	0.689	0.694	0.370
F1 as followed by fricative/vowel	0.853	0.658	0.624	0.288
F2 as followed by fricative/vowel	0.647	0.613	0.615	0.262

$p = .002$. For F1 mean absolute difference measures, post-hoc tests revealed significant differences ($p = .014$) in the degree of anticipatory coarticulation between the adult and 3-year-old speakers. For F2 mean absolute difference measures, significant differences ($p = .001$) were found between the adult and 4-year-old speakers. The absolute mean formant differences across age group for the stop-vowel context are illustrated in Figure 10.

Fricative-vowel context. A between-subjects ANOVA (age groups) conducted on the mean absolute difference measures also revealed a significant main effect of age for F1 values across fricative context, $F(3, 52) = 6.53$, $p = .001$. Post-hoc tests revealed that significant differences were found between the adult and 3-year-old speakers ($p < .001$), as well as between the adult and 4-year-old speakers ($p = .021$). A significant main effect of age was also found for the F2 measures, $F(3, 52) = 7.19$, $p < .001$. Post-hoc tests demonstrated significant differences between the adult group and each of the children's age groups ($p < .01$).

The degree of coarticulation across vowel context also varied as a function of speaker age for both F1, $F(3, 52) = 15.03$, $p < .001$, and F2 measures, $F(3, 52) = 14.82$, $p < .001$. For the mean absolute difference measures, post-hoc tests revealed significant differences ($p < .002$) in degree of anticipatory coarticulation between the adult speakers and each group of child speakers for both F1 and F2. The absolute mean formant differences across age group for the fricative-vowel context are illustrated in Figure 11.

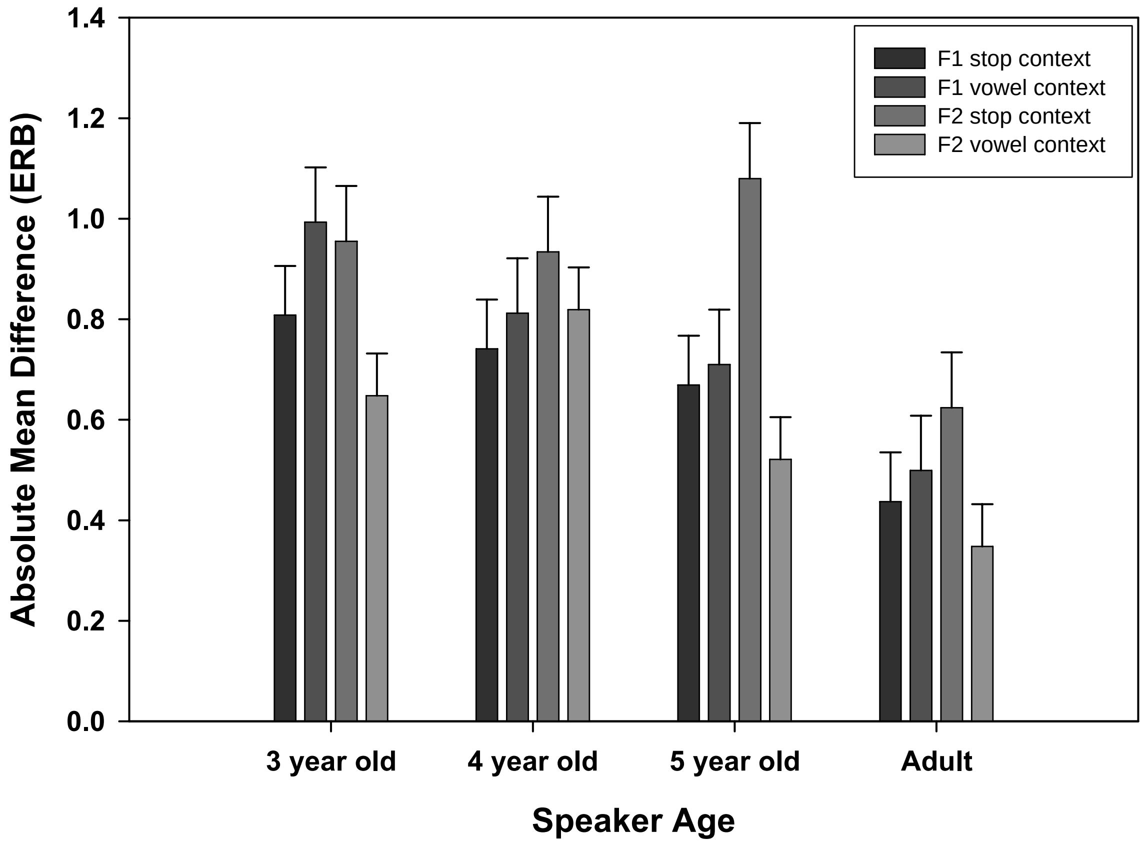

Figure 10. Absolute mean formant differences (in ERB) across age groups in stop and stop-vowel contexts.

