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The effect of segmental order on fricative labeling by children and adults

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We examined whether children modify their perceptual weighting strategies for speech on the basis of the order of segments within a syllable, as adults do. To this end, fricative–vowel (FV) and vowel–fricative (VF) syllables were constructed with synthetic noises from an /ʃ/-to-/s/ continuum combined with natural /ɑ/ and /u/ portions with transitions appropriate for a preceding or a following /ʃ/ or /s/. Stimuli were played in their original order to adults and children (ages of 7 and 5 years) in Experiment 1 and in reversed order in Experiment 2. The results for adults and, to a lesser extent, those for 7-year-olds replicated earlier results showing that adults assign different perceptual weights to acoustic properties, depending on segmental order. In contrast, results for 5-year-olds suggested that these listeners applied the same strategies during fricative labeling, regardless of segmental order. Thus, the flexibility to modify perceptual weighting strategies for speech according to segmental order apparently emerges with experience.

The acoustic signal of speech is naturally lacking explicit linguistic structure and is, rather, relatively continuous in nature. Under experimental control, this signal can be made even more continuous, to the point where there is a complete lack of discrete temporal units (see, e.g., Remez, Rubin, Pisoni, & Carrell, 1981; Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995). Nonetheless, under either natural or experimental conditions, skilled perceivers manage to organize the signal so that discrete linguistic elements are recovered. Examining how listeners organize the speech signal to derive phonetic structure, despite the apparent lack of such structure in the physical signal, has been *the* most important problem in the field throughout its short history (Pisoni, 1985).

The pioneering work of Abramson and Lisker (e.g., 1970; Lisker & Abramson, 1970) was some of the first to show that native language background influences how listeners organize the acoustic information relevant to phonetic decisions. Specifically, those studies showed that different listeners label the same acoustic stimulus as either a voiced or a voiceless stop, depending on language background. Early experience with a native language serves to enhance the attention paid to some acoustic properties of the signal and, at the same time, to divert attention from other signal properties. This experiential effect has been consistently observed in studies of adults' phonetic perception of second languages. For example, Japanese listeners cannot reliably label tokens from an /r/ to /l/ continuum (MacKain, Best, & Strange, 1981; Miyawaki et al., 1975; Mochizuki, 1981): The Japanese language has neither /l/ nor the retroflexed /r/. The main acoustic property differentiating the retroflexed /r/ of American English from the lateral /l/ is the frequency of the third formant. Miyawaki et al. showed that sensitivity to differences in this property is similar for listeners from the two language backgrounds, and so the differences observed in the labeling experiments must be due to differences in how perceptual attention is directed or, put another way, to differences in how perceptual weight is assigned. Similar effects of first-language learning on perceptual weighting strategies have been observed for labeling of postvocalic stops (Crowther & Mann, 1992, 1994; Flege, 1989), vowel quality (Gottfried, 1984), nasality (Beddor & Strange, 1982), and place of consonant closure (Werker, Gilbert, Humphrey, & Tees, 1981). Thus, how adults perceptually organize properties of the acoustic signal of speech seems to depend on their native language experience: Specifically, the weights assigned to these properties in any phonetic decision vary across native language background. Presumably, the perceptual weighting strategy used by skilled perceivers of any language provides for efficient and accurate recognition of phonetic structure in that language. Because these perceptual weighting strategies are language specific, it is likely that learning is involved in acquiring the most efficient strategies.

Supporting the suggestion that learning must be involved in acquiring language-specific weighting strategies are numerous studies showing that children's perceptual

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weighting strategies for speech are not always the same as those of adults (Greenlee, 1980; Krause, 1982; Morrongiello, Robson, Best, & Clifton, 1984; Nittrouer, 1992, 1996; Nittrouer, Crowther, & Miller, 1998; Nittrouer & Miller, 1997a, 1997b; Nittrouer & Studdert-Kennedy, 1987; Parnell & Amerman, 1978; Simon & Fourcin, 1978; Wardrip-Fruin & Peach, 1984). Of particular relevance to the present study, earlier work has repeatedly found differences between children and adults in labeling decisions of syllable-initial /ʃ/ or /s/ (Nittrouer, 1992, 1996; Nittrouer & Miller, 1997b; Nittrouer & Studdert-Kennedy, 1987). In those studies, stimuli consisting of fricative noises spanning an acoustic continuum from /ʃ/ to /s/ were combined with vocalic portions with formant transitions appropriate for either an initial /ʃ/ or an initial /s/ and were presented to adults and children for labeling. Results are plotted as the proportion of "s" responses given to each noise along the continuum, with separate functions for each transition condition. Findings consistently showed that children's functions are more widely separated than those of adults, depending on the characteristics of the formant transitions (i.e., whether they are appropriate for an initial /ʃ/ or an initial /s/). At the same time, the probability of responding "s" changes more gradually across the fricative-noise continuum for children than for adults, suggesting that children are less influenced by characteristics of the fricative noise. In summary, the relative weights assigned to formant transitions and fricative noise differ for adults and children.

Of course, these results with children must be reconciled with those with infants. In 1971, Eimas, Siqueland, Jusczyk, and Vigorito reported that 1- and 4-month-old infants were able to discriminate two synthetic speech stimuli that differed along an acoustic dimension associated with the voicing of initial stop consonants ($F1$-cutback). This term refers to the timing of onset of the first formant ($F1$), relative to the onset of the second and third formants ($F2$ and $F3$). As with adults, Eimas et al. found that infants were able to discriminate between stimuli with $F1$-cutbacks of +20 and +40 msec (i.e., $F1$ started, respectively, 20 or 40 msec later than $F2$ and $F3$). These settings placed stimuli on opposite sides of the phoneme boundary for English /p/ and /b/. When a difference of 20 msec between stimuli was implemented that placed both stimuli on the same side of the phoneme boundary, infants failed to discriminate between them, as adults fail to do. From this work, Eimas et al. concluded that infants are sensitive to the acoustic dimension that defines adult voicing categories.

That report sparked a great deal of research investigating infants' capacities for speech perception. The collective finding from these many studies is that infants approximately 1–7 months of age are able to discriminate most phonetic contrasts as adults do, regardless of whether or not the contrasts are in the infant's native language (e.g., Eilers, Bull, Oller, & Lewis, 1984; Eilers, Gavin, & Oller, 1982; Kuhl, 1979; Levitt, Jusczyk, Murray, & Carden, 1988; Moffitt, 1971; Morse, 1972; Streeter, 1976; Walley, Pisoni, & Aslin, 1984; but cf. Eilers, Wilson, & Moore, 1977; Eimas & Miller, 1980; Holmberg, Morgan, & Kuhl, 1977). Although not investigated as much, evidence was also found to support the second of Eimas et al.'s (1971) results, that infants fail to discriminate within-category acoustic differences (e.g., Aslin, Pisoni, Hennessy, & Perey, 1981; Eimas, 1974, 1975). Studies in which the abilities of slightly older infants (roughly 7–11 months) to discriminate nonnative contrasts were investigated show that these older infants are poorer at these tasks (Eilers, Gavin, & Wilson, 1979; Werker et al., 1981; Werker & Lalonde, 1988; Werker & Tees, 1984). Taken together, these studies of infant speech perception indicate that humans have innate perceptual capacities to distinguish phonemic categories and that language experience during the first year begins to hone those capacities for native-language contrasts, while attenuating them for nonnative contrasts. However, unless an infant is in a laboratory study, discriminating minimal pairs is not the first language task facing him or her; learning words is.

Evidence dating back to the early 1970s shows that toddlers (about 2 years old) have difficulty learning words that differ by one phonetic feature (Garnica, 1973; Shvachkin, 1973). More recently, Stager and Werker (1997) reported that 14-month-olds could not learn such words, even though 8-month-olds could discriminate them. They concluded that toddlers fail to use phonetic detail in word learning. Accordingly, work with infants largely demonstrates that auditory sensitivity for these youngest listeners is adequate for language learning but that, to investigate developmental changes in the perceptual organization of acoustic information for speech, the proper starting point is the point at which children begin using that information for linguistic purposes—namely, for word learning.

Clearly, adults' perceptual organization for the same acoustic signal differs, depending on whether they consider the signal to be speech or not (see, e.g., Bailey, Summerfield, & Dorman, 1977; Best, Morrongiello, & Robson, 1981; Best, Studdert-Kennedy, Manuel, & Rubin-Spitz, 1989; Miyawaki et al., 1975; Remez et al., 1981). On the basis of that finding, we infer that it is possible that children's perceptual organization (i.e., how they attend to, or weight, the acoustic properties) for speech signals may change when they begin to consider those signals linguistically significant, a change that would be discrete and separate from any gradual developmental changes in auditory sensitivity. Supporting that inference is work by Werker and Tees (1983) that showed that all the infants in their experiment were able to discriminate a nonnative speech contrast but that none of the 4-year-olds could. In that same experiment, half of the children 8 and 12 years of age, as well as two thirds of the adults, could discriminate the nonnative contrast. We suggest that 4-year-olds were using a weighting strategy designed to recover linguistic structure in their native language and were unable to modify that strategy when it would have benefited them to do so. Between 4 and 8 years of age, then, children apparently begin acquiring flexibility in these weighting strategies, so that they can modify them when warranted. The present study tested this suggestion by examining whether children between 4 and 8 years of age are able to modify their weighting strategies for speech when it benefits them to do so because of a change in segmental order.

Many investigators agree that toddlers and young children use *global* properties to represent words in the lexicon and that it is the pressure of a growing lexicon that leads to the emergence of more fine-grained representations (Charles-Luce & Luce, 1990, 1995; Jusczyk, 1986; Locke, 1988; Nittrouer, 1992; Nittrouer & Studdert-Kennedy, 1987; Studdert-Kennedy, 1981; Walley, 1993). Because most of these studies are not acoustic in nature, however, most of these authors have little to suggest as to what the physical correlates of *global* and *fine-grained* representations might be. One reasonable candidate for a global correlate is the formant transition. Transitions are perceptually salient and delimit signal portions corresponding to syllables. Regarding the acoustic correlates of fine-grained representations, presumably these correlates are all the language-specific properties that acoustic/phonetic research has found over the years to correspond to perceived phonetic units. When relatively few items are stored in the lexicon, global properties are sufficient for representing those items. As more items are added, the representations necessarily become more detailed, and so perceptual attention shifts to acoustic properties that can more efficiently provide that detail. This perceptual change has been termed the *developmental weighting shift*, or DWS (e.g., Nittrouer, Manning, & Meyer, 1993; Nittrouer & Miller, 1997a, 1997b).

