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Boundary alignment enables 11-month-olds to segment vowel initial words from speech*

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ABSTRACT

Past research has indicated that English-learning infants begin segmenting words from speech by 7·5 months of age (Jusczyk & Aslin, 1995). More recent work has demonstrated, however, that 7·5-month-olds' segmentation abilities are severely limited. For example, the ability to segment vowel-initial words from speech reportedly does not appear until 13·5 to 16 months of age (Mattys & Jusczyk, 2001; Nazzi, Dilley, Jusczyk, Shattuck-Hufnagel & Jusczyk, 2005). In this paper, we report on three experiments using the Headturn Preference procedure that investigate both phonetic and phonological factors influencing 11-month-olds' segmentation of vowel-initial words from speech. We replicate earlier findings suggesting that infants have difficulty segmenting vowel-initial words from speech. In addition we extend these findings by demonstrating that under certain conditions, infants are capable of segmenting vowel-initial words from speech at a much younger age than earlier studies have reported. Our findings suggest that infants' ability to segment vowel-initial words from speech is tightly constrained by acoustic-phonetic factors such as pitch movement at the onset of vowel-initial words and segmental strengthening. These

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experiments underscore the complexity of early word segmentation, and highlight the importance of including contextual factors in developmental models of word segmentation.

INTRODUCTION

Despite the lack of fully reliable cues to word boundaries in fluent speech, adults effortlessly hear utterances in their native language as a string of discrete words. This ability to extract words from speech is dependent on language experience, as is demonstrated by our difficulties in identifying word boundaries when we listen to an unfamiliar language. Yet, word segmentation is an important task for infants, as evidenced by recent work that shows that word segmentation is highly correlated with other tasks in language acquisition, such as acquisition of vocabulary and even grammar (Newman, Bernstein Ratner, Jusczyk, Jusczyk & Dow, 2006). The ways by which infants first learn to solve the word segmentation problem is a topic that has received a great deal of attention during the past ten years. Although some data support the idea that English-learning infants begin the task of word segmentation by 7·5 months (Jusczyk & Aslin, 1995), if not before under certain circumstances (Bortfeld, Morgan, Golinkoff & Rathbun, 2005), it is has become clear that early word segmentation cannot be viewed as a monolithic task. Rather, the infant learner treats various word classes (nouns and verbs), phonological structures (CVCV and VCVC), and prosodic structures (iambic and trochaic) differentially. For example, recent evidence indicates that while trochaic consonant-initial nouns are extracted by 7·5 months, iambic consonant-initial nouns are not extracted until 10·5 months (Jusczyk, Houston & Newsome, 1999). Extraction of verbs lags dramatically behind nouns, such that consonant-initial verbs are not reliably segmented until 13·5 months, with vowel-initial verbs not being segmented until 16·5 months (Nazzi *et al.*, 2005).

Nazzi *et al.* (2005) hypothesize that differences in the prosodic context surrounding nouns and verbs may explain why younger infants have more difficulty segmenting verbs from speech. If this is the case, it certainly is not the only example of how contextual factors can impact infants' segmentation abilities. The exact same word can be more or less difficult to segment depending on a wide variety of factors, such as the familiarity of the words that flank the target word (Bortfeld *et al.*, 2005), register (infant-directed (IDS) or adult-directed (ADS); Thiessen, Hill & Saffran, 2005), positioning within an utterance (Seidl & Johnson, 2006), presence versus absence of accompanying visual information (Hollich, Newman & Jusczyk, 2005), number of repetitions within a short period of time (Seidl & Johnson, 2006; Thiessen *et al.*, 2005), as well as the presence of overlapping speech

(Hollich *et al.*, 2005). The importance of these contextual factors is often downplayed in models of infant word segmentation, which can give the impression that the development of word segmentation proceeds in a straightforward manner with distinct milestones clearly achieved at specific ages. However, the relatively unexplored likelihood that remains is that at any point in development words of any type may be made easier to segment by manipulating the context within which a word appears (see Bortfeld *et al.*, 2005, for a similar argument). Thus, although it may be accurate to say that young infants find it more difficult to segment vowel- as opposed to consonant-initial nouns from speech, it is quite possibly unjustified to say that infants are incapable of segmenting vowel-initial nouns from speech until long after their first birthday.

As mentioned above, Headturn Preference studies of vowel-initial word segmentation suggest that infants do not begin segmenting vowel-initial words until 13·5 to 16 months. The difficulty infants have in segmenting vowel-initial words from speech may be rooted in a phonological constraint against words of this sort, favoring consonant-initial words over vowel-initial ones (Tesar & Smolensky, 2000). However, the literature consisting largely of developmental studies of some of children's earliest productions contains contradictory evidence concerning the presence of such a hard constraint (Hua & Dodd, 2000). In addition, although many children do demonstrate a tendency to favor simple CV syllables (e.g. [ba] for *bottle*) (Fikkert, 1994), there is clear evidence that, nonetheless, VC syllables exist in their vocabularies. For example, not only is *up* a highly common word in the early vocabulary of many English-learning infants, but many 15-month-olds (33%) also produce words such as *eye* (Dale & Fenson, 1996) at an age that seems to precede reliable vowel-initial word segmentation. Similarly, Grijzenhout & Joppen-Hellwig (2006) point to VC words as some of children's earliest productions. In short, if infants possess a phonological constraint against vowel-initial words, then this constraint must be violable and outranked at the point in development when these words were segmented. Otherwise, exposure to isolated words would provide the only reasonable explanation for the presence of vowel-initial words in children's early utterances. Although there is good reason to believe that words heard in isolation play a role in early word segmentation (Brent & Siskind, 2001), there is also strong evidence that infants are not dependent on hearing words in isolation in order to segment words from speech. For example, infants readily segment novel nonsense words from fluent speech, despite having never heard these words before in isolation (e.g., Johnson, 2005). Thus it is important to explore how these words might appear in their early vocabularies.

