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Segmentation of vowel-initial words is facilitated by function words*

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ABSTRACT

Within the first year of life, infants learn to segment words from fluent speech. Previous research has shown that infants at 0;7·5 can segment consonant-initial words, yet the ability to segment vowel-initial words does not emerge until the age of 1;1–1;4 (0;11 in some restricted cases). In five experiments, we show that infants aged 0;11 but not 0;8 are able to segment vowel-initial words that immediately follow the function word *the* [ði], while ruling out a bottom-up, phonotactic account of these results. Thus, function words facilitate the segmentation of vowel-initial words that appear sentence-medially for infants aged 0;11.

INTRODUCTION

By age 0;11, infants can comprehend several vowel-initial words, such as body parts (*arm, ear, eye*) and the verb *eat* (lexical norms of the MacArthur-Bates Communicative Development Inventories: Fenson, Dale, Reznick, Bates, Thal & Pethick, 1994; Bergelson & Swingley, 2012). However, the ability to segment vowel-initial words does not appear until the age of 1;1·5–1;4 (Mattys & Juszcyk, 2001). We investigate this lag between infants' comprehension vocabulary and their segmentation performance to determine the cues that infant might utilize to segment vowel-initial words at an earlier age.

To comprehend and learn new words, infants first need to segment words from fluent speech. Segmenting words from fluent speech is more complicated than it sounds because words are not always separated by silences in fluent speech. Less than 10% of the utterances infants hear consist of isolated

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words (van de Weijer, 1998); and even when mothers are specifically asked to teach their children new words, they produce words in isolation less than 20% of the time (Woodward & Aslin, 1990). Given that word segmentation is difficult but important for language learners, not only to learn words, but also to acquire grammar (Junge, Cutler & Hagoort, 2010; Junge, Kooijman, Hagoort & Cutler, 2012; Newman, Bernstein Ratner, Jusczyk, Jusczyk & Dow, 2006), infants' ability to do so has been investigated extensively for the past decade since the pioneering work by Jusczyk and Aslin (1995).

Numerous studies have looked at possible cues for word boundaries that both adults and infants might use to segment words. Substantial research on adults' spoken word recognition shows that adults use a variety of bottom-up cues, segmental as well as prosodic (e.g. Cutler, Mehler, Norris & Segui, 1986; Mattys, White & Melhorn, 2005; Salverda, Dahan & McQueen, 2003), in addition to top-down cues such as familiar words (e.g. Norris, McQueen & Cutler, 1995; Vroomen & de Gelder, 1995) to recognize words from fluent speech.

Word segmentation studies with infants have primarily explored the role of bottom-up cues – either segmental (e.g. transitional probabilities: Saffran, Aslin & Newport, 1996; phonotactic: Mattys & Jusczyk, 2001; phonological restrictions such as vowel harmony: Mintz & Walker, 2006; coarticulation: Johnson & Jusczyk, 2001; and allophonic variation: Jusczyk, Hohne & Bauman, 1999a) or prosodic (e.g. stress: Jusczyk, Houston & Newsome, 1999b; and clause/phrase boundaries: Gout, Christophe & Morgan, 2004) – and the relative weighting of cues when they conflict (e.g. Johnson & Jusczyk, 2001; Thiessen & Saffran, 2003).

Importantly, most of these studies have focused on infants' segmentation of consonant-initial words. There are a few studies in which segmentation of consonant-initial and vowel-initial words has been compared (Mattys & Jusczyk, 2001; Nazzi, Dilley, Jusczyk, Shattuck-Hufnagel & Jusczyk, 2005), with a focus on explaining why infants show different developmental timelines for the two. For example, Mattys and Jusczyk argue that vowel-initial words lack clear onsets, unlike consonant-initial words, and this might cause infants to favor consonant-initial words over vowel-initial words. As a consequence, infants successfully segment *dice* from a sequence such as *roll dice* at age 0;8·5, but only succeed in segmenting *ice* from sequences such as *cold ice* at 1;4 (Mattys & Jusczyk, 2001).

In the only study focusing on cues that facilitate the extraction of vowel-initial words, Seidl and Johnson (2008) found that infants at the age of 0;11 can segment vowel-initial words when they are placed at the beginnings or ends of sentences. However, when vowel-initial words were embedded in the middle of a sentence where there are no prosodic cues for word onset or offset, infants at age 0;11 failed to segment them.

In addition to bottom-up cues, top-down cues, like the presence of familiar words, are also known to facilitate infants' ability to segment words. Familiar words facilitate word segmentation by cuing the onset or the offset of a novel word. For instance, when presented after familiar content words (i.e. *mommy*, or the child's own name), infants can segment consonant-initial monosyllabic nouns at age 0;6 (Bortfeld, Morgan, Golinkoff & Rathbun, 2005; see also Mersad & Nazzi, 2012; Ngon, Martin, Dupoux, Cabrol, Dutat & Peperkamp, 2013). Without support from familiar words, English-learning infants have been shown to segment consonant-initial monosyllabic nouns only at 0;7·5 (Jusczyk & Aslin, 1995). Thus, even infants at 0;6 can use top-down information to segment novel words.

The natural question that follows is: What kinds of word can be categorized as familiar for infants? Within the first year of life, a parallel literature suggests that function words may also be familiar to infants. Although function words lack obvious and concrete meanings, they occur frequently enough for infants to map the sounds and their phonetic forms within the first year of life.

Even newborns – whether prenatally exposed to English or Chinese – have been shown to distinguish English function words from content words (Shi, Werker & Morgan, 1999). Thus, the ability to distinguish function words from content words seems to be independent of language experience, perhaps supported by phonological, distributional, and acoustic cues, at least in languages like Mandarin Chinese, Turkish, and English (Shi, Morgan & Allopenna, 1998; Shi *et al.*, 1999). Additionally, various cross-linguistic studies have shown that within the first year of life, infants can recognize function words from a [target function word + noun] phrase (0;7–0;9 for German-learning infants: Höhle & Weissenborn, 2003; and 0;6–0;8 for Canadian French-learning infants: Shi & Gauthier, 2005; Shi, Marquis & Gauthier, 2006b; and 0;11 for European French-learning infants: Hallé, Durand & de Boysson-Bardies, 2008).