Several studies over the past 20 years suggest that young children pay particular attention to formant transitions. For example, Parnell and Amerman (1978) presented various combinations of stop-vowel syllable portions (the release burst, the burst plus aspiration noise, the burst plus aspiration and transition, the transition, the transition plus vowel) for labeling to 4- and 11-year-old children and adults. Four-year-olds labeled stops as accurately as older listeners only when syllable portions included the transitions. In the early 1980s, three studies in which differences between young children (3 and 6 years old) and adults in the use of vowel duration and syllable-final transitions in decisions of voicing for final stops (Greenlee, 1980; Krause, 1982; Wardrip-Fruin & Peach, 1984) were investigated found that young children's decisions were based more than those of adults on the transitions and less on vowel duration. Finally, as was noted above, experiments on age-related differences in decisions of syllable-initial fricatives have demonstrated that children weight formant transitions more than adults and weight fricative noise less than adults (Nittrouer, 1992, 1996; Nittrouer & Miller, 1997a, 1997b). Thus, it seems that children initially pay particular attention to the acoustic properties that arise from movement of the vocal tract (i.e., formant transitions), just as they pay particular attention to movement in visual object recognition (Powell, 1996; Ruff, 1982; Spelke, von Hofsten, & Kestenbaum, 1989). Experience with a native language and pressure from an expanding lexicon lead to shifts in this perceptual attention. Gradually, more weight comes to be placed on the acoustic detail that most clearly specifies phonetic detail in the language being learned—for example, on the shapes of fricative-noise spectra that specify the precise place and shape of constriction. This model of developmental change in perceptual weighting strategies, the DWS model, is complementary to another model, the word recognition and phonetic structure acquisition, or WRAPSA model, proposed by Jusczyk (e.g., 1992, 1993). However, the WRAPSA model focuses on perceptual changes associated with first-word learning. The DWS model focuses on developmental changes associated with the discovery of phonetic structure, a process that begins after the ability to recognize individual words in the continuous speech stream is fairly well established. The general goal of the present study was to extend our understanding of how perceptual weighting strategies for speech change over the course of development in such a way as to allow children to access phonetic structure.

We know that adults' perceptual weighting strategies are not rigid. Although they are constrained by language experience and do seem to put more weight on properties that provide information explicitly about phonetic identity, they vary with phonological structure. For example, Dorman, Studdert-Kennedy, and Raphael (1977) explored the relative weights assigned to burst spectra and formant transitions in place decisions for syllable-initial stops. In those syllables in which formant transitions were extensive, this property influenced phonetic decisions more than burst spectra did. However, in those syllables in which formant transitions were relatively flat (owing to similarity in points of constriction for consonant and vowel), burst spectra influenced phonetic decisions more.

In another examination of the flexibility of adults' perceptual strategies for speech, Mann and Soli (1991) investigated changes in adults' weighting strategies in which there was dependence on the order of segments within the syllable. They found that adults paid less attention (assigned low weights) to both vocalic formant transition and to vowel quality in decisions of fricative identity when the fricative came after the vowel (i.e., syllable-final position), rather than before (i.e., syllable-initial position). In that experiment, the stimuli were hybrids of synthetic fricative noises from an /ʃ/ to /s/ acoustic continuum, combined with natural vocalic portions excised from syllables consisting of the vowels /ɑ/ and /u/ and either syllable-initial or syllable-final /ʃ/ and /s/. In the first experiment, Mann and Soli combined the synthetic noises with the natural vocalic portions so that the segmental order of the syllables from which the vocalic portions were extracted was preserved. These stimuli were presented to listeners for labeling. In another experiment, listeners labeled the fricative noises when these stimuli were played in reverse. Mann and Soli observed similar results for stimuli with the same segmental order, regardless of whether it was the original or the reversed order: Adults showed clear separations in labeling functions (plotted as the percent of "sh" responses at each fricative-noise step) owing to formant transitions and vowel quality for fricative–vowel (FV) syllables, but showed little separation in functions for vowel–fricative (VF) syllables. The experimental manipulation of playing the stimuli in reverse permits us to conclude that adults do not simply maintain the same perceptual strategy for mirror-image stimuli, with the outcome of this strategy differing, depending on acoustic structure. Instead, it seems that adults modify their perceptual attention on the basis of segmental order. The specific goal of this investigation was to determine whether children's perceptual weighting strategies would show similar flexibility. That is, would children show different weighting strategies for stimuli differing in segmental order and, if so, would the changes be the same as those of adults?

Two pieces of evidence suggested a priori that children's perceptual weighting strategies for speech may not be susceptible to modification when syllabic structure changes. First, the little evidence that exists suggests that children are less able than adults to redirect their perceptual attention (i.e., assign more weight) to signal properties that provide the best opportunity for detecting differences between stimuli, if they generally do not weight those properties strongly. Using a discrimination task, Nittrouer (1996) found that adults were able to tune their attention to formant transitions when that was the only property distinguishing between stimuli, even though little weight is placed on this property by adults in labeling tasks using stimuli with both formant transitions *and* fricative-noise spectra varying across stimuli. Children, on the other hand, had apparent difficulty tuning their perceptual attention to the fricative-noise spectrum when that was the only property distinguishing between stimuli in a discrimination task. In labeling tasks in which noise and transitions vary, children place more weight on formant transitions, a strategy they seem unable to overcome when it would benefit them to do so. The second piece of evidence suggesting that children's weighting strategies for speech might not be as malleable as those of adults comes from Nittrouer and Miller (1997b). In that study, children's fricative labeling responses showed less vowel-specific effects of changes in $F3$ transitions than did adults' responses. This property provides more information about syllable-initial fricatives for /u/ than for /ɑ/. Accordingly, adults' responses showed more attenuation of the transition effect (i.e., a decrease in the separation among labeling functions, depending on whether formant transitions were appropriate for /s/ or for /ʃ/) for fricative–/u/ than for fricative–/ɑ/ syllables when this property was held constant across stimuli. The responses of children showed similar effects for both vowels. Thus, adults' weighting strategies vary across variations in phonetic structure in order to take advantage of differences in the amount of phonetic information provided by acoustic properties, depending on the phonetic structure. Children's weighting strategies do not show this kind of flexibility.

In summary, adults show different perceptual weighting strategies in fricative labeling for FV and VF syllables, and children and adults differ in their weighting strategies for FV syllables. The present study was intended to investigate whether children would show shifts in weighting strategies, as adults do, for VF syllables. To achieve this goal, we could have simply replicated the procedures of Mann and Soli (1991) with children as listeners—that is, collect labeling data from children for FV and VF syllables (with samples presented in their original and reversed order) and examine whether labeling functions were similar for stimuli with the two kinds of syllabic structure. However, we included adults as listeners for two reasons. First, it seemed important to ensure that the general trends observed in previous developmental studies would be found for these stimuli. Also, it seemed important to make sure that the shifts in weighting strategies that Mann and Soli reported for adults could be replicated. Nonetheless, the critical tests are within groups: Do the same listeners modify perceptual weighting strategies on the basis of phonetic structure?

EXPERIMENT 1
Original Order

This experiment was designed to examine whether young children would demonstrate modifications in perceptual weighting strategies for fricative labeling, depending on segmental order. Mann and Soli (1991) showed that adults assign little weight to acoustic properties within the vocalic portion of the syllable when the fricative follows, rather than precedes, the vowel. We wished to determine whether children would show a similar decrease in perceptual attention to attributes of the vocalic portion of the syllable when the fricative came at the end of the syllable, rather than at the beginning. One of two possible outcomes was expected: Either the children would continue to show large transition effects for VF syllables, as they do for FV syllables, or the children would show almost a complete lack of both vowel and transition effects for the VF syllables, as adults did for VF syllables in the Mann and Soli study. Work by Wardrip-Fruin and Peach (1984) showed that 6-year-olds weighted final formant transitions more than did adults in decisions of syllable-final voicing for stops, providing some support for the prediction that 7- and 5-year-olds might continue to show a strong weighting of formant transitions in VF syllables. However, regardless of which of these two potential outcomes was found, one outcome seemed highly unlikely: that children would show large vowel effects for syllable-final fricatives. Children consistently demonstrate small vowel effects for syllable-initial fricatives (Nittrouer, 1992; Nittrouer & Miller, 1997b; Nittrouer & Studdert-Kennedy, 1987), and there was no reason to suspect anything different for syllable-final fricatives.

The effect traditionally termed the *vowel effect* refers to the common finding that adults give more "s" responses to syllable-initial fricative noises spanning an acoustic continuum from /ʃ/ to /s/ when the following vowel is /u/, rather than /ɑ/ (Kunisaki & Fujisaki, 1977; Mann & Repp, 1980; Nittrouer, 1992; Whalen, 1981). This finding has generally been attributed to the assumption that liprounding during fricative production in anticipation of the upcoming rounded vowel /u/ lowers some aspect of spectral structure of the /s/ noise, and so listeners assign "s" labels to noises with lower spectral characteristics when the following vowel is /u/ rather than /ɑ/. However, acoustic analyses of /ʃ/ and /s/ noises in each vowel environment have not supported this reasoning: Neither the overall center of gravity for the noise nor any of the individual poles is consistently lower before /u/ than /ɑ/ (Heinz & Stevens, 1961; Kunisaki & Fujisaki, 1977; Nittrouer, 1995). Noting this fact, Nittrouer and Miller (1997b) suggested, instead, that age-related differences in both transition and vowel effects for FV syllables could be attributed to age-related differences in how spectral structure at voicing onset is parsed. That is, $F2$ and $F3$ in FV syllables generally differ at voicing onset, depending on the place of constriction both of the preceding fricative and of the vowel. The amount of variability in these formants that a listener attributes to fricative or vowel articulation determines the magnitude of both the transition and the vowel effects. Nittrouer and Miller (1997b) suggested that children attribute most of the variability in formant frequencies at voicing onset (in FV syllables) to fricative articulation and so show larger transition effects than do adults. Adults, it was reasoned, attribute most of this variability in formant frequencies at voicing onset to vowel articulation and so show larger vowel effects. (See Nittrouer & Miller, 1997b, for a complete discussion of this position.) Whatever the source, Mann and Soli (1991) showed that vowel effects were greatly diminished for adults' judgments of syllable-final, as compared with syllable-initial, fricatives. This finding for adults only bolstered the prediction that children would not show a vowel effect for syllable-final fricatives.

Mann and Soli (1991) analyzed their data, using the proportion of "sh" responses given to each stimulus as the dependent measure. Consequently, they were unable to estimate specifically the weight assigned to the fricative-noise spectrum. That estimate is generally obtained from the slope of the labeling functions. When steps from the fricative-noise continuum are represented on the abscissa, we may use the slope of the function as an index of the weight assigned to that noise: the steeper the function, the greater the weight. In the present study, phoneme boundaries and slopes, derived from probit analysis, served as the dependent measures, and so we were able to extend Mann and Soli's results for adults by investigating how the weight assigned to the noise spectrum changed with the change in phonetic structure.

Method

Subjects

All the subjects were required to meet several criteria. They had to pass a hearing screening of the frequencies 0.5, 1.0, 2.0, 4.0, and 6.0 kHz presented at 25 dB HL (American National Standards Institute, 1989), be monolingual English speakers, be free from significant histories of early, chronic otitis media (defined as six or more episodes before the age of 2 years), and be free from histories of speech and language problems (defined as having received treatment). In addition, the children had to score better than the 20th percentile for their age group on the Goldman–Fristoe Test of Articulation (Goldman & Fristoe, 1986). The adults had to demonstrate at least an 11th grade reading level on the Wide Range Achievement Test–Revised (WRAT–R; Jastak & Wilkinson, 1984). Twenty-seven children between the ages of 4 years, 11 months and 5 years, 5 months, 16 children between 6 years, 11 months and 7 years, 5 months, and 16 adults between 20 and 40 years met these criteria. More 5-year-olds were recruited than 7-year-olds or adults, because past experience had shown that younger children have more difficulty completing the experimental task. In this experiment, this age-related difference in attrition rates was a particular concern, because there were four conditions to be completed.