Perceptual factors provide an additional explanation for infants' difficulties with segmenting vowel-initial words from speech. For example, the

lack of clear abrupt onsets for vowel-initial words, as well as the tendency for vowel-initial words to undergo resyllabification (e.g., *last hour* becomes *las tower*, Guy, 1991), could make it difficult for infants to perceive the onsets of vowel-initial words. Other factors, such as the susceptibility of vowels to contextual influences and the added time needed to identify vowels in fluent speech, could also serve to hinder the recognition of vowel-initial words in fluent speech (van Ooijen, 1994).

Although there are clearly several good explanations for infants' difficulty in segmenting vowel-initial words from speech, yet another possibility must be considered: It is conceivable, albeit unlikely, that the design of the vowel segmentation studies discussed above masked young infants' ability to segment vowel-initial words from speech. One confound earlier studies have contained is that the target items for infants were a mix of CVC and VC words (Nazzi *et al.*, 2005). If infants have a constraint against vowel-initial words, then any familiarity effects could have been overridden by a preference to listen to the more phonologically acceptable (CVC) words over the less phonologically acceptable (VC) words. Another confound found in earlier studies concerns the phonological similarity between familiarization items and test items. In the study by Mattys & Jusczyk (2001), the stimuli were purposely designed so that the onset of target words never coincided with phrase boundaries. This makes it likely that the vowel-initial familiarization items lacked a strong onset. The test items, on the other hand, were produced in isolation in list format and were therefore almost certainly produced with a strong and perhaps glottalized onset (one with a clear glottal closure). Normally, acoustic-phonetic differences between items produced in passages and items produced in lists pose no problem for infants, since several studies have shown that infants familiarized with consonant-initial words that never occur in utterance initial position readily recognize these same words when tested on them in list format (Johnson, 2005; Mattys & Jusczyk, 2001). However, if the 8-month-olds tested in Mattys & Jusczyk's study had not yet learned that glottal stops are not phonologically distinctive in English, then this could explain why infants failed to show any evidence of an ability to extract the target words from speech. This is highly likely given that recent work suggests that young infants do not yet know which contrasts present in the incoming acoustic stream are relevant phonological contrasts or features of contrasts in their input language. For example, Werker & Tees (1984) show that younger infants are sensitive to all phonemic contrasts yet to be tested, but older 12-month-old infants are not. This sensitivity to non-contrastive variation is relevant for segmentation since findings from Jusczyk & Aslin (1995) show that when just one feature is changed (e.g. the velar to an alveolar in *cup*/*tup*) infants show no evidence of recognizing the word in a similar segmentation task to ours.

Given that one-year-olds have vowel-initial words in their vocabularies, it seems likely that such words, though difficult to segment, can in fact be segmented. In this paper, we report on experiments designed to test the notion that the ability of infants to segment vowel-initial words from running speech may depend on the context in which they appear in such speech. In these experiments, we: (1) attempt to replicate the finding that infants have difficulty segmenting vowel-initial words from speech; and (2) attempt to determine whether infants' difficulty in segmenting vowel-initial words from speech is conditioned by phonetic-perceptual factors.

In order to test whether infants under 13·5 months really have difficulty segmenting vowel-initial words from speech, we tested 11-month-olds' ability to segment vowel-initial words from passages. We controlled for the two possible confounds we mentioned earlier. First, all of our target words were vowel-initial (unlike earlier studies that involved a mix between C- and V-initial target words), and second, during the familiarization phase, all target vowel-initial words occurred at phrase boundaries – low phrase boundaries in one condition and high phrase boundaries (sentence-initially) in the other. This placement ensured that our target vowel-initial words could have been produced as glottalized in both the familiarization and test phase. This meant, in turn, that if the infants we tested failed to segment vowel-initial words, that failure could not be attributed to either a preference for vowel- as opposed to consonant-initial words, or infants' inability to recognize that glottal stops are not phonemic in English.

The second issue we address in this study is whether or not contextual factors affecting perceptual saliency play an important role in infants' ability to segment vowel-initial words from speech. A large body of evidence has shown that speech segments are realized more fully when they are aligned with a strong as opposed to a weak prosodic boundary (e.g. Keating, Cho, Fougeron & Hsu, 2003). For example, vowels which occur at strong prosodic boundaries are more apt to be fully realized (Fougeron & Keating, 1997), to have more glottalization (Dilley, Shattuck-Hufnagel & Ostendorf, 1996), and to be coarticulated with preceding segments to a lesser degree (van Lieshout, Starkweather, Hulstijn & Peters, 1995), and they are less likely to be resyllabified with the preceding consonant. If perceptual factors make it comparatively more difficult for infants to recognize vowel-initial words, then placing vowel-initial words in prosodically salient positions may alleviate infants' difficulties in extracting them from speech. Thus, in the current study, we compared infants' ability to segment vowel-initial words when they were aligned with strong versus weak prosodic boundaries. We reasoned that if infants' difficulty with vowel-initial words were affected by phonetic factors, then the location of the word within the sentence should affect performance.

EXPERIMENT 1

Several studies have demonstrated that infants have difficulties segmenting vowel-initial words from speech (Mattys & Jusczyk, 2001; Nazzi *et al.*, 2005). In the current experiment, we seek to replicate these results while carefully controlling for possible confounds present in past studies. In addition, we investigate the possibility of a hard constraint against accepting vowel-initial words as viable word candidates. All infants were familiarized to two passages using the same version of the Headturn Preference procedure used in Jusczyk & Aslin (1995). Each passage contained six repetitions of a monosyllabic vowel-initial word. Half of the infants were familiarized with passages containing the target vowel-initial word in sentence-initial position and the other half of the infants were familiarized with passages containing the target vowel-initial word in sentence-medial position. If infants in both the initial and medial familiarization condition orient longer to familiar versus unfamiliar words during the test phase, then this would suggest that infants under a year of age do not have difficulties segmenting vowel-initial words from speech. If, on the other hand, infants in both familiarization conditions fail to segment the vowel-initial words from either medial or initial position, i.e. if they orient equally long to familiar versus unfamiliar words during the test phase, then this would provide evidence in support of the hypothesis that infants possess a hard constraint against accepting vowel-initial words as viable word candidates. A third possibility is that infants only segment vowel-initial words from speech when they are placed in sentence-initial position. This finding would demonstrate that contextual factors may determine how likely infants are to segment vowel-initial words from speech, which in turn would support the hypothesis that perceptual factors play an important role in explaining why infants have been reported to have difficulties in segmenting vowel-initial words from speech. At the same time, this finding would not preclude the possibility that infants learning English also possess at least a bias against onsetless words.