Three studies provide evidence that infants may be able to use function words to segment or recognize following words. Shi and colleagues (Shi, Cutler, Werker & Cruickshank, 2006a; Shi, Werker & Cutler, 2006c) have demonstrated that at 0;8, English-learning infants are able to use the frequently occurring determiner *the*, but not the less frequent determiner *her*, to segment pseudo nouns (*breek* or *tink*). Specifically, infants listened longer to a familiarized novel noun *breek* when familiarized with a two-word phrase consisting of a high-frequency, real function word, plus novel noun combination, *the breek*, and also the prosodically matched, nonsense function word plus novel noun combination, *kuh breek*; however, they did not listen longer to a familiarized noun *breek* when familiarized with a less frequent function word plus novel noun combination, *her breek*. This indicates that

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infants aged 0;8 are able to use the frequently occurring function word *the* to segment following words, although they do not yet have a detailed representation of its onset. By 0;11, infants were only successful when familiarized with *the breek* but not *kuh breek*, showing that they were not only able to use *the* in segmenting the following word, but also had a detailed representation of it. As for the less frequent function word *her*, infants aged 0;11 failed to segment the word following either *her* or the prosodically matched pseudo function word *ler*. This indicates that infants aged 0;11 cannot use the less frequent function word *her* to segment the following noun.

Shi and Lepage (2008) also show similar results with Canadian French-learning infants at 0;8. Canadian French-learning infants aged 0;8 were able to segment two novel nouns that were presented after the frequent function word *des* (/de/, indefinite plural article), but not the nonsense function word *kes*. However, they failed to segment the novel nouns when they were presented after a less frequent function word *vos* (/vo/ 'your', plural form). Although infants learning English and Canadian French differ in the age at which they are sensitive to the phonetic detail in function words, both of these studies suggest that infants aged 0;11 are familiar with high-frequency function words, and are able to use these function words to segment following nouns from two-syllable phrases. In this paper we investigate infants' ability to use function words to segment vowel-initial words within the first year of life.

EXPERIMENT 1

In Experiment 1, we tested whether, at 0;8, infants can segment vowel-initial words embedded sentence-medially when preceded by a familiar function word, *the*. This follows up on recent findings that infants use familiar words for segmentation (Bortfeld *et al.*, 2005; Shi *et al.*, 2006a, 2006c; Shi & Lepage, 2008), but applies it to vowel-initial words, a case that has previously been shown to be challenging for infants (Mattys & Jusczyk, 2001; Seidl & Johnson, 2008).

METHODS

Participants

Sixteen full-term monolingual English-learning infants aged 0;8 (mean age = 238 days; range 226:254; eight girls) participated in this experiment. According to parental report, none had a history of speech, language, or hearing difficulties, nor did they have a cold or ear infection on the day of testing; all were in good health and had at least 90% of their language input in English. Seven additional infants aged 0;8 were tested but their

TABLE 1. *Acoustic measures of passages and word lists*

	Experiments 1 & 3		Experiment 4	Experiment 5
Measures	Passages	Lists	Passages	Passages
Average duration (s)	18·5	22·1	19·2	18·6
Duration range (Min:Max)	17·9:19·1	21·5:22·9	18·9:19·8	17·6:19·8
Average pitch (Hz)	250	282	252	252
Pitch range (Min:Max)	122:418	128:414	125:422	123:418

data were discarded due to fussiness ($n=4$), falling sleep ($n=1$), or parental interference ($n=2$).

Stimuli

The four VC words used in the current study were *ice, eff, oats*, and *ash* (Mattys & Jusczyk, 2001). Based on the lexical norms of the MacArthur-Bates Communicative Development Inventories (CDI; Fenson *et al*., 1994), English-learning infants at 0;8 should treat these words as novel words. The words were recorded in four separate lists, with each list containing fourteen repetitions of one of the four words. Also, four six-sentence passages containing each of the four target words were recorded. These passages were based on the passages used by Seidl and Johnson (2008). These six-sentence passages are listed in 'Appendix A'. The position of the target words was always sentence-medial, following the function word *the*.

In American English, the function word *the* has two main pronunciation variants: [ði] before vowel-initial words and for emphasis (i.e. in focused position) and [ðə] before consonant-initial words (Garellek, 2012; Keating, Byrd, Flemming & Todaka, 1994). Production of [ði] before vowel-initial words is obligatory for older speakers, but can be as low as 60% in younger speakers (Keating *et al*., 1994; see also the corpus analysis reported in 'Experiment 4'). Our speaker produced all the instances of *the* as [ði], without any instruction.

The stimuli were recorded by a twenty-seven-year-old female native English speaker from Tacoma, Washington. She was instructed to read the words and the passages in an animated voice as if talking to a preverbal infant. The stimuli were recorded in a soundproof booth using a Shure SM10A head-mounted microphone. All the stimuli were digitized at a sampling frequency of 22050 Hz and 16-bit quantization. Acoustic characteristics of the four passages and the four lists of isolated words are reported in Table 1. Additionally, the average duration of target words was 282 ms ($SD=48$) in the passages and 831 ms ($SD=74$) in the lists.

Average pitch of target words was 232 Hz ($SD = 25$) in the passages and 282 Hz ($SD = 37$) in the lists. Average intensity was 81·2 dB ($SD = 2$) in the passages and 79·7 dB ($SD = 2$) in the lists. All the measurements and analyses were done using Praat (Boersma & Weenink, 2010). The average loudness level for all the stimuli during playback was 73 dB.

Procedure

The Headturn Preference Procedure (HPP) was used to test infants. The infant sat on their caregiver's lap in the center of a three-sided booth. On each side panel, a red light was located at eye level. A green light was mounted on the center panel, also at eye level, and a movie camera was mounted behind this panel, just above the green light. Each trial began when the green light on the center panel flashed. Once the infant oriented towards the center panel, one of the red lights on the side panels began to flash. When the infant turned her head towards that light, speech began to play. Stimulus presentation continued until the infant looked away from the flashing light for more than two consecutive seconds or at the end of the trial. The experimenter observed the infant through a monitor connected to the camera facing the infant and recorded infant looking time. The experimenter recorded the direction of the infant's headturns, which in turn determined the flashing of the lights and the presentation of the speech. Infants' looking time to the flashing lights was used as a proxy for listening time. Both the caregiver and the experimenter wore noise-cancelling headphones that delivered masking music so they could not influence the infants' behavior.