Equipment

All testing took place in a sound-proof booth. Hearing was screened with a Welch Allyn TM262 Auto Tymp tympanometer/audiometer using TDH-39 headphones. Recorded stories were presented via a Nakamichi MR-2 audiocassette player with AKG-K141 headphones. Presentation of stimuli and recording of responses were controlled by a computer. A Data Translation 2801A digital-to-analog converter with 12-bit resolution, a Frequency Devices 901-F filter, a Crown D-75 amplifier, and AKG-K141 headphones were used for stimulus presentation. Cartoon drawings were shown on a color graphics monitor.

Stimuli

Stimuli were created at a 10-kHz sampling rate and presented with low-pass filtering below 4.9 kHz. The synthetic fricative noises used in this experiment were similar to ones used before (Nittrouer, 1992, 1996; Nittrouer & Miller, 1997b) and are readily recognizable as "s" or "sh." They were made with a Sensimetric software synthesizer. The nine noises were single-pole, with center frequencies ranging from 2.2 to 3.8 kHz in 200-Hz steps. The vocalic portions used in this experiment were taken from a male speaker saying FV and VF syllables, with the fricatives being /ʃ/ and /s/ and the vowels /ɑ/ and /u/. The natural fricative noises were removed from these vocalic portions. Five tokens of each vocalic type were used so that variability on irrelevant acoustic parameters (such as duration and $f0$) would be random. Table 1 shows mean $F2$ and $F3$ frequencies across the five tokens of each vocalic type for the first or last pitch period, depending on whether the syllables were FV or VF. Vocalic portions were combined with each of the synthetic noises in the order of the original syllables. Figure 1 shows sample spectrograms of /ɑ/ stimuli. Each spectrogram shows one token of each type of /ɑ/ (i.e., with vocalic transitions appropriate for an initial or a final /ʃ/ or /s/) combined with the noise having a center frequency of 3.0 kHz. Figure 2 shows similar sample spectrograms of /u/ stimuli.

Procedure

The screening tasks were presented first, followed by the labeling task. The stimuli in each of the two conditions (i.e., FV or VF) with each of the two vowels were presented separately. Testing took place in two sessions occurring on different days for adults and 7-year-olds, with two sets of stimuli presented each day. Five-year-olds participated on 4 separate days, with one set of stimuli presented each day. The first set was selected randomly for each subject. The second set was the other vowel, presented in the other order from that

Table 1
Mean Formant Frequencies (in Hertz) for the First Pitch Period (of Syllable-Initial Fricatives) or the Last Pitch Period (of Syllable-Final Fricatives) Across Five Tokens of Each Syllable

Formant	/(s)u/	/(ʃ)u/	/(s)ɑ/	/(ʃ)ɑ/	/u(s)/	/u(ʃ)/	/ɑ(s)/	/a(ʃ)/
F2	1647	1769	1453	1657	1646	1598	1633	1700
F3	2473	2352	2583	1871	2347	2201	2436	2210

of the first set. The third set was the vowel from the first set in the order of the second set. The fourth set was whatever then remained.

The children were introduced to the response labels with tape-recorded stories accompanied by pictures. Each story was presented twice: once with natural speech and once with synthetic speech. These stories served both to familiarize the children with the response labels and to provide experience listening to synthetic speech. For each set of stimuli, two kinds of practice were provided to all the subjects: whole, unaltered syllables (i.e., natural noises and natural vocalic portions) and the best exemplars (i.e., the endpoint /ʃ/ or /s/ noise, with the vocalic portion having transitions appropriate for /ʃ/ or /s/, respectively). Ten items (5 of each category) were presented in each practice, and listeners had to respond correctly to 9 of these 10 items to proceed to the next stage of practice or testing.

In the test itself, each syllable type was presented 10 times in randomized blocks of 18: each of the nine noises paired with an /(ʃ)V/ and an /(s)V/ in the FV condition and each of the nine noises paired with a /V(ʃ)/ and a /V(s)/ in the VF condition. Within each block, specific tokens of the two vocalic types (out of the five tokens of each kind collected) varied. Across the 10 blocks, each vocalic token was presented with each noise twice. The listeners indicated their responses by pointing to one of two pictures and saying the response label. The experimenter entered the responses into the computer. Cartoon drawings were shown to the children at the end of each block, and they were allowed to move a marker to the next number on a game board. In this way, the children could keep track of their progress throughout the test. For a subject's data to be included in the final analysis, at least 80% accurate responses had to be given to the best exemplars during testing with each set, thereby ensuring that data were included only from subjects who had maintained attention to the task.

Labeling functions were derived for each vocalic context in each phonetic order and are the proportion of "s" responses given at each level of the fricative-noise continuum. These proportions were transformed to probit scores (Finney, 1964). From each probit distribution, a mean (i.e., the point on the fricative-noise continuum at which half of the responses were "sh" and half were "s") and a slope (i.e., change in probit units per kilohertz of change in fricative noise) were derived. The distribution mean serves as the phoneme boundary.

The question to be asked constrained the choice of the statistic to be used. Because we were interested in within-groups effects, we needed a statistic that would test those effects for each of the three age groups. Therefore, simple effects analyses were done on the phoneme boundaries and slopes. This analysis allowed us to examine the main effects of formant transition, vowel, and condition, as well as the interactions of these effects, for each age group separately. The advantage of this procedure over separate analyses of variance for each group is that the error term is based on data for all the listeners.

Results

Attrition

All the listeners in this experiment were able to meet the training criterion of achieving 90% correct responses to the best exemplars for at least one set. However, not all the listeners could meet, for all sets, this training criterion and/or the criterion of achieving at least 80% accurate responses to the best exemplars during testing. Data were completely excluded from analysis for those listeners who could not meet the training and testing criteria for all sets. This strict requirement was necessary because we were interested in comparing performance across sets. In the end, we had complete sets of data for fourteen 5-year-olds, thirteen 7-year-olds, and 14 adults. Of particular interest, attrition for each group was evenly spread across sets. That is, no one set was particularly problematic.

Comparisons With Previous Studies With Fricative–Vowel Syllables

Past results with FV syllables (Nittrouer, 1992, 1996; Nittrouer & Miller, 1997b; Nittrouer & Studdert-Kennedy, 1987) generally show that children demonstrate larger transition effects (i.e., differences in phoneme boundaries between functions for stimuli with transitions appropriate for /ʃ/ and functions for stimuli with transitions appropriate for /s/) than do adults, but smaller vowel effects (i.e., differences in phoneme boundaries between functions for stimuli with /ɑ/ and functions for stimuli with /u/). In addition, children's labeling functions are shallower than those of adults, indicating (when fricative noise is the parameter plotted across the abscissa) that children's responses are less influenced by the spectrum of the noise.

Table 2 displays mean vowel and transition effects for each age group for stimuli presented in their original order, for both FV and VF syllables. Results for FV syllables show that the developmental trends observed in earlier studies were replicated: The vowel effect increases with increasing age, and the transition effect decreases. Table 3 displays mean slopes for stimuli presented in their original order and again shows that previous results were replicated for the FV syllables: Slope increases with increasing age. Thus, the listeners participating in this experiment display similar developmental trends to those found in earlier experiments.

Present Findings for Fricative–Vowel and Vowel–Fricative Syllables, Presented in the Original Order

Table 4 shows the results of the simple effects analysis for phoneme boundaries for all age groups. *F*-ratios and *p* values are shown only for the main effects of vowel and transition, and for the vowel × condition and transition × condition interactions. Neither the other main effect (condition) nor either of the other interactions (vowel × tran-

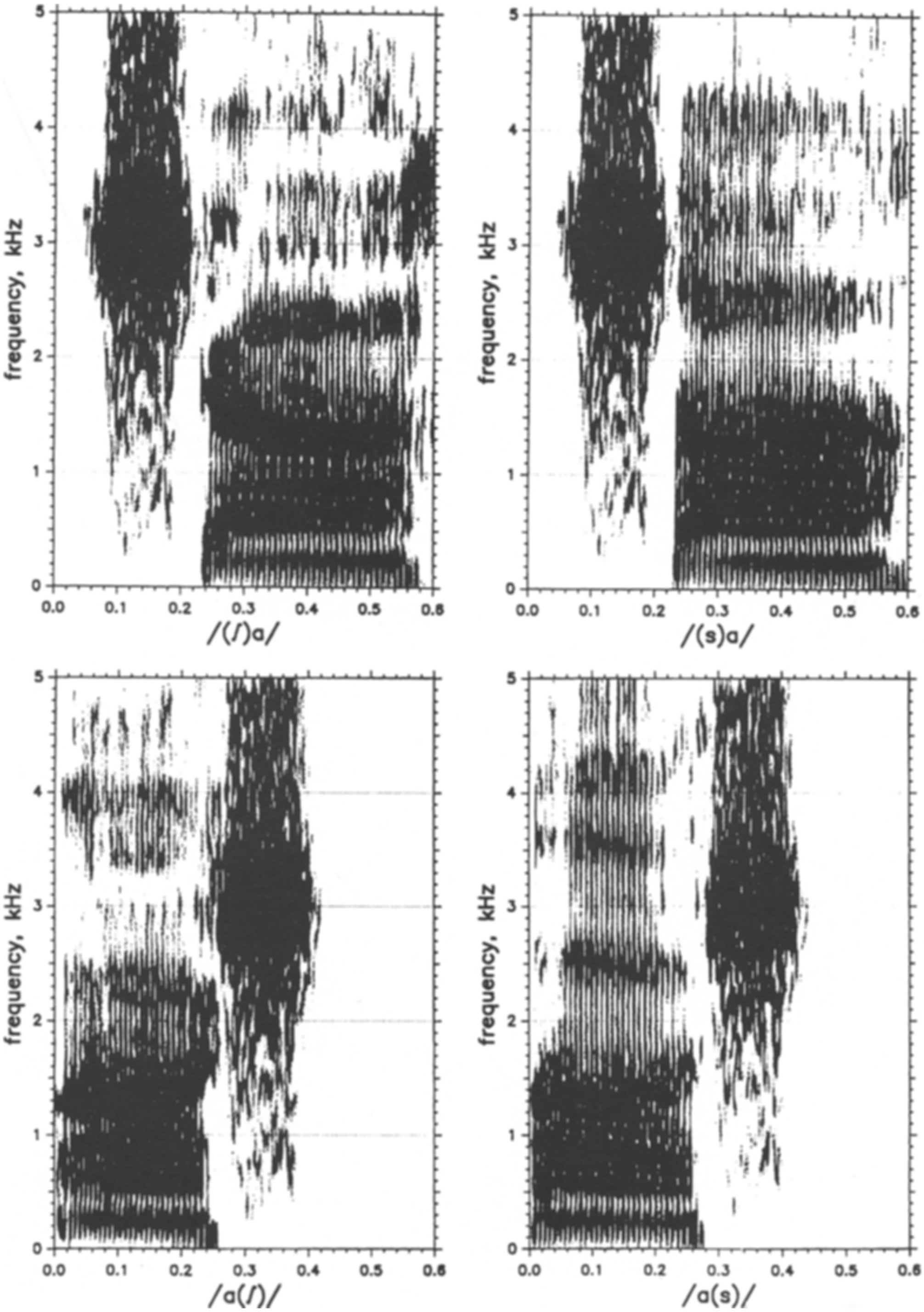

Figure 1. Sample spectrograms of /ɑ/ vocalic portions taken from a male speaker saying (clockwise from upper left) /ʃɑ/, /sɑ/, /ɑs/, and /ɑʃ/. These spectrograms were made for stimuli in which the vocalic portions were combined with the synthetic fricative noise that had a single pole centered at 3.0 kHz.