METHOD

Participants

Forty English-learning 11-month-olds from a large Northeastern city were tested (22 males and 18 females). The infants were approximately 11 months old, with a mean age of 0;11.2 (range 0;10.12 to 0;11.15). The data from two additional infants were excluded due to fussiness or parental interference. Parental consent was obtained for all participants. In appreciation for their participation, all infants were given a book and seven dollars for transport to the lab.

Stimuli

Two sets of four passages were recorded in an infant-directed manner by an American-English-speaking female naïve to the purpose of the study. Each passage contained six tokens of a target vowel-initial word: *ash, eeb, eff* or *igg*. In one set of passages, the target word always occurred in sentence-initial position. In the other set, the target word always occurred in sentence-medial position. The passages were matched for length at 15 s each. Examples of the familiarization passages can be found in the Appendix. Although *ash* and *eff* are words of English, they are not listed as being known to children on CDI norms even at 24 months (Fenson, Dale, Reznick, Bates, Thal & Pethick, 1994), thus we expected that infants would treat these as novel word forms. After the passages were recorded, 15 isolated tokens of each target word were recorded by the same speaker. The isolated tokens of each set of words were concatenated into a single wave file. The word lists were matched for length at 15 s each, with approximately 500 ms of silence separating words.

Acoustic analyses of the familiarization stimuli

As mentioned earlier, segments tend to be more fully realized when they are aligned with a strong prosodic boundary. In English, amplitude, pitch, duration and formant structure have all been shown to be exaggerated in sentence-initial position (particularly in IDS; see Cruttenden, 1986, for a summary). In our familiarization passages, the onsets of the medial targets were always aligned with a lower phrase boundary whereas the onsets of the initial targets were always aligned with a clause boundary. Thus, we expected the onsets of our vowel-initial targets to be more fully realized in initial than in medial position. In addition, we expected a strong pitch change to mark the onset of the initial targets. This is precisely what our acoustic measurements revealed.

In Table 1, we report the amplitude of the target word, pitch change from the vowel of the preceding word to the vowel of the target word, the duration of the vowel in the target word, and the amount of glottalization at the onset of the vowel-initial word. The amount of glottalization on initial words was determined by measuring the region from the first irregular glottal pulse to the first regular period, essentially where voicing for the vowel began. Many of the measurements of the glottalization on the sentence-medial vowels was similar to measuring those in initial position, e.g. after a stop (although, at times, the boundary between the two sounds was unclear). This occurred most often when the vowel-initial word was preceded by a vowel or glide-final word. When the boundary was unclear, we looked for the longest distance between glottal pulses and began our measurements at this point and ended our measurements once we saw the

TABLE 1. *Average acoustic measurements for sentence-initial, sentence-medial and sentence-final onsetless words*

	Glottalization average	Amplitude average	Pitch change average	Syllable length average
Initial	0·028 s	72 db	291 Hz	12 ms
Medial	0·023 s	70 db	97·2 Hz	13 ms
Final	0·024 s	71 db	184 Hz	42 ms

start of a regular waveform and regular glottal pulses. In addition, we also measured both F1 and F2 of the target word vowel (see Figure 1). Although we observed very little difference in the amplitude and duration of the initial versus medial targets, we found that the pitch change and length of glottalization were predictably much greater for the initial than for the medial words. Finally, we saw some evidence that there is more vowel dispersion in the initial vowels than there is in the medial vowels, with all initial vowels being pushed to the periphery, especially with regard to the second formant.

Design

Half of the infants were familiarized with passages containing the target words *ash* and *eeb* (Group 1) and the other half of the infants were familiarized with passages containing the target words *eff* and *igg* (Group 2). Within each of these groups, half of the infants heard passages containing the vowel-initial target word consistently positioned in sentence-medial position (Medial Condition) while the other half heard passages containing the vowel-initial target word consistently placed in sentence-initial position (Initial Condition). All infants were tested on the same four test items: *eff, igg, ash* and *eeb*. Thus, the words that were familiar for the infants familiarized with *eff* and *igg* were unfamiliar for the infants familiarized with *ash* and *eeb*, and vice versa.

Procedure and apparatus

In the Headturn Preference procedure (HPP) the infant sits in the center of the caregiver's lap on a chair in the center of a three-sided booth. A red light and a speaker are mounted on the center of each side panel. A green light is located in the center of the front panel. At the start of a given trial the light on the center panel begins to flash. When the child is facing towards the center light, a light will begin to flash on a side panel. When the infant turns her head toward that light, speech begins to play, and continues

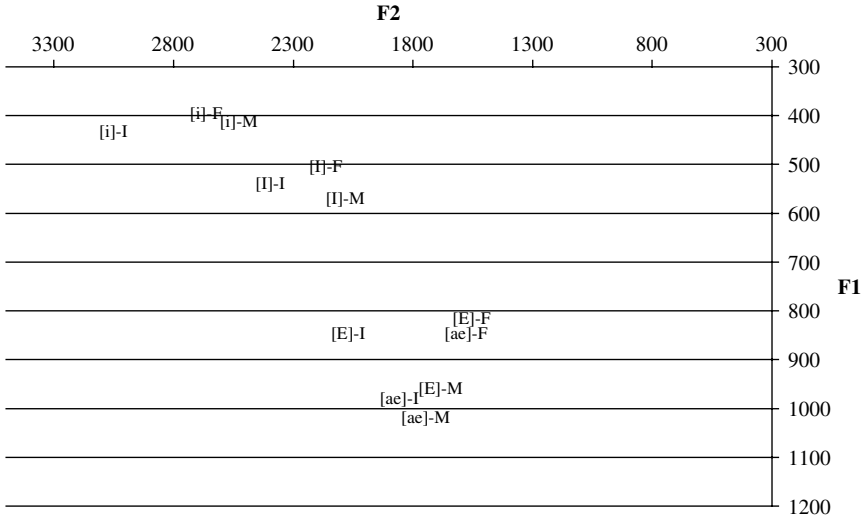

Fig. 1. F1 and F2 plot for sentence-initial, sentence-medial and sentence-final vowel-initial words (I = initial, M = medial and F = final).