Design

Infants were tested using the same paradigm as in Jusczyk *et al.* (1999b) and Seidl and Johnson (2008). Testing was done in two phases. During the familiarization phase, infants heard either the passages with *ash* and *eff* or *ice* and *oats* till they accumulated 45 seconds of listening time to each passage. The trials continued to alternate until the criterion was met for both passages. During the test phase that followed, infants were presented all four word lists, two familiar and two novel. The four word lists were presented in three blocks for a total of twelve test trials. The order of presentation of the word lists was randomized in each block. Listening time to familiar and novel test word lists were averaged separately and compared statistically.

RESULTS

Average listening times to the familiar (9·82 s; $SD = 3·3$) and novel word lists (9·05 s; $SD = 2·4$) are presented in Figure 1. Out of the sixteen infants tested,

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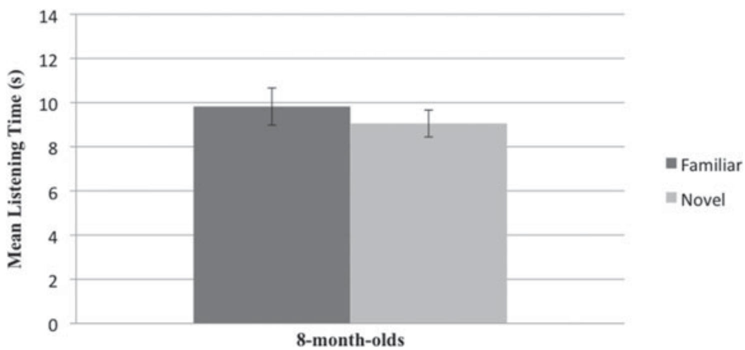

Fig. 1. Mean listening times (±*SE*) to the word lists containing the familiarized vowel-initial words or the novel vowel-initial words (Experiment 1, function word *the*+ vowel-initial word, infants aged 0;8).

nine listened longer to the familiar words compared to the novel words. A two-way mixed ANOVA was conducted with listening time as the dependent variable, Trial-type (familiar vs. novel) as the within-subjects variable and Condition (ash/eff vs. ice/oats) as the between-subjects variable. Neither the main effect of Trial-type ($F(1,14)=\cdot 8$, $p=\cdot 4$), or Condition ($F(1,14)=\cdot 03$, $p=\cdot 9$), nor the interaction between Trial-type and Condition ($F(1,14)=\cdot 2$, $p=\cdot 7$) was significant.

To confirm that simply adding a few subjects was not going to make the statistical comparison significant, we estimated the sample size needed to detect significance of an effect size of 0·262 with an alpha error of 0·05. One hundred and nineteen infants would be needed to provide 80% power in this case (calculated using G*Power 3 for paired *t*-tests: Faul, Erdfelder, Lang & Buchner, 2007). Thus, we conclude that infants aged 0;8 are not able to use function words to segment vowel-initial words embedded in the middle of sentences.

DISCUSSION

The infants aged 0;8 in the present study were not able to use the function word *the* to segment a vowel-initial word placed sentence-medially. This finding contrasts with that of Shi *et al*. (2006a, 2006c), who found that infants at 0;8 could segment consonant-initial words after the function word [ðə] or a prosodically matched foil [kə]. There are several possible explanations, not mutually exclusive, which may account for this disparity. First, it is possible that the infants aged 0;8 failed in this experiment but not in Shi *et al*.'s studies because the task here was harder. It may be harder for infants to segment vowel-initial words, as has been argued previously.

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Or infants might find it harder to segment words embedded in the middle of sentences, rather than from short phrases like *the breek*.

The second possibility is more intriguing. Recall that in the study by Shi *et al*. (2006a), at 0;8, infants were able to segment consonant-initial words when the words were presented either after the function word *the* [ðə], or its prosodically matched counterpart *kuh* [kə]. Both of these forms have phonological and acoustic characteristics of function words: they have the reduced schwa [ə]. Due to its phonological and acoustic similarity to [ðə], infants aged 0;8 might treat *kuh* as a function word as well and use it to segment words. However, recall that in our study the function word preceding the vowel-initial word was produced as [ði]; it is possible that the infants aged 0;8 were not able to recognize [ði] as an allomorph of [ðə], because it has a full vowel [i] and as such infants aged 0;8 did not treat it as a frequent function word. To determine the distribution of [ði] vs. [ðə] variants before vowel-initial words, we conducted a corpus study in Experiment 2.

EXPERIMENT 2

We analyzed the Brent Corpus (Brent & Siskind, 2001) from the CHILDES database (MacWhinney, 2000) to compare the distribution of the two pronunciations of the function word *the* – [ðə] vs. [ði] – and *her*. Recall that Shi *et al*. (2006a) used the function word *the* as representative of a high-frequency function word, and used *her* as a prototypical example of a low-frequency function word.

The Corpus includes transcripts as well as audio-recordings from mother–infant pairs recorded in their home, without any researchers around. We used the Brent Corpus because the infants' age (0;9–1;5), as well as the parent's SES background in the Brent Corpus matches that of the infants tested in the current study. Further, the audio quality was appropriate for transcribing the function words.

METHODS

Participants

Out of the sixteen mother–infant pairs in the Brent Corpus, data from nine mother–infant pairs matched for SES with the infants in our study – c1, d1, f1, f2, i1, j1, m2, q1, s1 – were analyzed for this experiment. Approximately fourteen sessions are available for each pair. Sessions were recorded about once every two weeks, and each session lasted one and a half to two hours. The middle 75 minutes of each session have been extracted and transcribed into the Corpus. The final dataset for this experiment included 144 hours of speech and 218,334 words.

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Procedure

The CLAN COMBO program was used to get the frequency counts for *the + vowel-initial word* sequences as well as *her + word* sequences in the Mother tier. After retrieving the sequences, each token for the function word *the* was labeled as either *the* or *thi*. For cases where the function word *the* was too short to decide its pronunciation by ear, PRATT was used to determine the label. In particular, the distribution of F1, F2, and F3 was analyzed. If the three formants were evenly spaced, the sound was labeled as *the*, whereas if F1 and F2 were apart and F2 and F3 were close, it was labeled as *thi*.