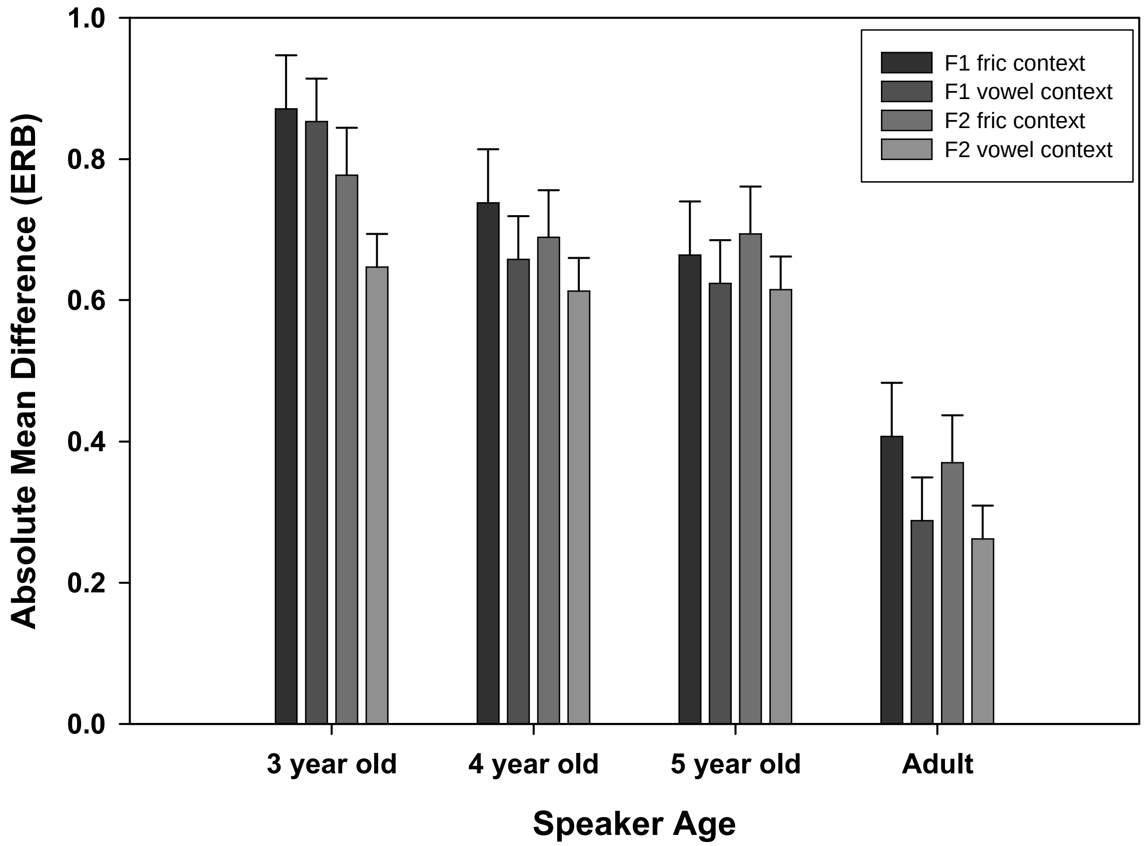

Figure 11. Absolute mean formant differences (in ERB) across age groups in fricative and fricative-vowel contexts.

Discussion

This study was designed to examine anticipatory coarticulation in children and compare their productions to a group of adult speakers. Specifically, this study has addressed three research questions raised at the outset of this investigation. In the following discussion, the summarized results of each experimental question are presented and discussed.

First, for the child and adult speakers, is the articulation of an unstressed and centralized vowel (/ə/) significantly affected by the articulation (place) of the initial obstruent and following vowel located in a subsequent syllable? Results of the ANOVA indicated that the target vowel was differentially affected depending on the articulatory place and manner of the following sound. When followed by a word with an initial stop, the F2 of the schwa changed significantly depending on the location of the stop production. As expected, the F2 values for the schwa were higher in a /t/ context than in a /k/ context. This finding coincides with the more forward position of the tongue during production of the /t/. Anterior tongue position corresponds with a higher F2 in vowels, and this phenomenon occurs in anticipatory coarticulation.