to play until she looks away from the light for more than two consecutive seconds. The experimenter observes the infant through a small hole in the booth. A button box is connected to a computer that controls the randomization and presentation of stimuli. The computer also records the duration of the time the infant looks in the direction of the loudspeaker from which each stimulus is emitted (the dependent measure). Both caregiver and experimenter wear sealed headphones and listen to masking music during the course of the experiment. In this use of the HPP there is a familiarization period immediately followed by a test period. In the familiarization period speech is presented until the infant has listened to the two familiarization passages for 45 seconds each. In the test period speech samples are presented which either do or do not contain the target familiarization stimulus. Half of the test trials contained familiar items and half contained unfamiliar items. There were twelve trials presented in three blocks, with trial order randomized within each block.

RESULTS AND DISCUSSION

Mean orientation times towards the direction of the sound source of the stimulus for familiar and unfamiliar test words were calculated for each of the 40 subjects. In the sentence-initial condition 16 of 20 subjects had

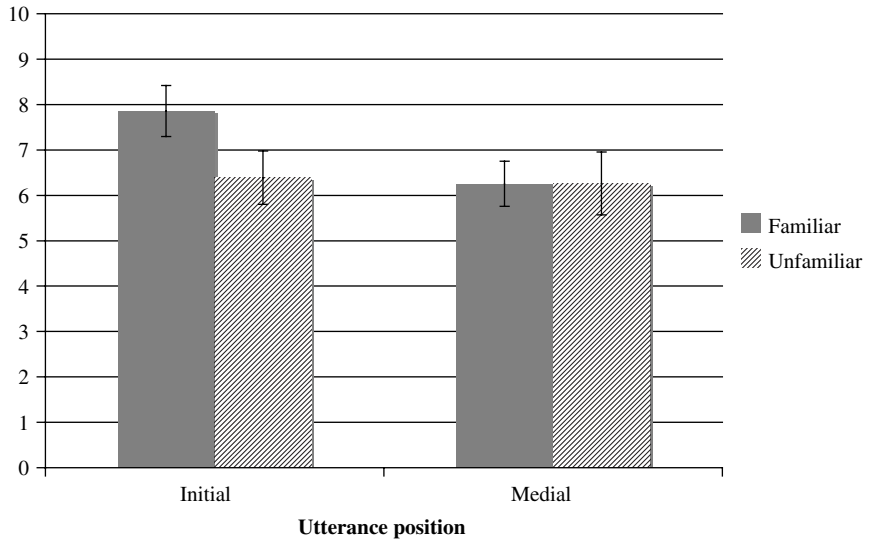

Fig. 2. Vowel-initial words sentence-initially and sentence-medially with bars showing Standard Error.

longer average orientation times for familiar over unfamiliar test items. In the sentence-medial condition 11 of 20 subjects had longer average orientation times for familiar over unfamiliar test items. A mixed-design ANOVA with Group (1 and 2) × Condition (Medial and Initial) × Test item type (Familiar and Unfamiliar) revealed a significant main effect of Group ($F(1,36)=6{\cdot}7$, $p=0{\cdot}013$ ($d=0{\cdot}84$)) and Test item type ($F(1,36)=4{\cdot}24$, $p=0{\cdot}046$ ($d=0{\cdot}67$)) and no effect of Condition ($F(1,36)=1{\cdot}6$, $p>0{\cdot}1$). Crucially, there was an interaction found between Test item type and Condition ($F(1,36)=4{\cdot}32$, $p=0{\cdot}04$ ($d=0{\cdot}67$)) but not for Group and Test item type ($F(1,36)<1$) or Test item type, Group and Condition ($F(1,36)<1$). As Figure 2 illustrates, these effects were attributable to longer orientation times to familiar words ($M=7{\cdot}8$, $SD=2{\cdot}4$) over unfamiliar words ($M=6{\cdot}4$, $SD=2{\cdot}5$) for the words in initial position, but not for the words in medial position.

The results of Experiment 1 show that 11-month-olds can segment vowel-initial nouns from speech when the words are aligned with a strong prosodic boundary, i.e., when they occur sentence initially. However, infants demonstrated no ability to segment words from sentence-medial position. These results provide the first experimental evidence that infants under a year of age can segment vowel-initial words from speech, even though this

only appears to be possible in limited contexts.[1] In addition, it is clear that infants have difficulties segmenting vowel-initial words from speech. Otherwise, they would have easily extracted the target vowel-initial words from both initial and medial positions. Finally, since infants were able to segment words from initial position, they must not possess a hard constraint against accepting vowel-initial words as viable word candidates. Therefore, this experiment suggests that contextual factors affecting the phonetic realization of vowel-initial words have a strong impact on the likelihood that infants can segment these words from speech.