RESULTS

Overall, we found that mothers were quite variable in their production of [ðə] vs. [ði] before vowel-initial words (144 vs. 291). In raw frequency, the total number of times that infants heard [ði] before vowel-initial words ($n = 291$) closely matched the total number of times they heard *her* ($n = 220$). Given that the average frequency of content words ($n = 689$) among the 1000 most frequent words in the same corpus is 107 (e.g. *go*, *get*, *come*, *see*, *mommy*), we can see that [ði] is only less frequent relative to high-frequency function words like [ðə]; in fact, it is more frequent than even the most frequent content words.

Additionally, although overall mothers produced the function word *the* as [ði] before vowel-initial words about 67% of the time, there was considerable variability across speakers. Out of nine mothers, seven used [ði] before vowel-initial words more than 50% of the time. Of the remaining two, d1 used [ði] 42% of the time, and q1 used [ði] only 24% of the time. Figure 2 illustrates the number of [ðə] and [ði] tokens produced by each mother.

Besides variability across mothers, there was also variability within mothers. For example, mother c1 produced *the animal* as [ðə ænəməl] and [ði ænəməl] within the same file. Even mothers who were relatively consistent users of [ði] before vowel-initial words, e.g. f1 and s1, used [ðə] and [ði] interchangeably.

DISCUSSION

Thus, based on raw frequency alone, it is possible that infants treat [ði] as a low-frequency function word. This would explain why the infants aged 0;8 in Experiment 1 were unsuccessful at segmenting vowel-initial words preceded by [ði]. However, we cannot rule out the fact that infants might learn the relationship between [ðə] and [ði] early, due to the restricted distribution of [ði], and the not inconsiderable between- and within-speaker variation in its pronunciation before vowel-initial words, as well as the similarity of the pronunciation of the two variants.

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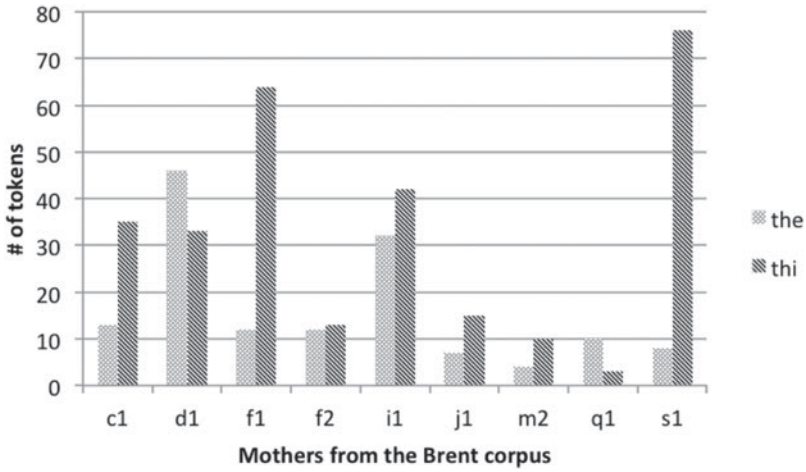

Fig. 2. The number of [ðə] and [ði] tokens before vowel-initial words produced by nine mothers from the Brent Corpus.

EXPERIMENT 3

In Experiment 3, we asked whether infants aged 0;11 can use the function word [ði] to segment vowel-initial words presented sentence-medially. Recall that Shi *et al.*'s (2006a) study illustrated that infants at the age of 0;11 have a relatively detailed representation of the function word *the*. Unlike infants aged 0;8, those aged 0;11 were able to use *the* [ðə], but not the prosodically matched counterpart *kuh* [kə] in segmenting consonant-initial words in [the + target word] phrase. Also, there is evidence that infants aged 0;10·5 are sensitive to allophonic variations (Jusczyk *et al.*, 1999a; Mattys & Jusczyk, 2001) and infants learn phonological alternations between the age of 0;8·5 and 1;0 (White, Peperkamp, Kirk & Morgan, 2008; White & Sundara, 2014). Given results from the corpus study that [ðə] and [ði] are acoustically similar and largely in complementary distribution, infants aged 0;11 may treat [ði] as a function word, possibly a variation of the frequent function word [ðə], and be able to use it to segment the following word. So, if function words facilitate segmentation of vowel-initial words, we expected the infants aged 0;11 to succeed in Experiment 3.

METHODS

Participants

Sixteen infants aged 0;11 (mean age = 343 days; range 326:346; six girls) participated in this experiment. As in Experiment 1, infants did not have

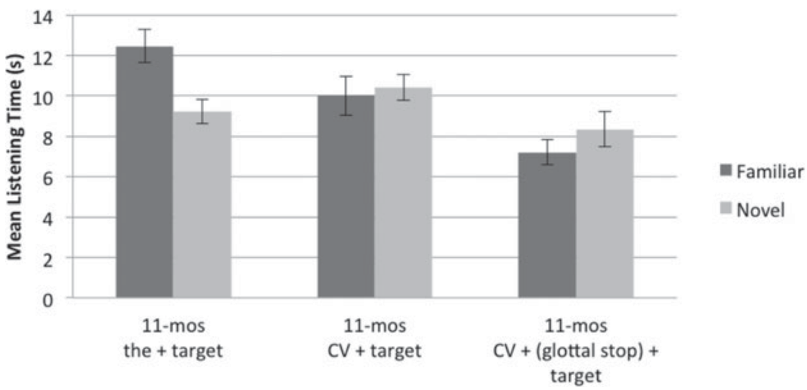

Fig. 3. Mean listening times (±*SE*) to the word lists containing the familiarized vowel-initial words or the novel vowel-initial words (Experiment 3, function word *the*+vowel-initial word, infants aged 0;11; Experiment 4, CV+vowel-initial word, infants aged 0;11; Experiment 5, CV+glottal stop+vowel-initial word, infants aged 0;11).

any history of speech, language, or hearing difficulties, nor did they have a cold or ear infection on the day of the testing. At least 90% of their language input was in English. Nine additional infants aged 0;11 were tested but their data were discarded due to fussiness ($n=7$) or parental interference ($n=2$).

Stimuli

The stimuli were the same as for Experiment 1. According to the MacArthur-Bates CDI, English-learning infants at 0;11 do not know the four target words that we used.

Procedure

The procedure was the same as in Experiment 1.

Design

The design was the same as Experiment 1.