When followed by a word with an initial fricative, both F1 and F2 of the schwa changed as a function of fricative place of articulation. Differences in F1 were only found between the /s/ and /ʃ/ contexts. The F1 values for the schwa were higher in the /ʃ/ context when compared to the /s/ context. No significant differences for F1 were found for the /θ/ context when compared with the /s/ and /ʃ/ contexts. These differences in F1 may be due to variation in tongue placement. However, due to the limitations of this study we cannot rule out the involvement of other articulatory factors, such as jaw movement. The F2 values for the schwa were higher in a /θ/ context than in a /ʃ/ context. Consistent with the higher F2 values found in the more forward-placed stop contexts, the more forward-placed /θ/ also produced a higher F2 value than the posteriorly placed /ʃ/.

The target schwa was also affected by the vowel context of the subsequent syllable. However, the first and second formants for the schwa demonstrated different effects for the vowel contexts when the schwa followed the stops and fricatives: differing vowel contexts following stops altered both the F1 and F2 of the preceding schwa, whereas the differing vowel contexts following fricatives only affected the schwa's F2. Collapsed across stops, F1 values proved highest in the context of /i/, then /ɑ/, and lowest with /u/. This finding is surprising when tongue positioning for each of these vowels is examined. Of the three vowels, /i/ is placed the highest in the mouth, which would generally indicate a lower F1. It is unclear why this particular result was obtained. Collapsed across stop contexts, F2 for the vowel context followed a more predictable pattern. The schwa followed by /i/ demonstrated the highest F2 values, followed by the /u/, and then the /ɑ/. This pattern coincides with the more anterior tongue position of the /i/, with the more posterior tongue position producing lower F2 values. When followed by a fricative-vowel context, the schwa yielded F2 patterns similar to the stop-vowel context. Collapsed across fricatives, the schwa followed by /i/ demonstrated the highest F2 values, followed by the /u/, and then the /ɑ/. Again, this pattern coincides with the more anterior tongue position of the /i/, with the more posterior tongue position producing lower F2 values.

Second, have the younger speakers acquired patterns of lingual coarticulation similar to the adult speakers? The ANOVA revealed no significant age interaction effects, indicating that the overall patterns of anticipatory coarticulation were similar across speaker age groups. Although the extent of this study is limited, these results do indicate that children as young as age 3 have acquired patterns of lingual anticipatory coarticulation similar to adults in some of the limited contexts examined in this study. This finding supports the research of Katz et al. (1991), who found a distinct similarity in overall patterns of coarticulation among adults and children 3 years old and older. This finding is also supported by the studies of Sereno et al. (1987), Sharkey & Folkins (1985), and Turnbaugh et al. (1985).

Third, does the degree of anticipatory lingual coarticulation differ significantly as a function of speaker age? While the overall patterns of anticipatory coarticulation are similar across age groups, the degree of coarticulation of the neutral schwa varied among the age groups according to the contexts which it preceded.

In the stop context (with results collapsed across the vowel contexts), the only significant difference in the degree of coarticulation among the four groups of speakers occurred between the adults and 5-year-old children, and then only for the F2 measures. The 5-year-old speakers exhibited a greater degree of coarticulation between the /t/ and /k/ contexts at a *p*-value of .045. In addition, no significant differences in patterns of coarticulation were found between the adults and the 3- and 4-year-old children. In the stop-vowel contexts, the discrepancy in the degree of F1 coarticulation was between the 3-year-old group and the adults, and between the 4-year old speakers and adults for F2 measures. For both F1 and F2, the child speakers exhibited significantly more coarticulation. In a fricative context, significant differences in the degree of coarticulation among the different speaker groups were apparent. Both the 3- and 4-year-olds demonstrated a greater degree of coarticulation for F1 values than the adult group, and all three children's speaker groups demonstrated a greater degree of F2 coarticulation than did the adult group. Each group of child speakers also exhibited a greater degree of coarticulation than the adult speakers across fricative-vowel contexts.

There are several possible explanations as to why the children examined in this study exhibited a greater degree of coarticulation than the adult speakers. It is possible that children at very young age have not yet acquired the process of coarticulation and therefore initially have less coarticulation than adults. However, when children begin to acquire the process of coarticulation they may overshoot the newly acquired process, a characteristic that is then corrected to a more adult-like pattern with maturation. This theory is supported in the findings of this study, in that the earlier-acquired stop phonemes exhibited a more adult-like coarticulatory pattern among children, while the children demonstrated more coarticulation in the later developing fricatives. It is possible that the children, most notably the 3-year-old group, have already developed (in part at least) an adult-like coarticulation pattern for the stop context, but are still overshooting the fricative context.