EXPERIMENT 2

In Experiment 1, we found clear evidence that infants can segment vowel-initial words from speech when those words are located in sentence-initial position. In this experiment, we attempted to determine which phonetic cues might be the most important in enabling infants to segment vowel-initial words from speech. Although we found significant suprasegmental (pitch, amplitude) and segmental (glottalization, vowel dispersion) acoustic cues that presumably made it easier for infants to perceive our initial tokens than our sentence-medial ones, it could be the case that these cues alone do not account for the differences in the findings for medial and initial words. Perhaps the most parsimonious explanation for infants' ability to segment sentence-initial vowel-initial words is that these words are in a sense pre-segmented since the target words in the sentence-initial condition of Experiment 1 were preceded by a longer pause than the sentence-medial words. (Pauses between sentences were an average of 410 ms with a range of 300 ms to 560 ms.) Thus, it is likely that this pause may have facilitated segmentation. In this experiment, we tested whether this pause was a necessary acoustic cue driving infants' ability to segment vowel-initial words from speech by removing all the pauses between the sentences in the sentence-initial familiarization set from Experiment 1. All other aspects of this experiment were identical to Experiment 1. If infants fail to segment the vowel-initial words in this experiment, then this suggests that pause duration is a necessary perceptual cue enabling infants to segment the sentence-initial vowel-initial words in Experiment 1. If, on the contrary, they succeed in segmenting the words despite the lack of pauses, we take this as evidence that for infants cues other than pause, such as pitch reset,

[1] One alternative explanation for this pattern of results pointed out by an anonymous reviewer might be that medial vowel-initial words are in fact easier to segment than sentence-initial ones and that we find no preference with these words because infants are transitioning between a novelty and familiarity preference. Though consistent with our data, we find this unlikely, given that even experienced infants and adults have difficulty in extracting sentence-medial words (Golinkoff & Alioto, 1995; Seidl & Johnson, 2006).

degree of glottalization or vowel dispersion, are sufficient to segment vowel-initial words from initial position.

METHOD

Participants

Twenty English-learning 11-month-olds from a Midwestern university town were tested (10 males and 10 females). The infants were approximately 11 months old, with a mean age of 0;11.3 (actual range 0;10.21 to 0;11.21). The data from four additional infants were excluded due to fussiness and the data from two additional infants were excluded because their difference scores on the task were more than three standard deviations off the mean. Parental consent was obtained for all participants. In appreciation for their participation, all infants were given a book and a ''sippy cup'' for coming into the lab.

Procedure and apparatus

A replica of the procedure and apparatus used in Experiment 1 was used to conduct this experiment.[2]

Stimuli

The familiarization stimuli differed from Experiment 1 only in that all pauses were excised at sentence boundaries before the target words. To remove the pauses we excised all silence between words that was greater than 60 ms. Thus, we made all pauses approximately equal to the duration of pauses between words with no syntactic boundary. The test words and lists were the same as those used in the sentence-initial condition of Experiment 1.

RESULTS AND DISCUSSION

Mean orientation times for familiar and unfamiliar test words were calculated for each of the 20 subjects. Fifteen of 20 subjects had longer average orientation times for familiar over unfamiliar test items. An ANOVA on Group (1 and 2) × Test item type (Familiar and Unfamiliar) revealed a significant main effect of Test item type ($F(1,18)=11{\cdot}06$, $p=0{\cdot}004$ ($d=1{\cdot}57$)) and no effect of Group ($F(1,18)=1{\cdot}3$) and no interactions. As Figure 3 illustrates, these effects were attributable to longer orientation

[2] The same equipment was used as in Experiments 1 and 2 except that we used a newly constructed three-sided booth.

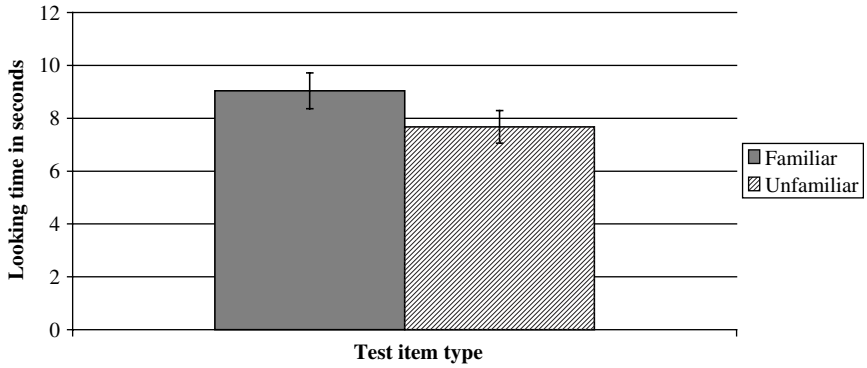

Fig. 3. Vowel-initial words sentence-initially with all inter-sentential pauses removed.

times to familiar words ($M = 9{\cdot}04$, $SD = 3{\cdot}04$) over unfamiliar words ($M = 7{\cdot}77$, $SD = 2{\cdot}76$).

These results indicate that, regardless of the duration of the pause, infants are able to segment vowel-initial words from sentence-initial position. This means that pause duration alone is not a sufficient explanation for the difference between infants' segmentation of initial and medial vowel-initial words. We conclude that pause cues are not necessary for infants to segment sentence-initial words and that the infants must be able to rely upon other cues in segmenting these vowel-initial words, and that these cues are not present (or are weaker) in sentence-medial position. Vowels in sentence-initial position are less likely to be reduced (e.g., Fougeron & Keating, 1997; van Lieshout *et al.*, 1995) or coarticulated with the previously-occurring segment, and the glottalization preceding them may be less likely to be identified as 'belonging' to a preceding vowel exhibiting word-final glottalization (e.g., an ambisyllabic glottalized sound). In addition, words at sentence boundaries are more likely to be marked with pitch resets as found in our stimuli. Given that we found greater use of all of these cues on vowels in sentence-initial position (see Table 1 and Figure 1), it seems reasonable to conclude that these cues are the driving force behind infants' ability to segment vowel-initial words from sentence-initial position.