RESULTS

Average listening times to the familiar (12·5 s; $SD=3{\cdot}8$) and novel word lists (9·2 s; $SD=2{\cdot}5$) are presented in Figure 3. Out of the sixteen infants tested, thirteen listened longer to the familiar words compared to the novel words. A two-way mixed ANOVA was conducted with listening time as the dependent variable, Trial-type (familiar vs. novel) as the within-subjects variable and Condition (*ash/eff* vs. *ice/oats*) as the between-subjects variable. A significant main effect was found for Trial-type ($F(1,14)=19{\cdot}3$, $p=\cdot001$,

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$\eta_p^2 = \cdot 58$). Neither the main effect of Condition (*ash/eff* vs. *ice/oats,* $F(1,14) = 1 \cdot 9$, $p = \cdot 2$) nor the interaction between Trial-type and Condition ($F(1,14) = 2 \cdot 4$, $p = \cdot 1$) were significant. This result shows that at 0;11, English-learning infants are able to use function words to segment vowel-initial words embedded in the middle of sentences.

DISCUSSION

Recall that it has previously been shown that infants aged 0;11 can segment vowel-initial words in the beginning or the end of sentences, but not in the middle (Seidl & Johnson, 2008). Contrary to the results from Seidl and Johnson's (2008) study, in Experiment 3 we have shown that, at 0;11, infants successfully segment vowel-initial words even when they appear in the middle of sentences. The difference between the two studies is the use of a function word before the sentence-medial target words. This suggests that function words facilitate the segmentation of vowel-initial words at 0;11.

The failure of infants aged 0;8 along with the success of those aged 0;11 can be interpreted in several ways. It is possible that infants aged 0;11 recognize [ði] as an allomorph of [ðə], treat it as a frequently occurring function word, and use it to segment the following noun. Recall that infants aged 0;11 can only use the frequent function word *the* [ðə] but not the less frequent function word *her* to segment following words (Shi *et al.*, 2006a, 2006c). This suggests that our infants aged 0;11 treated [ði] differently from *her*, possibly as a frequent function word.

Alternatively, infants aged 0;11 might also have segmented vowel-initial words in Experiment 3 using bottom-up cues in the stimuli. Vowel-vowel sequences in English are rarely word-internal, that is, infants encounter various words that end with a vowel or start with a vowel (at utterance edges), but rarely encounter a word that has two consecutive vowels in them. A lexical search of over 2 million words produced in the presence of infants in the entire CHILDES corpora (Daland, 2013) showed that a V-V sequence (vowel hiatus; e.g. in the word *stoic*) is present within only 223 words (token frequency 3,720). Thus, it is possible that infants aged 0;11 exploit their native language phonotactic knowledge about vowel hiatus to segment vowel-initial words following [ði] in Experiment 3.

How infants acquire phonotactic knowledge without knowing the boundaries of a word is an important yet difficult question to answer. One possibility is that infants start learning the phonotactics of a language at utterance edges (e.g. Daland & Pierrehumbert, 2011). Previous research shows that infants are not only sensitive to native language phonotactics by 0;9 (Jusczyk, Friederici, Wessels, Svenkerud & Jusczyk, 1993; Jusczyk, Luce & Charles-Luce, 1994) but are also able to use phonotactics to segment words (Mattys & Jusczyk, 2001; Mattys, Jusczyk, Luce & Morgan, 1999).

TABLE 2. *Glottalization indices for stimuli used in Experiments 1, 3 and 5 (Passages in Experiment 4 did not have glottalization, so they are not included. The lists used were identical across the three experiments.)*

Measures	Passages in Experiments 1 & 3	Passages in Experiment 5	Lists
# glottal stops	5/24	24/24	14/14 (per list)
Duration of glottal stops (ms)	5·9	95·5	14·3
Glottalization before the target word (ms)	10·4	24·7	10·8
Glottalization during the target word (ms)	29·5	13·5	40

For example, English-learning infants aged 0;9 were able to segment the target word *gaffe* when preceded by *bean* but not *fang* – note that the sequence /ng/ is only seen in English between words, whereas the sequence /ŋg/ is quite frequent within words. Experiments 4 and 5 were designed to rule out the possibility that infants aged 0;11 are using phonotactic cues, specifically vowel hiatus, to segment vowel-initial words. Given that infants aged 0;8 were unable to segment in Experiment 1, there is no evidence that they can exploit such phonotactic regularities.

EXPERIMENT 4

In English, V-V sequences can be produced in two ways – with a glottal stop, or without one. As can be seen in Table 2, we see both kinds of productions in the stimuli for Experiment 1 (and 3). Out of 24 instances of the target word, our speaker inserted a glottal stop (or glottalized vowel) 5 times between V#V sequence such as [the ice] (relevant vowels are underlined), and produced 19 instances without a glottal stop in-between.

In the absence of a glottal stop, phonotactically illegal V-V sequences in English are traditionally thought to be resolved by glide insertion (McCarthy, 1993). Recent phonetics research challenges this description by demonstrating that there are substantial acoustic differences between vowel-vowel sequences and vowel-glide-vowel sequences (Britain & Fox, 2008; Cruttenden, 2008; Davidson & Erker, 2014; Heselwood, 2006; Newton & Wells, 2002). We designed Experiment 4 to show that it was the occurrence of the function word specifically, rather than the occurrence of a V#V sequence without a glottal stop, that enabled infants aged 0;11 to succeed in Experiment 3.

In Experiment 4, instead of presenting infants [the + vowel-initial word] frame as in Experiments 1 and 3, [CV + vowel-initial word] frames, where the CV was a content word, were presented to infants aged 0;11. If infants

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in Experiment 3 were using their knowledge of phonotactic regularities in segmenting vowel-initial words, then infants should successfully segment sentence-medial, vowel-initial words in Experiment 4 as well. However, if infants were using the function word to segment vowel-initial words in Experiment 3, then infants aged 0;11 should fail to segment the sentence-medial, vowel-initial words in Experiment 4.

METHODS

Participants

Participants were sixteen full-term monolingual, English-learning infants aged 0;11 (mean age = 338 days; range 320:352; five girls). Selection criteria were identical to those in Experiment 1. Six additional infants were tested, but their data were discarded due to fussiness ($n = 5$) and falling asleep ($n = 1$).

Stimuli

The target words were identical to that used in Experiments 1 and 3 (*ash*, *eff*, *ice*, and *oats*). The difference was that in Experiment 4, instead of the function word *the*, several different words that ended in a vowel (such as *saw*, *pray*, *two*, etc.) preceded the vowel-initial target words ('Appendix B'). All these CV words were unknown to infants at 0;11 based on the CDI lexical norms. Because of previous reports that vowel-initial words embedded sentence-medially are very difficult to segment (Seidl & Johnson, 2008), we varied the CV words, in order to maximize the presence of transitional probability cues to word segmentation (Saffran *et al.*, 1996).