sition and vowel × transition × condition) resulted in *p* values of less than .10 for any of the age groups. Precise *p* values are reported only when they are between .001 and .10. The main effects of both vowel and transition were highly significant for all age groups, indicating that more "s" responses were generally given for /u/ than for /ɑ/ and for /s/ than for /ʃ/, for both FV and VF syllables. For the purposes of this investigation, however, the two interactions reported in Table 4 are of primary interest, because they indicate whether the magnitudes of the vowel and

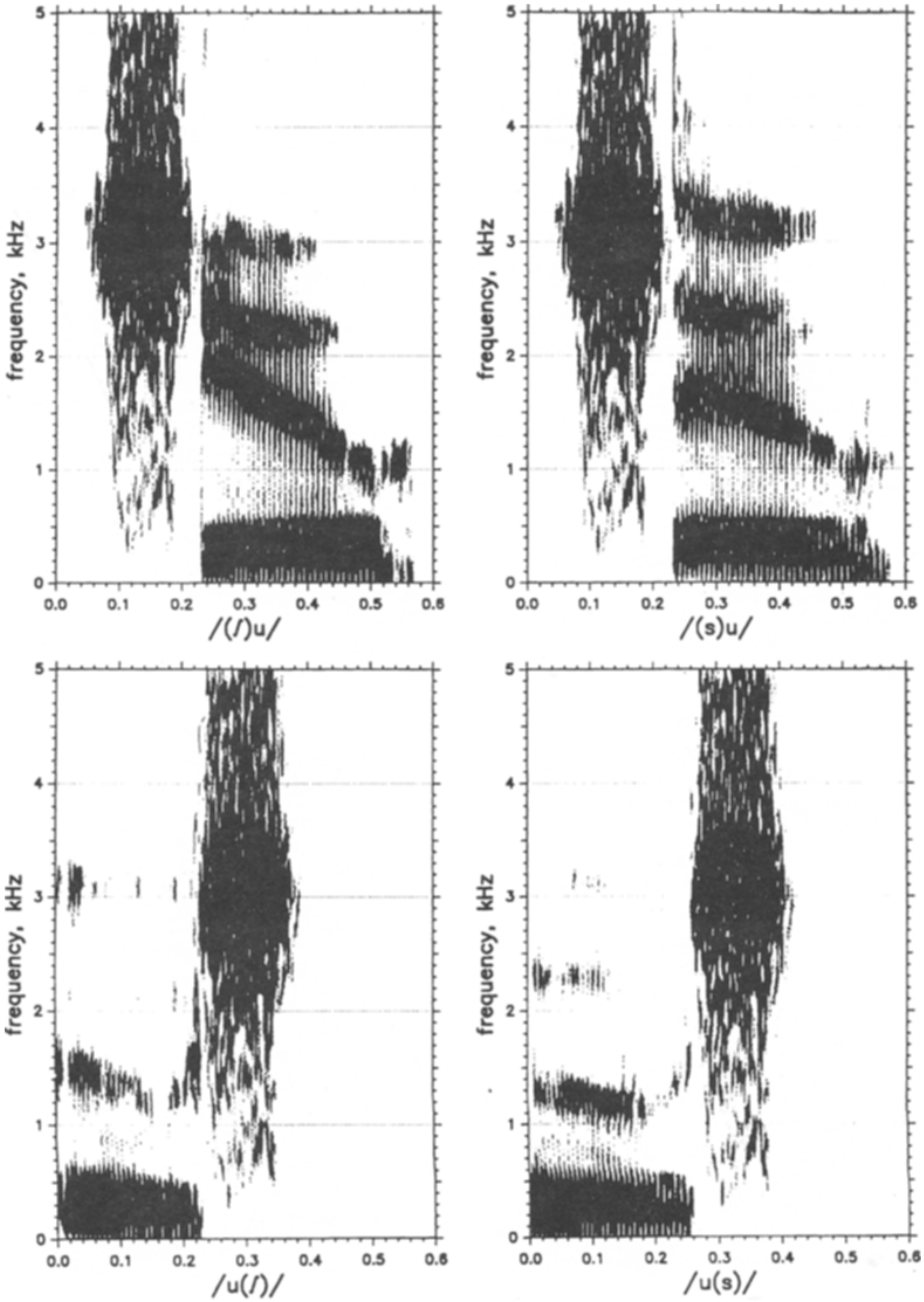

Figure 2. Sample spectrograms of /u/ vocalic portions taken from a male speaker saying (clockwise from upper left) /ʃu/, /su/, /us/, and /uʃ/. These spectrograms were made for stimuli in which the vocalic portions were combined with the synthetic fricative noise that had a single pole centered at 3.0 Khz.

transition effects changed with the change in segmental order. Mean phoneme boundaries for each syllable type for each age group in this experiment can be found in Appendix A.

A table of results for the simple effects analysis of slopes is not provided, because only two effects (one each for adults and 7-year-olds) had *p* values of less than .10. Mean slopes for each syllable type for each age group are given in Appendix B.

Adults. Labeling functions for adults are illustrated in Figure 3 and show that transition and vowel effects are generally reduced for VF syllables, as compared with FV

Table 2
Mean Differences in Phoneme Boundaries (in Hertz) as a Function of Vowel Quality (/ɑ/ Boundary Minus /u/ Boundary) and Transition (/ʃ/ Boundary Minus /s/ Boundary) for the Fricative–Vowel (FV) Stimuli and for the Vowel–Fricative (VF) Stimuli Presented in the Original Order (Experiment 1)

Effect	5-Year-Olds	7-Year-Olds	Adults
FV Mean Vowel Effect	55	174	232
/s/-transition only	−37	148	199
/ʃ/-transition only	147	201	264
FV Mean Transition Effect	652	492	470
/ɑ/ only	744	518	502
/u/ only	560	454	438
VF Mean Vowel Effect	224	125	115
/s/-transition only	232	73	58
/ʃ/-transition only	216	177	172
VF Mean Transition Effect	44	67	65
/ɑ/ only	52	119	122
/u/ only	49	15	8

Note—The first number is the mean across transitions or vowels; the next two numbers are for each transition or vowel separately.

syllables. Table 2 reveals that the magnitude of the vowel effect for adults for VF syllables was half what it was for FV syllables, but this effect does not reach statistical significance. Therefore, we may not conclude that the weight adults assigned to vowel quality differed for the two conditions. Table 2 also indicates that the magnitude of the transition effect was greatly reduced in the VF condition, as compared with the FV condition and that this effect was statistically significant. Thus, the weight assigned to formant transitions by adults in decisions of fricative labeling was less when the syllables were VF, rather than FV.

Table 3 shows that adults' labeling functions were steeper in the VF than in the FV condition. This finding was close to the .05 level of significance [$F(1,38) = 3.59$, $p = .066$]. The slope of the labeling functions serves as an estimate of the perceptual weight assigned to the fricative–noise spectrum: steeper functions, greater weight; shallower functions, less weight. Although the F-ratio did not quite reach the .05 level of significance, it seems fair to conclude that adults generally weighted the fricative–noise spectrum more for VF than for FV syllables.

Seven-year-olds. Figure 4 shows labeling functions for 7-year-olds and gives the impression of a reduced transition effect for VF syllables, as compared with FV syllables: The filled and open symbols are closer. This pattern of result is also apparent in Table 2 and is supported by a significant transition × condition interaction. The vowel effect remained roughly the same across conditions. Thus, we may conclude that the weight assigned to formant transitions decreased for VF syllables, as compared with FV syllables, but the weight assigned to vowel quality remained constant.

There was no difference in the slopes of the functions for the FV and the VF syllables for 7-year-olds, and so we may conclude that the perceptual weight they assigned to the fricative-noise spectrum was similar for these two types of syllables. However, the analysis of slopes did show a significant main effect of vowel [$F(1,38) = 5.23$, $p = .028$], reflecting the fact that mean slope, across conditions and transitions, was 2.92 for /ɑ/ and 3.50 for /u/. This finding is not relevant to the main question addressed by this investigation.

Five-year-olds. Figure 5 shows labeling functions for 5-year-olds and clearly suggests a different pattern across the FV and VF syllables than what we saw for adults and 7-year-olds. For FV syllables, there is a strong separation in functions, depending on whether the formant transitions were appropriate for /s/ or /ʃ/ (filled vs. open symbols), but little separation that depended on vowel (squares vs. circles). For the VF syllables, we see the opposite pattern: appreciable separation that depended on whether the vowel was /u/ or /ɑ/, but little separation that depended on formant transitions. The effects provided in Table 2 support those observations. The statistical analysis resulted in a strong transition × condition interaction and a weaker vowel × condition interaction. It seems fair to conclude that the 5-year-olds' transition effect was less in the VF than in the FV condition and that the vowel effect was greater in the VF condition.

No change in slope across the two types of syllables was observed for 5-year-olds.

Discussion

The principal goal of this experiment was to examine whether children demonstrate differences in perceptual weighting strategies across differences in syllabic structure and, if so, whether these differences mirror those of adults. The adults in this experiment showed effects of segmental order that were similar to those in Experiment 1 of Mann and Soli (1991), which presented syllables in the original order. The transition effect was significantly attenuated for the VF syllables, as compared with the FV syllables. The vowel effect was reduced for VF, compared with FV syllables, but this difference was not statistically significant for the adults in our study, as it had been for the adults in Mann and Soli's study. In this experiment, we also found somewhat steeper slopes for VF than for FV syllables. Thus, we conclude that adults weight the noise spectrum more and weight formant transitions less in decisions of fricative identity when the fricative is at the end of a syllable, rather than at the beginning. This result is complementary to that of Dorman et al. (1977) for stop-vowel syllables: Their adult listeners showed a reciprocal

Table 3
Mean Slope (in Probit Units per Kilohertz of Noise) Across Vowels and Formant Transitions for the Fricative–Vowel (FV) Stimuli and for the Vowel–Fricative (VF) Stimuli Presented in the Original Order (Experiment 1)

Stimuli	5-Year-Olds	7-Year-Olds	Adults
FV	2.76	3.30	3.94
VF	2.72	3.21	4.38

Table 4
F-Ratios and Probabilities From the Simple Effects Analysis on Phoneme Boundaries (Experiment 1)

	5-Year-Olds		7-Year-Olds		Adults	
	F-Ratio	p	F-Ratio	p	F-Ratio	p
Main Effects						
Vowel	18.82	<.001	19.59	<.001	29.89	<.001
Transition	75.13	<.001	43.21	<.001	43.67	<.001
Two-Way Interactions						
Vowel × condition	3.85	.057	.22	>.10	1.91	>.10
Transition × condition	47.68	<.001	21.52	<.001	21.60	<.001

Note—Degrees of freedom are 1/49 for all tests.

relation in the weighting of burst spectra and formant transitions.