EXPERIMENT 3

As the stimulus section of Experiment 1 demonstrates, there are many potential cues marking the edges of vowel-initial words in sentence-initial position as distinct from those in sentence-medial position. In Experiment 2 we showed that pause is not a necessary cue for the segmentation of vowel-initial words from sentence-initial position. Infants' non-dependence on

pause fits in well with related findings from the segmentation of clauses and phrases from continuous speech (Seidl, 2007; Soderstrom, Seidl, Kemler Nelson & Jusczyk, 2003). In this experiment, we examined whether it is only the presence of enhanced cues from sentence-initial position that make vowel-initial words easier to segment, or whether the enhanced cues from sentence-final position also make it easier for infants to segment these difficult to segment words. The cues present on sentence-final target words are crucially distinct from those in sentence-initial position because the beginning of the word, in this case, is not aligned with an utterance boundary. However, we know that words are in many ways more salient when they are in final position. Indeed, it has been hypothesized that infants find it easier to segment words from clause-final than from any other sentence position (Aslin, Woodward, LaMendola & Bever, 1996; Slobin, 1973) and evidence suggests that attention to the ends of units persists into adulthood (Golinkoff & Alioto, 1995). Thus, we are properly prepared to ask whether easier segmentation results from mere alignment with a boundary or if alignment with an initial boundary is required. In this experiment we placed all target words utterance-finally and once again examined their segmentation. Given that utterance-final words tend to undergo significant preboundary lengthening (Cooper & Paccia-Cooper, 1980; Klatt, 1975; Wightman, Shattuck-Hufnagel, Ostendorf & Price, 1992) and that often words placed in this position bear sentential pitch accents (Cinque, 1993) lending to perceptual prominence, we expect to once again find successful segmentation.

METHODS

Participants

Twenty English-learning 11-month-olds from a Midwestern university town were tested (9 males and 11 females). The infants were approximately 11 months old, with a mean age of 0;11.0 (actual range 0;10.15 to 0;11.12). The data from four additional infants were excluded due to fussiness. Parental consent was obtained for all participants. In appreciation for their participation, all infants were given a book or a toy for coming into the lab.

Procedure and apparatus

The same procedure and apparatus was used as in Experiment 2.

Stimuli

The familiarization stimuli differed from those in Experiments 1 and 2 only in the placement of the target word. This time all targets occurred in

sentence-final position. Examples of these sentences may be found in the Appendix. The test words and lists were those used in Experiment 1. The stimuli were recorded by the same speaker as they were in Experiment 1.

Acoustic analyses of the familiarization stimuli for Experiment 3

Once again we measured amplitude, change in pitch, syllable length and vowel dispersion (see Table 1 and Figure 1). In addition, we measured the amount of glottalization in these sentence-final words in the same manner as was done in Experiment 1. There were three important differences between the measurements made here and those made in the earlier experiment. First, we found less change in f0 in the sentence-final words than in those in sentence-initial position, but approximately double the magnitude of change in f0 in sentence-final position as there was in sentence-medial position. This large change in f0 is predictable given that the words measured at the sentence end often bear the nuclear pitch accent for the sentence (Cinque, 1993), and it is expected that words with nuclear pitch accent will be acoustically marked. While there was little change in the amount of glottalization, there was a slight shift in both F1 and F2, such that there appears to be slightly less vowel dispersion in the sentence-final targets than in the sentence-initial targets, but still a greater amount than in sentence-medial target vowels (see Figure 1). Finally, and most markedly, there was a large difference in vowel duration, such that sentence-final vowels undergo significant lengthening preceding the sentential boundary.

RESULTS AND DISCUSSION

Mean orientation times for familiar and unfamiliar test words were calculated for each of the 20 subjects. Fifteen of 20 subjects had longer average orientation times for unfamiliar over familiar test items. An ANOVA on Group (1 and 2) × Test item type (Familiar and Unfamiliar) revealed a significant main effect of Test item type ($F(1, 18) = 4{\cdot}7$, $p = 0{\cdot}041$ ($d = 1{\cdot}02$)), no effect of Group ($F(1, 18) < 0{\cdot}3$) and no interactions. As Figure 4 illustrates, these effects were attributable to longer orientation times to unfamiliar words ($M = 6{\cdot}48$, $SD = 2{\cdot}4$) than to familiar words ($M = 5{\cdot}46$, $SD = 2{\cdot}1$).

Infants clearly show a difference in their looking to familiar and unfamiliar test items. Thus infants were able to segment the target words from sentence-final position. Unexpectedly, infants exhibited a novelty preference for unfamiliar words rather than familiar words. The most logical explanation for this is that extracting words from sentence-final position was easier for the infants than extracting the words from initial position. Switches in preference from familiarity to novelty due to increases in task complexity are well documented in the developmental literature (e.g.,

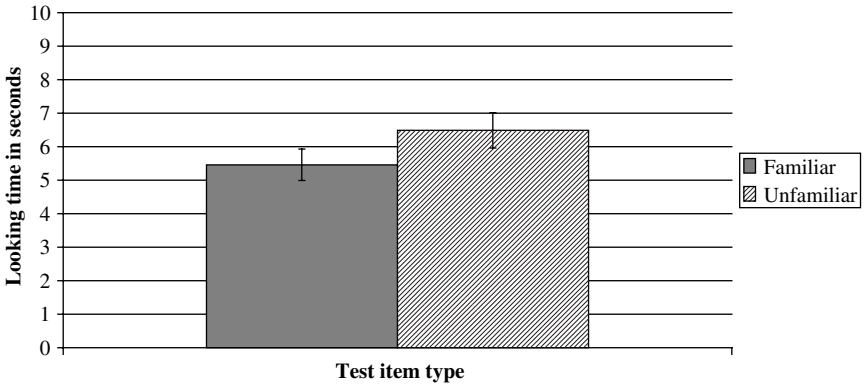

Fig. 4. Vowel-initial words sentence-finally.

Hunter & Ames, 1988; Thiessen *et al.*, 2005). Thus, it may be that infants begin the task of segmenting vowel-initial words in sentence-final position, moving next to sentence-initial position and finally to sentence-medial position. Given that infants at 11 months displayed a novelty preference in segmenting vowel-initial words in sentence-final position it may be that even younger infants are able to segment these words in sentence-final position. For example younger infants may show a familiarity preference for vowel-initial words in sentence-final position, but no recognition for these same words in sentence-initial or sentence-medial positions. Such a finding would fit well with developmental studies arguing that infants attend to the ends of utterances; however it would contradict the intuition that word onsets are crucial for word recognition, and therefore that words aligned with the onsets of sentences should be easier to segment than words aligned with the ends of sentences.