The speaker, who was a trained phonetician, was instructed to produce the target words WITHOUT a glottal stop or glottalization. The acoustic characteristics of the four passages are reported in Table 1. In the passages, the average duration of target words was 311 ms ($SD = 67$), the average pitch was 213·5 Hz ($SD = 21$), and the average intensity was 82·5 dB ($SD = 2$). Recall that the lists used here were identical to the lists used in Experiment 1. The average loudness level for all the stimuli during playback was 73 dB. Further, using a spectrogram, we also confirmed that all VV sequences were produced without a glottal stop (or glottalization) in the stimuli used in Experiment 4. All the measurements and analyses were done using Praat (Boersma & Weenink, 2010).

Procedure

The procedure was the same as in Experiments 1 and 3.

Design

The design was the same as in Experiments 1 and 3.

RESULTS

Average listening times to the familiar (9·99 s; $SD = 2·38$) and novel word lists (10·41 s; $SD = 3·32$) are presented in Figure 3. Out of sixteen infants, six listened longer to the familiar words compared to the novel words. This difference was not only in the wrong direction, but statistically non-significant. A two-way mixed ANOVA with listening time as the dependent variable, Trial-type (familiar vs. novel) as the within-subjects variable and Condition (*ash/eff* vs. *ice/oats*) as the between-subjects variable show no significant main effects (Trial-type ($F(1,14) = ·3$, $p = ·6$); Condition ($F(1,14) = ·3$, $p = ·6$)) or interaction (Trial-type × Condition ($F(1,14) = ·1$, $p = ·7$)).

This is a medium effect size (0·557), and the estimated sample size needed to provide 80% power in detecting significance in a paired *t*-test with an alpha error of 0·05 was 28 (G*Power 3: Faul *et al.*, 2007). This is somewhat larger than the typical sample size for word segmentation experiments (range: 16–20 subjects). However, to be conservative, we cannot rule out that infants learning English might have some knowledge that a V#V sequence without a glottal stop implies that there is a word boundary between the two vowels.

Crucial to our study, the possible sensitivity of infants aged 0;11 to vowel hiatus without a glottal stop cannot account for their success in Experiment 3. In Experiment 3, infants aged 0;11 listened significantly longer to the familiar word lists compared to the novel word lists, showing that they were successful at segmenting the vowel-initial word when given the function word [ði]. In contrast, in Experiment 4, when given phonotactic cues – specifically, vowel hiatus without a glottal stop – their listening times were longer for the novel word lists compared to the familiar word lists and this difference did not reach significance.

To confirm that the difference between the two experiments was statistically significant, we compared the performance of the infants aged 0;11 in Experiments 3 and 4 using a two-way mixed ANOVA with listening time as the dependent variable, and Trial-type (familiar vs. novel) as the within-subjects variable, and Experiment (3 vs. 4) as the between-subjects variable. The main effect of Trial-type (familiar vs. novel) was significant ($F(1,30) = 7·5$, $p = ·01$, $\eta^2 = ·2$). There was no significant main effect of Experiment ($F(1,30) = 0·462$, $p = ·5$). Most importantly, there was a significant interaction between Trial-type and Experiment ($F(1,30) = 12·6$, $p = ·001$, $\eta^2 = ·296$). Thus, infants aged 0;11 behaved differently in the two experiments.

DISCUSSION

Experiment 4 shows that infants aged 0;11 failed to segment vowel-initial words when they were preceded by monosyllabic words ending in vowels. This result is consistent with previous studies showing that vowel-initial words are difficult to segment. Findings from Experiment 4 show that the infants aged 0;11 in Experiment 3 did not use the phonotactic cue, specifically the presence of vowel hiatus, to segment vowel-initial words. However, given the medium effect size, we cannot rule out that infants aged 0;11 might be able to use phonotactic regularities, i.e. vowel hiatus without a glottal stop, to detect vowel-initial words that are embedded sentence-medially.

EXPERIMENT 5

Experiment 5 was designed to rule out the possibility that infants aged 0;11 were using vowel hiatus information, particularly a glottal stop inserted between the two vowels. In American English, a vowel is frequently glottalized (Dilley, Shattuck-Hufnagel & Ostendorf, 1996; Pierrehumbert, 1995) or a glottal stop is inserted (Dilley *et al.*, 1996; Umeda, 1978) at the onset of vowel-initial words, especially when these words appear in sentence-initial position. Even when vowel-initial words appear in the middle of sentences, glottalization occurs frequently if it is preceded by a prosodic break, or if it is focused (Pierrehumbert, 1995). Recent research has shown that any vowel-vowel sequence across a word boundary (V#V) in American English is primarily produced with glottalization or a glottal stop about 45% of time (Davidson & Erker, 2014). More specifically, vowel-initial words, especially when they occur after the function word [ði], are always produced with a glottal stop (Garellek, 2012). Thus, glottalized and non-glottalized instances occur as allophones of the same vowels. Such allophonic variation in the experimental stimuli, i.e. a glottal stop (or a glottalized vowel) rather than the function word [ði] per se, could have helped infants aged 0;11 to segment vowel-initial words in Experiment 3.

Previous research indicates that infants by 0;9 can use allophonic cues to segment words. Jusczyk *et al.* (1999a) have shown that although infants aged 0;9 require both allophonic and distributional cues to segment bisyllabic words from fluent speech, by 0;10·5 infants are able to rely solely on allophonic cues. Experiment 5 was conducted to determine whether infants were relying on phonotactic cues augmented by allophonic cues to segment vowel-initial words in Experiment 3.

Segmentation of vowel-initial words might be facilitated by the presence of glottal stops for two additional reasons. It has been argued that vowel-initial words lack clear onsets, unlike consonant-initial words, and

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this lack of perceptual cues might cause infants to favor consonant-initial words over vowel-initial words (Mattys & Jusczyk, 2001). Because glottal stops serve as onsets, they might facilitate infants' ability to segment vowel-initial words. Furthermore, in word segmentation studies, glottal stops at the onset of vowel-initial words might also make the target words produced in word lists and in passages more similar to each other, facilitating their segmentation (Seidl & Johnson, 2008).