Children in both age groups showed a great reduction in the size of the transition effect for the VF syllables, as compared with the FV syllables. However, 5-year-olds showed a general increase in the size of the vowel effect for the VF syllables, as compared with the FV syllables, and so showed an effect of segmental order in the opposite direction to that of adults. Interestingly, this response pattern is the one that, before testing, was predicted to be least likely to occur. For FV syllables, 5-year-olds' responses showed large transition effects and small vowel effects, a pattern observed consistently for children's responses to FV syllables in the past (e.g., Nittrouer, 1992, 1996; Nittrouer & Miller, 1997b; Nittrouer & Studdert-Kennedy, 1987). However, 5-year-olds' responses to VF syllables showed strong vowel effects. On first consideration, this finding seems to indicate that 5-year-olds change their perceptual weighting strategies on the basis of the segmental order within syllables. However, further consideration suggests that this conclusion would be erroneous.

In this experiment, 5-year-olds showed vowel effects for VF syllables that were similar in magnitude to the vowel effects demonstrated by adults for FV syllables. This finding leads naturally to the suggestion that 5-year-olds attribute a large proportion of the variability in formant frequencies at voicing offset (in VF syllables) to vowel articulation. Although this explanation sounds reasonable, the spectral structure of the signal at voicing offset does not support it: The relations of $F2$ frequency to fricative and vowel production are not the same for FV and VF syllables. Table 1 shows that $F2$ at voicing onset is consistently higher for /u/ than for /ɑ/ in FV syllables, regardless of transition, a finding that has been found previously for FV syllables in English (e.g., Nittrouer, 1992; Nittrouer & Miller, 1997b). It is this spectral difference that is thought to be responsible for adults' vowel effect for FV syllables (Nittrouer & Miller, 1997b). For VF syllables, $F2$ is not consistently higher for /u/ than for /ɑ/, so *vowel-related* differences in spectral structure cannot explain 5-year-olds' apparent vowel effect. Nonetheless, the spectral structure of the syllables must account for the effect: When a perceptual effect is observed, it must be based on something in the physical structure of the stimuli.

We suggest that the reason for the 5-year-olds' enhanced vowel effect for syllable-final fricatives is that the 5-year-olds retained the same perceptual weighting strategy across segmental order, but differences in the spectral structure of FV and VF syllables caused this strategy to produce different patterns of response for the two kinds of syllables. Support can be garnered for this suggestion from the formant transitions illustrated in Figures 1 and 2. To consider /ɑ/ first, Figure 1 shows that $F2$ is more steeply falling in /(ʃ)ɑ/ than in /(s)ɑ/. Although less per-

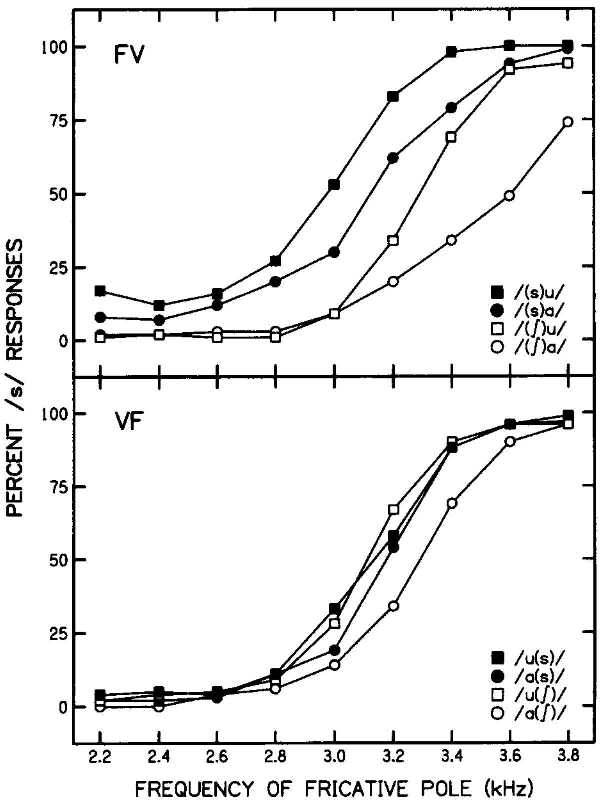

Figure 3. Adults' labeling functions for Experiment 1, with the stimuli played in the original order.

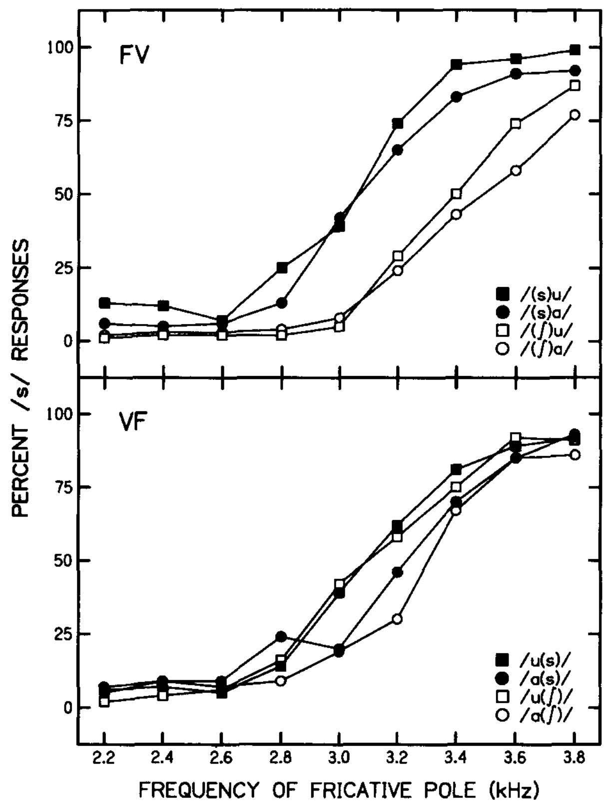

Figure 4. Seven-year-olds' labeling functions for Experiment 1, with the stimuli played in the original order.

ceptually distinct, $F3$ also shows differences between the two transition conditions: For /(ʃ)ɑ/, $F3$ is rising; for /(s)ɑ/, $F3$ is falling. For vocalic portions taken from syllables with final fricatives, both formant transitions may be described as more closely resembling the mirror image of /(ʃ)ɑ/ than that of /(s)ɑ/. The $F2$ transition is now steeply rising. The $F3$ transition may be described as either flat or gently falling. In any event, it is certainly not rising, as would be the case if it were a mirror image of the $F3$ transition in /(s)ɑ/. To consider /u/ next, it can be seen that $F2$ transitions are extensive in FV syllables, with $F2$ in /(ʃ)u/ demonstrating more of a fall than $F2$ in /(s)u/. $F3$ in fricative–/u/ syllables differs, depending on the place of fricative constriction, and Nittrouer and Miller (1997b) showed that this property provides perceptual information to adults and children in the labeling of syllable-initial fricatives. However, the spectral tilt of the vocalic portion in VF syllables is so great that $F3$ may not provide much information for fricative labeling in this situation. Instead, $F2$ transitions appear to be the primary source of information available from the vocalic portions in the VF syllables, and these transitions lack the extensive change that is observed for $F2$ transitions in /(ʃ)u/. Although $F2$ transitions in /u(ʃ)/ and /u(s)/ are not nearly as extensive as the $F2$ transition in /(s)u/, they more closely resemble mirror images of this transition than those of the more extensive $F2$ transition in /(ʃ)u/. If a listener strongly bases fricative decisions on these offset transitions, as we suggest 5-year-olds do, it is reasonable that more "s" responses would be given to syllables with /u/ and more "sh" responses to syllables with /ɑ/. Thus, it seems that 5-year-olds did not modify their perceptual weighting strategies on the basis of segmental order. Instead, acoustic asymmetries in the syllables led to different response patterns when the same strategies were used.

EXPERIMENT 2
Reversed Order

Mann and Soli (1991) were able to conclude that adults modify their perceptual weighting strategies on the basis of segmental order, because they played their stimuli in reverse for listeners and obtained the same order effects they had found when they had been played in the original order (i.e., smaller vowel and transition effects for VF than for FV syllables). In this experiment, we obtained labeling responses from listeners to the stimuli from Experiment 1, with the order of samples reversed, as a check on our conclusions that adults and, to some extent, 7-year-olds modify their perceptual weighting strategies when segmental order changes, whereas 5-year-olds do

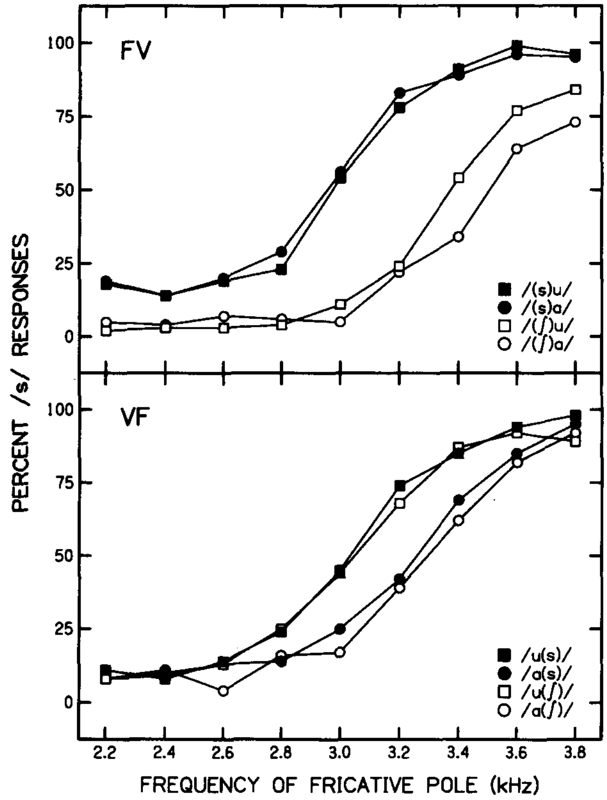

Figure 5. Five-year-olds' labeling functions for Experiment 1, with the stimuli played in the original order.