If our interpretation is correct, and the 11-month-olds in Experiment 3 truly found it easier to segment vowel-initial words from final position than initial position, then what acoustic cues could be responsible for this effect? While it is plausible that it was both the large amount of pitch change at the word edge as well as the significant preboundary lengthening of the vowels in these words that led to easier segmentation, an examination of Table 1 makes it appear more likely that the latter cue accounts for the difference between the segmentation of words in this experiment and in the Initial Condition of Experiment 1. The two cues that most strongly differentiate the final tokens from the medial tokens are pitch change and syllable length. Thus, it seems reasonable to suspect that the pitch change at the onset of the words aligned with utterance boundaries is the common driving force that makes utterance-aligned words easier to segment than utterance-medial

words. At the same time, the fact that we observed a novelty preference in Experiment 3 suggests that sentence-final words are easier to segment than sentence-initial words. The one cue that is clearly stronger in sentence-final position than sentence-medial position is syllable lengthening. Thus, it is possible that while large pitch changes make utterance-aligned words easier to segment than sentence-medial words, vowel lengthening makes final position an even easier position from which to segment words. It is also possible that it is the additive cues of pitch and vowel length that make sentence-final vowel-initial word easier to segment. Only further research will help to adjudicate between these different explanations; however, evidence from English-learning infants' segmentation of clausal units suggests that infants weight pitch changes more heavily than they weight vowel duration cues to those unit edges (Seidl, 2007).

GENERAL DISCUSSION

It has been argued that although infants begin segmenting consonant-initial words from speech by 7·5 months of age, the ability to segment vowel-initial words from speech does not become robust until around 16 months of age (Mattys & Jusczyk, 2001; Nazzi *et al.*, 2005). The experiments presented in this paper suggest that infants acquire the ability to segment speech via a protracted process in which a variety of factors, including phonological structure, prosodic structure, word class and sentential position are implicated.[3] Infant learners are resourceful enough to exploit many strategies to extract words from running speech, but recent data suggest that adult-like segmentation skills may take quite a while to develop.

In this study we have confirmed the findings of prior research concerning the general difficulties that infants have in segmenting vowel-initial words from speech while also demonstrating that they are capable of such segmentation at a far younger age than has been reported before. We have shown, then, that it is not necessary for the infant to hear vowel-initial words in isolation in order to explain how highly frequent vowel-initial words enter children's early vocabularies (e.g., *eye* and *apple*). At the same time, however, our research also indicates that younger infants were able to segment vowel-initial words from speech only when we placed target words in a highly salient position, i.e. sentence-initial or sentence-final position. That infants are able to extract vowel-initial words from speech when words were placed in salient positions provides strong evidence against the notion that infants come to the task with a strong phonological constraint against

[3] English has a relatively fixed word order, resulting in the tendency for specific word types to occur in certain sentence positions. Thus, the fact that sentential position affects segmentation may provide an indirect explanation for why some words are easier to segment than others.

accepting vowel-initial words as viable word candidates. In addition, given that utterances are shorter in infant-directed speech, alignment with a boundary may be common enough to enable the infant to extract vowel-initial words relatively easily.

If infants perceive vowel-initial and consonant-initial words as equally good word candidates, then why is the ability to segment vowel-initial words from speech so delayed in comparison with the ability to segment consonant-initial words? The possibility explored here, and supported by evidence from these experiments, is that perceptual factors make vowel-initial words more difficult to recognize in fluent speech. As discussed earlier, vowel-initial words are not marked by the clear abrupt acoustic landmarks affiliated with stop consonants. In addition, as mentioned, vowel-initial words are often resyllabified with preceding consonant-final words and the information identifying vowels is spread out over a much longer time period than the information identifying consonants. Vowels are also highly susceptible to coarticulatory influences from neighboring sound segments, and we know that coarticulatory cues have a strong influence on infants' segmentation behavior (Johnson & Jusczyk, 2001). Thus, it is reasonable to suspect that these and other related factors make the recognition of vowel-initial words difficult for young infants. Indeed, the adult literature reports that listeners process consonants and vowels very differently (van Ooijen, 1994), so it is not unreasonable to suspect that these processing differences could be related to infants' difficulties with segmenting vowel-initial words from speech. Then again, it is also possible that infants do possess a soft constraint or bias against accepting vowel-initial words as viable word candidates. Indeed, given the infants' sensitivity to the typical sound patterns of words in their language, and the much greater frequency of consonant-initial words to vowel-initial words in English, it is possible that infants have a preference for CV over VC word forms. Only additional research will clarify these issues.

Regardless of whether or not infants possess a weak constraint or bias against accepting vowel-initial words as viable word candidates, it is clear that their ability to segment vowel-initial words from speech becomes more robust over the course of development. The ability to segment vowel-initial words is not completely absent prior to 13·5 months, but it is highly constrained by the acoustic-phonetic realization of the target word. Placing vowel-initial words in sentence-initial or sentence-final position facilitates infants' extraction of these words. Thus, it may be that infants' difficulties with vowel-initial words are due primarily to perceptual issues related to recognizing and processing them. If this is the case, then infants' ability to extract vowel-initial words from sentence-initial and sentence-final position is likely driven by phonetic factors present in the speech signal. An interesting implication of these findings is that other word types that are

reportedly difficult for infants to segment might also be possible to segment earlier than the literature reports if the speech signal contained sufficient evidence in favor of the segmentation of these words. For example, English-learning infants under 10·5 months of age reportedly cannot segment non-initially stressed words from speech (Jusczyk *et al*., 1999). However, it may be possible that alignment with an utterance boundary would facilitate early segmentation of iambic words in the same way that alignment with highly familiar words can facilitate segmentation of adjacent words (Bortfeld *et al*., 2005).

At least part of our original puzzle, that despite infants' difficulties with the extraction of onsetless words, infants are able to acquire them sufficiently to produce them at a young age, is solved. Although exposure to isolated words is likely to play a role in early segmentation (Brent & Siskind, 2001), infants clearly can segment vowel-initial words from speech even when they have never heard them in isolation. In Experiment 1, infants segmented onsetless words from speech when they were placed in sentence-initial but not sentence-medial position. Experiments 1, 2 and 3 extended these earlier findings by suggesting that infants are able to segment onsetless words from speech if they are placed in a perceptually salient position, i.e., if they are aligned with the initial or final boundary of an utterance. Infants' ability to segment onsetless words from initial and final, but not medial position, provides support for the hypothesis that, though phonological constraints against onsetless words may exist, perceptual factors play an important role in infants' difficulty in segmenting onsetless words from speech. These results also crucially provide an explanation for the presence of some highly frequent onsetless words in children's early vocabularies (e.g., *eye* and *apple*).