In Experiment 5, we presented infants aged 0;11 the same [CV + vowel-initial word] frames, where the CV was a content word, as in Experiment 4. Additionally, we controlled the phonetic implementation of the V#V sequence – ALL V#V sequences were produced with a glottal stop in-between. If the infants in Experiment 3 were using the glottal stop as the onset of the vowel-initial words, then those aged 0;11 should be able to segment sentence-medial vowel-initial words in Experiment 5 as well. However, if the infants in Experiment 3 were using the function word to facilitate segmentation of vowel-initial words, then those aged 0;11 should fail in Experiment 5.

METHODS

Participants

Participants were sixteen full-term monolingual, English-learning infants aged 0;11 (mean age = 340 days; range 318:357; four girls). Selection criteria were identical to that in Experiments 1, 3, and 4. Eight additional infants were tested, but their data were discarded due to fussiness ($n = 5$), parental interference ($n = 1$), technical issues ($n = 1$), and falling asleep ($n = 1$).

Stimuli

The target words were identical to that used in Experiments 1, 3, and 4. The familiarization passages were the same as Experiment 4 – target words were presented in [CV + vowel-initial word] frames, where the CV was a content word. The speaker, who was a trained phonetician, was instructed to produce the target words with a glottal stop onset. The rest of the instructions and recording set-up were identical to that in Experiment 1. All the measurements and analyses were done using Praat (Boersma & Weenink, 2010). The acoustic characteristics of the four passages used in Experiment 5 are also provided in Table 1; the lists were identical to the ones used in Experiment 1. As for the passages, the average duration of target words was 363 ms ($SD = 57$), average pitch was 251·6 Hz ($SD = 56$), and the average intensity was 81·8 dB ($SD = 2$). The average loudness level for all the stimuli during playback was 73 dB.

Glottalization is known to be extremely variable even within speakers (Dilley *et al.*, 1996) and can be characterized using several different acoustic measures (Redi & Shattuck-Hufnagel, 2001). Following Redi and Shattuck-Hufnagel (2001), we report two measures to index glottalization in our stimuli: duration of full glottal stop, and extent of aperiodicity or creak. Aperiodicity or creak can occur either before or during vowel-initial words. Therefore, we report its extent during the target word as well as in the duration preceding the target vowel. We report glottalization indices for the stimuli used in Experiment 5 as well as Experiment 1 (and 3) for comparison. These measures are presented in Table 2.

We can see from Table 2 that, as expected, all target words in Experiment 5 were produced with a glottal stop. Further, most target words were also accompanied by glottalization, either during the target word or before it. In contrast, in the stimuli for Experiment 1 (and 3), only 5 out of 24 target words were produced with a glottal stop. And even when present, the glottal stop was very short and variable in duration.

Procedure

The procedure was identical to that of Experiment 1.

Design

The design was the same as in Experiment 1.

RESULTS

Average listening times to the familiar (7·19 s; $SD=2·44$) and novel word lists (8·33 s; $SD=3·2$) are shown in Figure 3. Out of sixteen infants, six listened longer to the familiar words compared to the novel words. Again, this difference was not only in the wrong direction, but statistically non-significant. A two-way mixed ANOVA with listening time as the dependent variable, Trial-type (familiar vs. novel) as the within-subjects variable and Condition (*ash/eff* vs. *ice/oats*) as the between-subjects variable show no significant main effects (Trial-type ($F(1,14)=1·6$, $p=·2$); Condition ($F(1,14)=0·5$, $p=·8$)) or interaction (Trial-type × Condition ($F(1,14)=0·008$, $p=·9$)). Note that the effect size in Experiment 5 is very small. A sample size of 52 would be necessary to get 80% power for an effect size of 0·4, with an alpha level of 0·05 (G*Power 3; Faul *et al.*, 2007). In other words, infants aged 0;11 showed no evidence that they have the knowledge that a V#V sequence in English with a glottal stop implies that there is a word boundary between the two vowels.

These results are also in contrast to the findings from Experiment 3. To confirm that the performance of infants aged 0;11 on Experiments 3 and 5 were different, we conducted a two-way mixed ANOVA with listening time as the dependent variable, Trial-type (familiar vs. novel) as the within-subjects variable, and Experiment (3 vs. 5) as the between-subjects variable. The main effect of Trial-type (familiar vs. novel) was not significant ($F(1,30) = 3{\cdot}2$, $p = {\cdot}08$). There was a significant main effect of Experiment ($F(1,30) = 11{\cdot}69$, $p = {\cdot}002$, $\eta^2 = {\cdot}28$); overall, infants aged 0;11 had longer listening times in Experiment 3 compared to Experiment 5. Crucially, there was a significant interaction between Trial-type and Experiment ($F(1,30) = 14{\cdot}028$, $p = {\cdot}001$, $\eta^2 = {\cdot}319$). This shows that the infants aged 0;11 behaved differently in Experiments 3 and 5.

Recall that both Experiments 4 and 5 involved testing infants' sensitivity to vowel hiatus, albeit with differing phonetic implementation, without a glottal stop in the former and with a glottal stop in the latter. To determine if there was an overall sensitivity to vowel hiatus, we conducted a two-way mixed ANOVA with listening time as the dependent variable, Trial-type (familiar vs. novel) as the within-subjects variable and Experiment (4 vs. 5) as the between-subjects variable. There was a significant main effect of Experiment ($F(1,30) = 8{\cdot}3$, $p = {\cdot}007$, $\eta^2 = {\cdot}217$), but neither the main effect of Trial-type ($F(1,30) = 1{\cdot}9$, $p = {\cdot}2$), nor the interaction between Trial-type and Experiment ($F(1,30) = 0{\cdot}4$, $p = {\cdot}5$) was significant. Thus, even virtually doubling the number of subjects in the analysis, infants aged 0;11 did not show any sensitivity to the vowel hiatus (there was no main effect of Trial-type).

DISCUSSION

These results show that the presence of a glottal stop signaling the onset of a vowel-initial word embedded sentence-medially does not help infants aged 0;11 to segment them. In Experiment 5, the glottal stop was present in the familiarization passages as well as in test items, and this match of the glottal stop also did not facilitate vowel-initial word segmentation. Thus, it is not likely that infants in Experiment 3 used the phonotactic cue, specifically the presence of the glottal stop, to segment vowel-initial words. The success of infants aged 0;11 in Experiment 3 and their failure in Experiments 4 and 5 confirm that it is the function word that facilitates the segmentation of sentence-medial vowel-initial words for infants aged 0;11.