Table 5
Mean Differences in Phoneme Boundaries (in Hertz) as a Function of Vowel Quality (/ɑ/ Boundary Minus /u/ Boundary) and Transition (/ʃ/ Boundary Minus /s/ Boundary) for the Fricative–Vowel (FV) Stimuli and for the Vowel–Fricative (VF) Stimuli Presented in the Reversed Order (Experiment 2)

Effect	5-Year-Olds	7-Year-Olds	Adults
FV Mean Vowel Effect	150	135	173
/s/-transition only	30	87	85
/ʃ/-transition only	269	184	261
FV Mean Transition Effect	92	59	70
/ɑ/ only	284	108	159
/u/ only	−19	11	−18
VF Mean Vowel Effect	−140	32	6
/s/-transition only	−128	−75	−31
/ʃ/-transition only	−152	108	23
VF Mean Transition Effect	134	70	69
/ɑ/ only	128	160	97
/u/ only	146	−20	36

Note—The first number is the mean across transitions or vowels; the next two numbers are for each transition or vowel separately.

not. This check was critical to this study because, as Table 1 shows, acoustic asymmetries were found in formant frequencies adjacent to fricative segments. When voicing ends in VF syllables, the frequencies of $F2$ and $F3$ do not differ as much as a function of the place of fricative constriction as when voicing starts in FV syllables. Furthermore, Figures 1 and 2 show that the asymmetries in formant frequencies across FV and VF syllables found in Table 1 actually underestimate acoustic asymmetries. Especially with /u/, asymmetries are seen in formant trajectories, which are more extensive for FV than for VF syllables. Furthermore, spectral tilt is greater for /u/–fricative than for fricative–/u/ syllables. This last observation suggests that even the attenuated differences that are present in formant frequencies (particularly in $F3$) across place of fricative constriction may not be very salient for /u/–fricative syllables. In sum, offset transitions in VF syllables attenuate differences between fricative contexts but emphasize differences between vowels.

Thus, two mutually exclusive predictions can be made about the outcome of this second experiment. If modifications in listeners' perceptual weighting strategies were responsible for differences in transition effects (and, when found, in vowel effects) for FV and VF syllables in Experiment 1, we should find the same differences across conditions in Experiment 2: that is, greater transition effects (and possibly, vowel effects) for FV than for VF syllables. This is the prediction for adults and, to a lesser extent, for 7-year-olds. However, if the results of Experiment 1 were obtained because of acoustic asymmetries for FV and VF syllables (i.e., the listeners' perceptual strategies remained constant, but led to different response patterns because of acoustic asymmetries), we should find a pattern of responses in this experiment opposite to that observed in Experiment 1. This is the prediction for 5-year-olds.

Method

Subjects

The listeners were required to meet the same criteria as those in Experiment 1. Thirteen adults, fifteen 7-year-olds, and fifteen 5-year-olds meeting these criteria were recruited.

Stimuli

To make these stimuli, the order of the samples of the stimuli in Experiment 1 were simply reversed. Consequently, the FV syllables in this experiment were the VF syllables from Experiment 1, with the order of the samples reversed. Similarly, the VF syllables were the FV syllables from Experiment 1, with the samples reversed.

Equipment

All equipment was the same as that used in Experiment 1.

Procedure

The procedures for adults and 7-year-olds were exactly the same as those used in Experiment 1. However, 5-year-olds had great difficulty meeting the training and testing criteria with these reversed stimuli. Therefore, the procedures were modified for these youngest listeners. First, two blocks of training (20 stimuli) were provided with each of the unaltered stimuli and the best exemplars. (In this experiment, of course, the best exemplars were stimuli played in reverse.) The children were expected to label at least 90% of the unaltered stimuli correctly to move to training with the best exemplars. To move to testing, however, the criterion with the best exemplars was relaxed from what it had been in Experiment 1. In this experiment, 8 out of the last 10 stimuli presented needed to be labeled correctly for the child to move to testing. In testing itself, the criterion for including data was relaxed for 5-year-olds. They did not need to obtain 80% correct responses to the best exemplars during testing to have their data included; they only needed to obtain 75% correct responses. If a child did not meet the training or testing criteria for correct responses to best exemplars, they were not simply dismissed. In order to ensure that it was the nature of reversed stimuli that was responsible for the attrition, and that we had not simply recruited a sample of children who, for one reason or another, were having difficulty with the task, we had the children respond to a block of the best exemplars from Experiment 1—that is, the same stimuli presented in the original order. Finally, we did not include data only from those 5-year-olds who could meet the training and testing criteria for all four sets of stimuli. Instead, we included 5-year-olds' data for those sets in which the criteria were met.

Results

Attrition

Data from five 7-year-olds were excluded because these children could not meet the training or testing criteria for one or more sets. Unlike the results for Experiment 1, the pattern of failure to meet these criteria showed a strong condition effect. Every 7-year-old whose data were excluded had difficulty meeting criteria in the VF condition.

Every 5-year-old was able to meet the training criterion with the unaltered stimuli for every set. Every 5-year-old who failed to meet the training or testing criteria with best exemplars for one of the sets met the criterion of 90% correct for best exemplars presented in the original order. This finding is strong evidence that these reversed stimuli presented a challenge to 5-year-olds, not that we had recruited a sample of children who had special difficulty

Table 6
***F*-Ratios and Probabilities From the Simple Effects Analysis on Phoneme Boundaries (Experiment 2)**

	5-Year-Olds		7-Year-Olds		Adults	
	F-ratio	*p*	*F*-ratio	*p*	*F*-ratio	*p*
Main Effects						
Vowel	.04	>.10	8.89	.007	13.18	.001
Transition	22.40	<.001	15.19	<.001	22.96	<.001
Two-Way Interactions						
Vowel × condition	4.26	.050	1.27	>.10	4.33	.048
Transition × vowel	5.82	.024	17.62	<.001	17.58	<.001
Three-Way Interaction						
Transition × vowel × condition	6.23	.020	1.18	>.10	2.74	>.10

Note—Degrees of freedom are 1/24 for all tests.

with the task. Also, only one 5-year-old with one set benefited from our relaxed criterion of requiring only 75% correct responses to best exemplars during testing. That 1 child obtained only 75% correct responses with /u/–fricative syllables. In short, if children were able to perceptually organize these stimuli, their responses were consistent. If they could not perceptually organize these stimuli, they failed miserably. The following numbers (out of 15) of 5-year-olds provided data for each set: 13 for fricative–/ɑ/, 8 for fricative–/u/, 11 for /ɑ/–fricative, and 4 for /u/–fricative.

Present Findings for Fricative–Vowel and Vowel–Fricative Syllables, Presented in Reversed Order

Table 5 provides mean vowel and transition effects for these reversed stimuli, and Table 6 shows the results of the simple effects analysis done on phoneme boundaries. In this experiment, all age groups demonstrated a significant main effect of transition, as was the case in the first experiment. However, no group demonstrated a significant transition × condition interaction, which all groups had in the first experiment. Consequently, statistical results for that interaction are not shown in Table 6. Mean phoneme boundaries for each syllable type for each age group in this second experiment can be found in Appendix C.

Table 7 provides mean slopes for FV and VF syllables. Appendix D provides slopes for each type of syllable. As in the first experiment, only a few results from the simple effects analysis on slopes were significant, and they are presented when appropriate.

Adults. Labeling functions for adults for these reversed stimuli are illustrated in Figure 6. As with stimuli presented in their original order, functions are generally more separated for FV than for VF syllables. Table 5 suggests that, in this experiment, this difference across conditions is largely due to a reduction in the vowel effect for VF, as compared with FV, syllables; the mean transition effect remained the same across conditions. These impressions are supported by the simple effects analysis: The vowel × condition interaction was significant for adults, but, again, no group demonstrated a significant transition × condition interaction. Thus, these interactions, the results of most importance to the hypothesis being tested, indicate that adults did not perform exactly as they had when the stimuli were presented in the original order. The vowel effect was larger for FV than for VF syllables in this second experiment. Although this cross-condition trend was observed in Experiment 1, it was not statistically significant in that experiment. Unlike Experiment 1, the transition effect was the same across conditions in this experiment. In fact, the transition effect was roughly the same magnitude as it had been for adults listening to the VF syllables in Experiment 1, for both conditions in this experiment. Unlike Experiment 1, the vowel × transition interaction was also significant for adults. An inspection of Figure 6 and Table 5 indicates that this significant interaction was due to the vowel effect's being noticeably larger for stimuli with /ʃ/ transitions, rather than /s/ transitions.

For this experiment, we see a different pattern for slopes than what was observed in Experiment 1. In fact, we see the opposite pattern: Functions were steeper for the FV than for the VF syllables in this second experiment. This finding was supported by a significant main effect of condition [$F(1,24) = 27.97, p < .001$]. No other effect or interaction was found to be significant for adults in the simple effects analysis of slopes, except for the main effect of transition [$F(1,24) = 7.90, p = .010$]. This last finding reflects the fact that adults demonstrated slightly steeper functions for stimuli with /s/ transitions than for those with /ʃ/ transitions: 4.61 versus 4.22, respectively.

Both the finding of a significant vowel × transition interaction for phoneme boundaries and that of a significant main effect of transition for slopes may arise from the same source: stronger weight being assigned to the transition for the /(ʃ)ɑ/ and /ɑ(ʃ)/ syllables than for the

Table 7
Mean Slope (in Probit Units per Kilohertz of Noise) for the Fricative–Vowel (FV) Stimuli and for the Vowel–Fricative (VF) Stimuli Presented in the Reversed Order (Experiment 2)

Stimuli	5-Year-Olds	7-Year-Olds	Adults
FV	2.22	3.60	5.19
VF	2.56	2.88	3.64

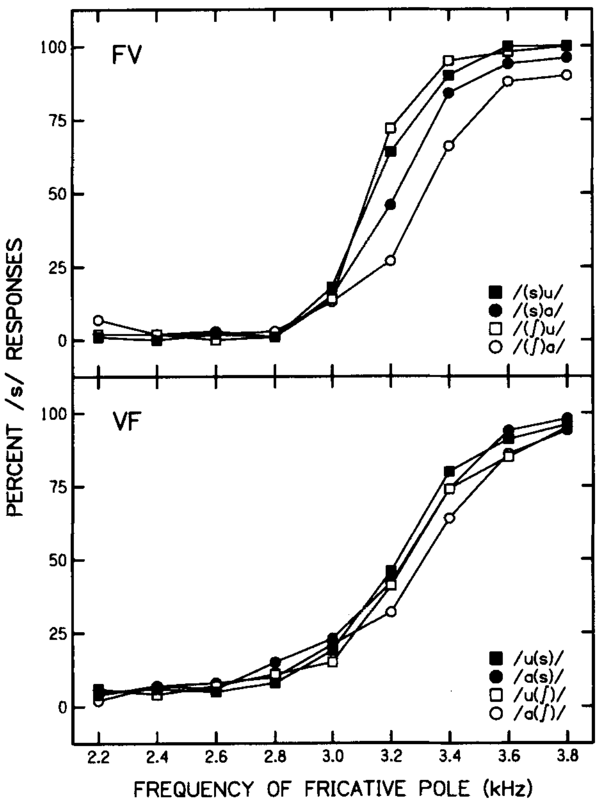

Figure 6. Adults' labeling functions for Experiment 2, with the stimuli played in reversed order.

other syllable types. This weighting strategy resulted in the /(ʃ)ɑ/ or /ɑ(ʃ)/ function's being generally separated from adults' other functions, toward the end of the noise continuum (Figure 6 and Appendix C): There is less than a 100-Hz separation among the other three functions, but the /(ʃ)ɑ/ or the /ɑ(ʃ)/ function is more than 100 Hz away from the nearest function (/(s)ɑ/ or /ɑ(s)/). Regarding slope, the /(ʃ)ɑ/ or the /ɑ(ʃ)/ function is shallower than the other three for the same segmental order (Appendix D). This trend is further support for the suggestion of Dorman et al. (1977), that there is a reciprocal relation between the weight assigned to the transition and to the noise: The finding of a particularly separated function indicates that the transition was weighted heavily; the finding of a shallow function indicates that the noise spectrum was not weighted heavily. Although this general trend of weighting the /ʃ/ transition particularly strongly for /ɑ/ stimuli was apparent in Experiment 1, it was not as great as it was in this experiment. Be that as it may, this trend is not particularly relevant to the hypothesis under investigation in this study. The pertinent result for adults' data is that perceptual weighting strategies did not appear to change across FV and VF syllables in the same way for Experiments 1 and 2.