In Experiment 2, we found that infants' ability to extract onsetless words from utterance-initial position persisted even when the pauses between utterances were removed. In combination, these results suggest that perceptual, or acoustic-phonetic, factors play an important role in infants' early difficulties with onsetless words. The difference in perceptual salience of words at high, as opposed to low, syntactic boundaries may be particularly relevant in IDS, given the greater changes in pitch in IDS vs. ADS (Cruttenden, 1986). In particular, pitch changes have been shown in recent work to be particularly helpful in word (Thiessen *et al*., 2005) and clause (Seidl, 2007; Soderstrom *et al*., 2003) segmentation tasks. These phonetic factors may not only serve to make the vowel-initial words at high syntactic boundaries more perceptible to infants, but may also show that segmentation of these words appears at a younger age when these conditions hold. More specifically, given the results of Experiment 2 and 3, acoustic correlates of utterance onsets such as initial strengthening of word onsets, preboundary lengthening, pitch accent and pitch resets at the juncture

between utterances appear to be the most likely perceptual cues enabling infants to spot onsetless words in speech. Our findings for pitch are in line with recent findings which suggest that infants and adults rely very heavily on pitch in segmenting clauses as well as words (Thiessen *et al.*, 2005; Seidl, 2007), suggesting that infants rely heavily on these sorts of suprasegmental cues to segmentation rather than solely on the segmental phonological constraints present in a given word.

A hard phonological constraint against vowel-initial words in infants' grammar would have entailed not only that infants' ability to segment consonant- and vowel-initial words would not be affected by acoustic factors, but also that there would be no difference in performance between sentence-final and sentence-initial vowel-initial words. Given that we did find such distinctions, we conclude that there is no clear evidence that hard phonological constraints contribute to infants' difficulty in segmenting onsetless words from speech. But the fact still remains that children's early productive vocabularies tend to contain far fewer vowel- than consonant-initial words. It is possible that this reflects the input which, in English, contains more consonant- than vowel-initial words. However, it is also possible that motoric development might account for some portion of the discrepancy between production and perception here. Specifically, given that perception, unlike production, is not limited by the development of the vocal tract, different results over each of these domains is to be expected. On this account, despite exceptions mentioned earlier, CV syllables are initially produced by children in their first words, possibly not for any phonological reason, but because, despite the fact that both CV and VC syllables are found in babbling, the production of a word requires more resources than babbling (Heisler, Goffman & Younger, 2004). Thus motoric control may change as a function of lexical status. On this account then it is plausible that CV syllables are preferred word forms because when the child opens his or her mouth (arguably the jaw is the primary articulator in early childhood, Gick, Campbell, Oh & Tamburri-Watt, 2005) while continuously phonating, the result is a CV syllable (MacNeilage & Davis, 1990; Meier, McGarvin, Zakia & Willerman, 1997). Onsetless syllables would be initially more difficult to produce, since presumably following from the idea that continuous phonation results in a CV syllable, a vowel onset would require more control of the timing of phonation since vowels involve a cessation of phonation in the opening mode or preceding the opening mode (MacNeilage & Davis, 1990). This motoric explanation for children's initial preference for producing CV syllables would explain why we find predominantly CV syllables in the early production or words, yet no clear preference for them in perception.

A new avenue of research suggested by our findings, as well as the findings of Thiessen *et al.* (2005), would focus on the role of intonation in infants'

early segmentation strategies. We know infants tune into pitch early in development (in fact newborns use prosody to perceive the differences between languages, Ramus, 2002); therefore, it may be that intonational patterns play an important role in enabling infants to learn the wide array of probabilistic language-specific cues used by adults to segment speech. If intonation really does play a key role in early word segmentation, it may be found not only that onsetless words are easier to segment from IDS as opposed to ADS, given that intonation changes are presumably greater in IDS, but also that if the realization of medial words were manipulated such that they were marked with large pitch changes, they would also be more easily segmented.

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APPENDIX

Familiarization passage for Initial Condition Group 1, Experiment 1:

Eff runs a circus in Toronto.
Eff has no clue about juggling.
Eff hires acrobats to run the show.
Eff wants a town names after him.
Eff would be a tiny little city.
Eff could be located in the hills.

Familiarization passage for Initial Condition Group 2, Experiment 1:

Ash makes me smile in spring.
Ash can stand on his head for hours.
Ash learned to do flips for me.
Ash also loves to cook new food.
Ash named a dish after himself.
Ash is chicken soaked in lime juice.

Familiarization passage for Medial Condition Group 1, Experiment 1:

I like how Eff runs the circus.
I wonder if Eff wants to juggle too.
We know Eff has a great time.
We're sure Eff would love to learn.
I think Eff could do a great job.
They say Eff hires clowns all year.

Familiarization passage for Medial Condition Group 2, Experiment 1:

It seems like Ash is very creative.
I see Ash can stand on his head.
I see that Ash named this dish.
Somehow Ash makes us laugh.
We suspect Ash loves to cook.
I'm sure Ash learned to do flips.

Familiarization passage for Group 1, Experiment 3:

At the silly circus I like low Eff.
It is such bad luck to have a rough Eff.
We'll have to tell her that we know Eff.

The lion tamer knows how to ensure Eff.
The elephants always want to thank Eff.
The clowns start dancing when they say Eff.

Familiarization passage for Group 2, Experiment 3:

This baby giraffe seems creative like Ash.
I'll stand on a chair so I can see Ash.
He isn't nearly as shiny as that Ash.
I'm going to learn how to grow Ash.
We need to be sure to always correct Ash.
It is easy to make food that lures Ash.