GENERAL DISCUSSION

The current study was designed to find cues that infants aged 0;8 and 0;11 might use in segmenting vowel-initial words. Using corpus analysis and behavioral experiments, we showed that infants aged 0;11, but not 0;8, were able to use a top-down cue, a function word, to segment vowel-initial words in a very challenging environment where vowel-initial words appear in the middle of sentences (Experiments 1–3). In contrast, when provided with phonotactic cues to word boundaries – i.e. the target words were preceded by a monosyllabic word ending in a vowel, infants aged 0;11 failed to segment vowel-initial words. Neither the presence (Experiment 5) nor the absence of a glottal stop between the two vowels (Experiment 4) supported the segmentation of vowel-initial words embedded sentence-medially for infants aged 0;11.

The stimuli in Experiments 4 and 5 differed from that in Experiment 3 (and 1) in one other way that might explain infants' success in the latter but not former two experiments. In Experiment 3, target words were always presented in a fixed frame [the + vowel-initial word], whereas in Experiments 4 and 5 variable frames [CV + vowel-initial word] were used. It is possible that this made the word segmentation process more challenging in Experiments 4 and 5.

However, existing research on the role of variability in the input actually suggests that variable frames may in fact help the language acquisition process. The benefit of variability in phonological processing has been previously documented (McMurray & Aslin, 2005; Rost & McMurray, 2009). These studies have shown that infants are sensitive to within-category variation and profit from variable structures in detecting words. Further, variable frames provide transitional probability cues to signal word onsets and offsets (Gomez, 2002; Saffran *et al.*, 1996). Thus, although our infants aged 0;11 did not get any benefit from variability, we do not believe that the presence of variable frames in itself made word segmentation more challenging in Experiments 4 and 5.

The results from this study have four implications. First, infants aged 0;11 can not only segment vowel-initial words in sentence-initial or -final position, as has been shown previously (Seidl & Johnson, 2008), they also succeed when these words are placed sentence-medially. These results are in contrast with early studies, where only infants aged 1;1 to 1;4 successfully segmented vowel-initial words (Mattys & Jusczyk, 2001).

Second, the current study shows one way in which function elements are likely to facilitate children's language development. Just like frequently occurring content words, such as *mommy* or a baby's name (Bortfeld *et al.*, 2005; Mersad & Nazzi, 2012), function words also bootstrap prelinguistic infants' segmentation of new word forms. Previous studies on function word acquisition have shown a facilitative effect of function words in segmenting consonant-initial words from two-word phrases (Shi *et al.*, 2006a, 2006b, 2006c; Shi & Lepage, 2008). Our results show that this facilitative effect can scale up to the challenge of connected speech, i.e. full sentences and paragraphs, where the target word is a vowel-initial word embedded sentence-medially. What remains to be determined is whether this facilitative effect is driven by the fact that infants aged 0;11 treat [ði] as an allomorph of [ðə], or as a less frequent function word in its own right.

Third, results of the corpus study and Experiment 3 reinforce the idea that infants aged 0;11 might have some knowledge of phonological alternations, specifically variation associated with allomorphy. The corpus study shows that the frequency of [ði] ($n = 291$) before vowel-initial words closely matches the frequency of *her* ($n = 220$). That is, they are both among the less frequent function words in the child's input (overall frequency of *the* in the same corpus is 7768). However, in Experiment 3, infants aged 0;11 successfully used [ði] to segment vowel-initial words. Recall that infants aged 0;11 cannot use *her* to segment the following consonant-initial words (Shi *et al.*, 2006a, 2006c). Infants' success at segmenting words that follow [ði] but not *her* suggests that they are treating [ði] and *her* differently. This is possible if infants have some knowledge of the alternation between [ðə] and [ði] (see also White *et al.*, 2008; White & Sundara, 2014, for evidence that infants aged 1;0 have some knowledge of phonological alternations).

Finally, these results add to our understanding of the role of allophonic variation in word segmentation. Previous studies have demonstrated that infants at 0;9 are able to segment words using allophonic cues (Jusczyk *et al.*, 1999a; Mattys & Jusczyk, 2001; Mattys *et al.*, 1999). However, the infants aged 0;11 tested in Experiment 5 failed to segment vowel-initial words using the glottal stop/glottalized vowel allophone. This discrepancy can be explained in several ways. First, in previous studies the target words usually appeared twice in initial position, twice sentence-medially, and twice at the end of the sentence. In contrast, in our study, target words were only presented sentence-medially. Given evidence that sentence-medial words are harder to segment than target words embedded at the ends of utterances (Seidl & Johnson, 2006, 2008), it is possible that infants can use allophonic cues in segmenting words only when the cues appear at utterance boundaries. Second, unlike other allophones in English, both degree and rate of glottalization vary a lot, within as well as across individuals (Redi & Shattuck-Hufnagel, 2001). Besides signaling allophonic differences, glottalization in English also varies with register and speech rate, and, most prominently, with the presence of prosodic boundaries (Eddington & Channer, 2010). All the above reasons are likely to make glottalization (including the presence of a glottal stop) a poor cue for word segmentation. So perhaps it is not surprising that infants fail to use glottalization as a cue to word boundaries (see Seidl, Cristià, Bernard & Onishi, 2009, for another case where infants aged 0;11 fail to use allophonic differences, this time to learn novel phonotactic patterns). Future research is needed to adjudicate between these possibilities.

In conclusion, the experiments in this paper demonstrate that within the first year of life, infants can use function words to segment vowel-initial words in a challenging context – the middle of sentences in connected speech.

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APPENDIX A: PASSAGES USED IN EXPERIMENTS 1 AND 3

EFF/ICE

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

ASH/OATS

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

APPENDIX B: PASSAGES USED IN EXPERIMENTS 4 AND 5

EFF/ICE

He wants to be ice when he grows up. We have seen raw ice for months. They knew ice hires clowns all year. They are giving out free ice today. I grow ice in my back yard. They say true ice is rarely found these days.

ASH/OATS

I saw oats standing on his head. My sister and I pray oats gets better. There are three oats lying on the grass. There is a picture of gray oats in my room. I wonder if new oats wants to learn. I see two oats jumping around.