Seven-year-olds. Figure 7 shows labeling functions for 7-year-olds. No differences were found in the simple effects of phoneme boundaries across conditions for 7-year-olds (Table 6): That is, there was neither a significant interaction of transition and condition nor one of vowel and condition. As with adults, however, the main effects of vowel and transition were significant, as was the transition × vowel interaction. As with adults, this last effect was due to the vowel effect's being greater for stimuli with /ʃ/ transitions, rather than /s/ transitions.

Seven-year-olds demonstrated steeper functions for FV syllables than for VF syllables, as adults did. As with adults, this trend produced a significant main effect of condition in the simple effects analysis for slopes [$F(1,24) = 4.62, p = .042$]. Thus, these children weighted the fricative-noise spectra more in FV than in VF syllables in this experiment. The main effect of transition was also significant for slopes [$F(1,24) = 14.42, p < .001$]. Just as with adults, this significant effect reflects steeper functions for stimuli with /s/ transitions than for those with /ʃ/ transitions: 3.55 versus 2.94, respectively.

Five-year-olds. Figure 8 shows labeling functions for 5-year-olds for these reversed stimuli. For this figure, as well as for Tables 5 and 7 and Appendices C and D, data from all 5-year-olds who met the training and test criteria

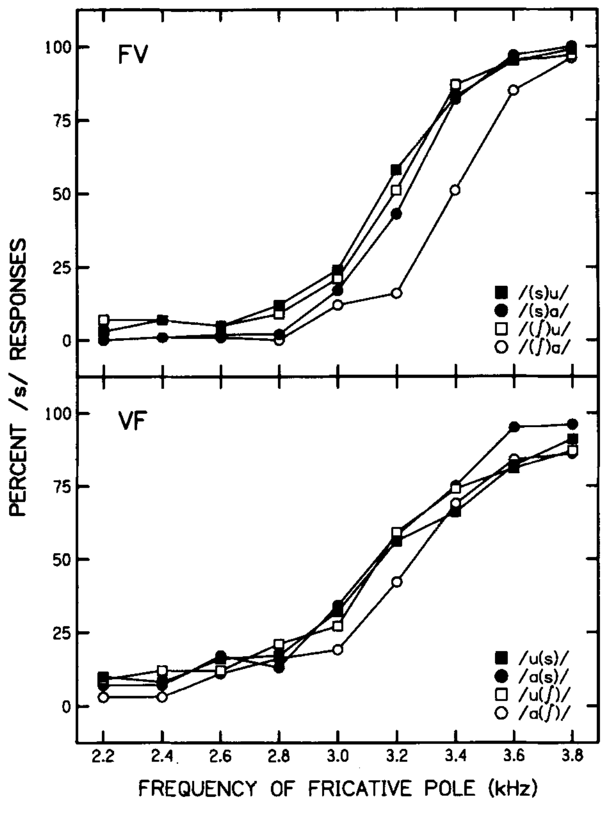

Figure 7. Seven-year-olds' labeling functions for Experiment 2, with the stimuli played in reversed order.

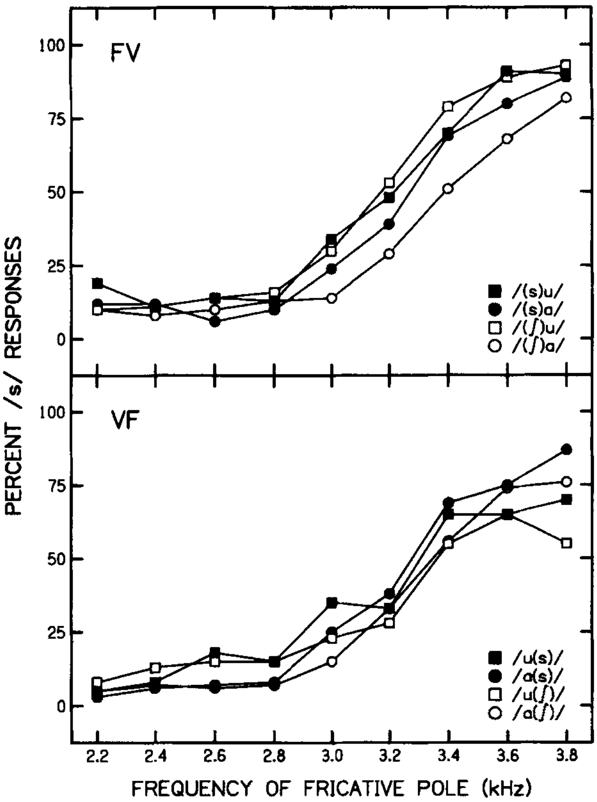

Figure 8. Five-year-olds' labeling functions for Experiment 2, with the stimuli played in reversed order.

for a particular stimulus set were used in the computation of the descriptive statistics for that set. However, for the simple effects analysis reported in Table 6, only data from the four 5-year-olds who completed all four conditions were used.

The most important finding from these data is that 5-year-olds demonstrated a pattern of vowel effect differences across conditions opposite to that which they demonstrated in Experiment 1. That is, their vowel effect was greater for FV than for VF syllables in this experiment. This result is supported by the significant vowel × condition interaction.[1] As was found for the two groups of older listeners, 5-year-olds showed a significant transition × vowel interaction for phoneme boundaries. Unlike the older listeners, however, 5-year-olds showed a significant three-way interaction, transition × vowel × condition. This interaction probably reflects the fact that 5-year-olds did not show the same vowel effect for stimuli with /s/ and /ʃ/ transitions, for both conditions. Whereas 7-year-olds and adults demonstrated greater vowel effects for stimuli with /ʃ/ than with /s/ transitions, regardless of whether segmental order was FV or VF, 5-year-olds showed this pattern only in the case of FV syllables. For VF syllables, the vowel effect was similar (and quite negative) across stimuli with both /ʃ/ and /s/ transitions.

No significant effects or interactions were found for the 5-year-olds' slopes.

Discussion

The goal of this experiment was to investigate whether the order effects observed in Experiment 1 were due to perceptual or acoustic asymmetries. It was hypothesized that response patterns should be similar to those of Experiment 1, if adults and, to some extent, 7-year-olds modify their perceptual strategies on the basis of segmental order. Across FV and VF syllables, adults' response patterns for this experiment resemble those of Experiment 1 in only one way: Vowel effects were larger for FV than for VF syllables. This result, which is modest because the effect was not significant in the first experiment, adds some support to the suggestion that mature listeners modify their perceptual weighting strategies on the basis of segmental order, using information available in the vocalic portion of the syllable to judge fricative identity to a greater extent when the fricative precedes rather than follows the vowel. However, transition effects for the reversed FV syllables were not nearly as large as those for the original FV syllables. At first, this finding seems to indicate that adults' weighting strategies are not modified according to segmental order. Instead, we suggest that this finding indicates that weighting strategies are constrained by the amount of acoustic information available. Formant transitions provided less information about fricative place of constriction in these natural VF syllables than in the FV syllables, and so the reversed FV syllables (which were originally VF syllables) could not provide as much information as the original FV syllables had. Even perceptual strategies that weight formant transitions considerably cannot recover information that simply is not there. On the other hand, adults showed greatly reduced transition effects for the VF syllables in this second experiment, as compared with the effects shown for FV syllables in Experiment 1, even though the same amount of information was available. Thus, we conclude that adults were not attending to this rich source of information in the reversed VF syllables. This finding strongly bolsters the suggestion of a perceptual asymmetry across syllable types offered by Mann and Soli (1991) for adults. Finally, adults demonstrated steeper functions for the FV than for the VF syllables in this second experiment, a cross-condition finding that is opposite to that of Experiment 1. With the attenuation of information available from formant transitions in the FV syllables, adults apparently turned their attention to the noise spectra more than they had in Experiment 1, where formant transitions were more informative in FV syllables.

The 5-year-olds in this second experiment produced a response pattern that suggested that young children largely maintain the same perceptual weighting strategies, regardless of segmental order. It had been predicted that 5-year-olds would show greater vowel effects for FV than for VF syllables in this second experiment, if they continued to weight formant transitions as a primary source of information about fricative place of constriction. That is precisely what was found. Although the transition effect did not differ in magnitude across the two conditions, for VF syllables it was nearly twice as large as that observed for adults and 7-year-olds. Thus, it seems fair to conclude that, to a large extent, these youngest listeners were basing their phonetic decisions on this source of information for these reversed VF syllables. As in the first experiment, 7-year-olds demonstrated a response pattern developmentally intermediate between those for 5-year-olds and adults.

The finding that 5-year-olds and adults demonstrated vowel effects that are similar in magnitude for the reversed FV syllables requires examination because it seems to conflict with recent claims (Nittrouer & Miller, 1997b) that adults assign most of the variability in formant frequencies at voicing onset (in FV syllables) to vowel production and children assign most of the variability to fricative production. In fact, this similarity in results is commensurate with that suggestion. The largest vowel effects for both adults and 5-year-olds for these reversed syllables were found for stimuli with /ʃ/, rather than /s/, transitions, and so the discussion will focus on those stimuli. Children would demonstrate a vowel effect for these stimuli if they followed the perceptual rule that a low *F*2 at the edge of voicing specifies an adjacent /s/ and a high *F*2 specifies an adjacent /ʃ/: *F*2 at voicing offset is 100 Hz lower for the original /u(ʃ)/ than for /ɑ(ʃ)/. For adults, the suggestion is that they attribute a high *F*2 at the edge of voicing in natural FV syllables to /u/ and a low *F*2 to /ɑ/. By attributing some of the "high" quality of *F*2 in fricative–/u/ to vowel production, the effective frequency of the formant is rendered lower, and so the probability of a "sh" response is decreased. Similarly, if some of the "low" quality of *F*2 at in natural FV syllables voicing onset for fricative–/ɑ/ is attributed to vowel production, the effective frequency of the formant is rendered higher, and the probability of responding "s" is decreased. Consequently, a stimulus with the same fricative noise but different vowels would receive more "s" labels in the context of /u/ and more "sh" labels in the context of /ɑ/. For these reversed FV syllables, *F*2 is lower in fricative–/u/ than in fricative–/ɑ/ anyway, and so the predicted vowel effect clearly should be found for adult listeners, and it was.