Another possible explanation for the greater degree of coarticulation in children is a misrepresentation of the data due to the ERB transformation. It may be possible that the ERB transformation is not ideally suited for normalizing anatomical vocal tract differences between children and adults. It may be more effective to normalize formant data by another method, such as an intrinsic method that normalizes the values obtained from the schwa based on other vowels produced by that same speaker.

Another, more likely possibility for the increase in children's coarticulation as compared with adults is that the younger speakers have a relatively high level of coarticulation at the outset of speech development. As the children's speech matures, their degree of coarticulation decreases to more adult-like levels. The children gain more motor control over their articulators and are able to fine-tune the process of coarticulation to more closely simulate an adult-like form. Again, this theory is also supported in the findings of this study, in that the earlier-acquired stop phonemes exhibited a more adult-like coarticulatory pattern among children, while the youngest children demonstrated more coarticulation in the later developing fricatives.

Additional studies of the speech of children younger than age 3 may provide evidence that very early speech does in fact yield a greater degree of anticipatory coarticulation among children in stop as well as fricative contexts. An examination of older children's coarticulation in the context of fricatives and other later-developing phonemes may also shed further light on this theory. It is possible that older children may exhibit adult-like patterns of coarticulation in fricative contexts, but demonstrate greater coarticulation in a more phonetically complex context.

The findings of the present study indicate that the degree of coarticulation varies according to the speaker's age, but also varies according to the coarticulatory context. This may be attributed to the respective articulatory complexity of the sounds that are being coarticulated. It is acknowledged that for Standard American English, children typically acquire and master stop consonants at an earlier stage than fricatives. The children in this study exhibited an adult-like degree of coarticulation for the stop context but not the fricative context. This may be due to the articulatory complexity of the fricative sound types included in this study and the fact that some of the children may not have mature fricative production abilities.

Previous research supporting the notion that children exhibit greater coarticulation than adults (Nittrouer et al., 1989; Nittrouer et al., 1996; Nittrouer & Whalen, 1989) focused primarily on a CV context involving the fricatives /s/ and /ʃ/. The present study supports their results inasmuch as this study found that children do exhibit greater anticipatory coarticulation in a fricative context. The previous studies did not, however, collapse their findings across the fricative contexts to investigate the effect of the vowel that followed the fricative, as did the present study. The present results indicate that although fricative context alone influences coarticulation, the vowel which follows the fricative segment also has a significant effect on the degree of coarticulation of the target phoneme.

In contrast to the findings of this investigation, several previous studies found that children exhibited less coarticulation than adults (Hodge, 1989; Repp, 1986; Sereno & Lieberman, 1987). Such diverse findings in the literature may be due to differences in methodology. Although both studies examined the coarticulation of an unstressed schwa, Hodge (1989) based her conclusion from contexts in which /t/ and /st/ followed the target schwa, while Sereno and Lieberman (1987) limited their investigation to a velar context (/k/).

Conclusions

The results of this study indicate that articulation of the unstressed and centralized vowel (/ə)/ is significantly affected by the articulation of the initial obstruent and following vowel located in a subsequent syllable. In addition, for the limited contexts investigated in this study, it appears that speakers as young as three years of age have acquired some of the features of adult lingual coarticulation. However, the degree of anticipatory coarticulation across age groups or obstruent contexts was not found to be uniform. In general, this study found that the child speakers exhibited a greater degree of coarticulation than adults, in particular when followed by a fricative context.

This study has some inherent limitations in its scope of research. The results of this study were found by imbedding a neutral schwa in a carrier phrase, and may not be entirely representative of true conversational speech. Future researchers investigating anticipatory coarticulation in children and adults may wish to elicit speech samples from a more naturalistic setting. It would also be of interest to investigate the impact that different patterns and degrees of coarticulation have on the perceptual intelligibility of speech. Do the statistically significant production differences noted in this study make a measureable difference in communication? Furthermore, future studies may examine if the results found in this study also exist in additional linguistic contexts. Also, this study was limited to children between 3 and 6 years of age, but research into the coarticulation patterns of children younger than 3 may provide additional insights into the development of speech at any early age. Despite these limitations, this study is a valuable contribution to the developmental view of how children acquire and improve their speech communication abilities.

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