GENERAL DISCUSSION

The overall goal of this study was to examine whether children modify perceptual weighting strategies on the basis of the order of phonetic segments within syllables and, if so, whether these changes mirror changes in adults' weighting strategies across within-syllable segmental order. Looking first at adults' responses, the combined results of Experiments 1 and 2 were not exactly what we predicted and did not completely replicate the findings of Mann and Soli (1991). Nonetheless, these results generally support the claim of Mann and Soli that adults modify their perceptual weighting strategies across changes in segmental order: Adults pay less attention to information provided by the vocalic portion of the syllable regarding fricative place of constriction when the syllables are VF than when they are FV. In fact, these effects were quite striking, particularly for FV syllables played in their original order and then in reversed order. The transition effect was only 15% as large when these stimuli were played as VF, rather than as the original FV, syllables (69 vs. 470 Hz). We know that the information provided by these formant transitions is considerable and available to adults because the transition effects observed for the original FV syllables were substantial. However, adults must largely ignore (perceptually) this information when these same syllables are played in reverse order. We know from the formant frequencies displayed in Table 1 that little information about place of fricative constriction is generally provided by *F*2 and *F*3 in VF syllables. Through years of experience with such syllables, listeners apparently learn to turn their perceptual attention away from these syllable-final formant transitions. Then, even when information is made available in these transitions, listeners fail to use it because of the perceptual strategies they have developed. In summary, the combined results for adults in Experiments 1 and 2 generally confirm the claims of Mann and Soli: Adults modify perceptual weighting strategies as a function of segmental order.

Of course, we did find one result for adults' labeling that conflicted with the results of Mann and Soli (1991). For the reversed stimuli, they found that adults showed greater transition effects for FV than for VF syllables. We did not. Most likely, this discrepancy in perceptual results across studies is due to the difference in the acoustic structure of the stimuli in the two studies. Mann and Soli used stimuli that did not differ in transition extent for the FV and VF syllables. Therefore, when they played their VF syllables in reversed order, there was as much information available about place of fricative constriction as in the original FV syllables. We suggest that the acoustic asymmetry of our stimuli is probably more typical of natural speech; otherwise, there is no explanation for the perceptual asymmetry reported by both Mann and Soli and by us. Our specific suggestion is that adults have learned not to look to the vocalic portion of the syllable for information about fricative identity in VF syllables because no information is usually available. If information about fricative identity were commonly available in the vocalic portions of VF syllables, there would be no reason for the learned ignoring that both Mann and Soli and we report for adults. Of course, more empirical data will be needed to evaluate what the typical acoustic structure of VF syllables is. In the meantime, our casual observation of speech samples suggests that VF syllables generally lack information about place of fricative constriction. Furthermore, G. G. Weismer (personal communication, October 15, 1998) reports that only 20%–30%

of the VF syllables examined in his laboratory show differences in offset transitions as a function of the place of fricative constriction.

The strongest evidence regarding whether children modify their perceptual weighting strategies as a function of segmental order comes from the measured vowel effect of 5-year-olds across experiments. In earlier experiments of fricative labeling with FV syllables, young children have shown greatly attenuated vowel effects (as compared with adults). In fact, at times children between 3 and 5 years of age have even demonstrated a *reversed* vowel effect, such as we found in the second experiment for VF syllables—that is, more "s" responses to /ɑ/ than to /u/ stimuli (Nittrouer & Miller, 1997b; Nittrouer & Studdert-Kennedy, 1987). Consequently, it was initially a surprise when 5-year-olds showed an enhanced vowel effect for the original VF syllables, as compared with the FV syllables. Examination of the spectrograms (Figures 1 and 2) and of the formant offset frequencies (Table 1), however, indicates that a strategy of responding "sh" to syllables with high $F2$ frequencies at voicing offset and responding "s" to syllables with low $F2$-offset frequencies would produce this result. The alternative hypothesis was that, when labeling VF syllables, children invoke the strategy that adults use for FV syllables of attributing a large proportion of the variability in $F2$ and $F3$ at voicing edge to vowel quality. However, two facts argue against that conclusion. First, the vowel-related differences in formant frequencies present for FV syllables simply are not present in VF syllables. Second, children demonstrated similar vowel effects when the VF syllables of Experiment 1 were played in reversed order (as FV syllables), providing support for the notion that 5-year-olds adhere to the same perceptual strategies regardless of segmental order. This strict adherence to a perceptual strategy led to different effects across FV and VF syllables for these young listeners. In fact, the *reversed* vowel effect observed with children for the reversed VF stimuli supports the suggestion. For both /s/ and /ʃ/ transitions (in the original FV syllables), $F2$ is lower for /ɑ/ than for /u/, which would lead to more "s" responses, if the rule were followed that lower $F2$ frequencies specify /s/ constrictions. By 7 years of age, however, children are apparently starting to learn how the amount of information available from the vocalic portion of the syllable usually differs with segmental order, and to adjust their weighting strategies accordingly.

The results of these two experiments allow us to adjust our model of developmental changes in perceptual weighting strategies. As was described in the introduction, earlier work has suggested that children's weighting strategies shift gradually through childhood to allow better access to phonetic structure. It is likely that some kinds of acoustic properties (e.g., shapes of noise spectra) provide better access to articulatory/phonetic detail, such as location and shapes of consonantal constrictions, than do other kinds of acoustic properties (e.g., formant transitions). However, the amount of phonetic information provided by any one acoustic property varies, depending on phonological structure. According to studies such as Dorman et al. (1977) and Mann and Soli (1991), mature listeners can tune their perceptual attention to take advantage of how phonetic informativeness commonly varies across phonological structure in their native language. The present experiments suggest that young children's perceptual weighting strategies are rigid, in the sense that they are not sensitive to how available information usually changes with changes in phonological structure, such as segmental order. We may speculate, then, that another developmental change in children's perceptual weighting strategies is that they become more flexible, changing according to how the native language structures the acoustic signal as a function of such factors as segmental order.

In conclusion, in this study we examined whether children modify their perceptual weighting strategies according to segmental order within syllables, as adults do. In labeling experiments, adults show substantial effects of the information available in the vocalic portion of the syllable on decisions of fricative identity for FV syllables, but they largely ignore that information for labeling of fricatives in VF syllables. The youngest children in this study showed an inflexible perceptual strategy, responding similarly to the same acoustic information regardless of segmental order. Thus, flexibility in perceptual weighting strategies is apparently a skill that emerges through experience with a language, and 5-year-olds have not yet had enough experience, at least for fricative labeling, to show this kind of flexibility.

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NOTE

1. As a check, the simple effects analysis reported in Table 6 was also conducted with group means entered as phoneme boundaries for each child for those sets that were not completed. That is, the phoneme boundaries actually obtained from the child were used for most sets, with the group mean entered for the (usually one) set (or sets) in which the endpoint criteria were not met for training or testing. The only difference this procedure made to the results was that the vowel × condition interaction had a more significant *F*-ratio for 5-year-olds [$F(1,32) = 6.42, p = .016$] and for adults [$F(1,32) = 4.77, p = .037$] than it did when only data from the four 5-year-olds completing all four sets were used.

APPENDIX A
Mean Phoneme Boundaries (in Hertz; With Standard Deviations) for the FV Stimuli and for the VF Stimuli Presented in the Original Order (Experiment 1)

	5-Year-Olds		7-Year-Olds		Adults	
	M	*SD*	*M*	*SD*	*M*	*SD*
/(s)u/	2870	343	2966	207	2858	308
/(s)ɑ/	2833	374	3100	235	3057	236
/(ʃ)u/	3430	187	3419	223	3295	139
/(ʃ)ɑ/	3577	310	3618	442	3559	303
/(u)s/	2983	158	3129	219	3094	114
/(ɑ)s/	3202	225	3203	176	3152	114
/(u)ʃ/	3032	173	3145	188	3102	135
/(ɑ)ʃ/	3254	214	3322	216	3274	155

APPENDIX B
Mean Slopes (With Standard Deviations) for the FV Stimuli and for the VF Stimuli Presented in the Original Order (Experiment 1)

	5-Year-Olds		7-Year-Olds		Adults	
	M	*SD*	*M*	*SD*	*M*	*SD*
/(s)u/	2.93	1.31	3.20	1.25	4.26	1.82
/(s)ɑ/	2.71	1.42	3.41	1.72	3.81	1.65
/(ʃ)u/	3.19	1.31	3.57	0.97	4.43	1.21
/(ʃ)ɑ/	2.23	1.04	2.77	1.70	3.25	1.46
/(u)s/	2.71	0.95	3.56	1.95	4.33	1.71
/(ɑ)s/	2.91	1.49	2.74	1.51	4.52	1.60
/(u)ʃ/	2.55	0.92	3.67	1.83	4.33	1.48
/(ɑ)ʃ/	2.78	1.38	2.88	1.55	4.32	1.28

APPENDIX C
Mean Phoneme Boundaries (in Hertz; With Standard Deviation) for the FV Stimuli and for the VF Stimuli Presented in the Reversed Order (Experiment 2)

	5-Year-Olds		7-Year-Olds		Adults	
	M	*SD*	*M*	*SD*	*M*	*SD*
/(s)u/	3129	179	3121	123	3143	85
/(s)ɑ/	3219	204	3208	106	3228	79
/(ʃ)u/	3110	112	3132	113	3125	88
/(ʃ)ɑ/	3503	512	3316	199	3386	118
/(u)s/	3378	389	3150	388	3200	158
/(ɑ)s/	3325	320	3092	269	3169	159
/(u)ʃ/	3524	460	3130	357	3236	188
/(ɑ)ʃ/	3453	406	3252	255	3266	144

APPENDIX D
Mean Slopes (With Standard Deviations) for the FV Stimuli and for the VF Stimuli Presented in the Reversed Order (Experiment 2)

	5-Year-Olds		7-Year-Olds		Adults	
	M	*SD*	*M*	*SD*	*M*	*SD*
/(s)u/	2.15	1.18	3.90	1.63	5.54	1.12
/(s)ɑ/	2.70	1.40	4.18	1.46	5.27	1.14
/(ʃ)u/	2.46	1.57	3.33	1.31	5.34	1.34
/(ʃ)ɑ/	1.99	1.21	3.01	1.10	4.63	0.82
/(u)s/	1.59	0.31	2.96	1.71	3.86	1.70
/(ɑ)s/	3.13	1.70	3.16	1.41	3.67	1.53
/(u)ʃ/	1.56	0.78	2.70	1.63	3.46	1.53
/(ɑ)ʃ/	2.46	1.12	2.71	0.78	3.35	1.53

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