The Learnability of Phonotactic Patterns in Onset and Coda Positions

Yuanyuan Wang

Linguistics Department, Purdue University

Amanda Seidl

Department of Speech, Language, and Hearing Sciences, Purdue University

Cross-linguistically, languages allow a wider variety of phonotactic patterns in onsets than in codas. However, the variability of phonotactic patterns in coda position in different languages suggests these patterns must, at least in part, be learned. Two experiments were conducted to explore whether there is an asymmetry in English-learning infants’ ability to learn novel phonotactic patterns in word-medial onset and coda positions. In Experiment 1, English-learning 8- and 12-month-olds were familiarized with bisyllabic nonsense words with voiced fricatives restricted to either word-medial onset (Onset condition) or word-medial coda positions (Coda condition). At test, infants heard novel words that either followed or violated the familiarized patterns. Twelve-month-olds in the Onset condition showed a preference for the familiarized pattern; however, 12-month-olds in Coda condition as well as 8-month-olds in both conditions displayed no such preference. To explore whether there is a developmental pattern in these positional effects, in Experiment 2, 15-month-olds were tested in only the Coda condition. These toddlers showed a preference for the familiarized phonotactic pattern. These findings support the hypothesis that infants’ learning of positional phonotactics is asymmetrical.

Languages vary in which syllable structures are legal (e.g., English allows closed and open syllables, but Hawaiian allows only open syllables) as well as which phoneme sequences are permitted in syllables (e.g., /st/ is an allowable cluster in English but not in Japanese). Further, phonotactics and syllable structure interact. For example, many languages have a wider variety of phonotactic patterns in onset position than in coda position. For example, in Chinese, only certain segments (e.g., nasal consonants) can occur in coda position whereas onset position allows many different consonants and even consonant clusters. Based on these data some phonological theories suggest that languages favor onsets over codas (e.g., Prince & Smolensky, 1993). However, the range of cross-linguistic variability of phonotactics in coda position means that these patterns must be learned during phonological acquisition (e.g., English-learning infants learn more phonotactic patterns are legal in codas than Chinese-learning infants).
Thus, an intriguing question is whether phonotactic patterns in onset and coda positions are learned at different stages of development. There are two possible hypotheses. The Symmetrical Hypothesis suggests that all phonotactic patterns are equally learnable regardless of syllable position. Thus, the cross-linguistically fewer phonotactic patterns that we see in coda position may be due to other phonological/acoustic/sociolinguistic pressures (e.g., it is possible that production constraints lead sounds to be more difficult to produce in coda position, and thus some codas in production are likely to be deleted). In contrast the Asymmetrical Hypothesis suggests that the learnability of phonotactic patterns varies as a function of syllable position, such that onset and coda phonotactics are learned at different points during the course of language acquisition. If we find an asymmetry in infants’ learning of onset and coda phonotactics, we will then consider the relationship between this infant learning pattern and cross-linguistic data. If, however, we find that there is no such difference, we will have evidence in support of the Symmetrical Hypothesis.

To begin with, there is evidence showing that, from an early age, infants become sensitive to the sound organization of their ambient language. For example, ample work suggests that syllables are present as salient units in infants’ mental representations from early infancy (Bertoncini, Flocia, Nazzi, & Mehler, 1995; Bijeljac-Babic, Bertoncini, & Mehler, 1993; Cutler, Mehler, & Norris, 1986; Eimas, 1994; Massaro, 1974; Mehler, Dommergues, & Frauenfeld, 1981; van Ooijen, Bertoncini, Sansavini, & Mehler, 1997). Further, from 1 to 3 months, infants become sensitive to more fine-grained constituents, such as onset, nucleus, and coda (Bertoncini & Mehler, 1981; Fais, Kajikawa, Amano, & Werker, 2009; Fernald & Swingley, 2001; Hayes & Slater, 2008; Jusczyk, Goodman, & Baumann, 1999; Jusczyk & Thompson, 1978; Karzon, 1985; Swingley, 2005, 2009; Tincoff & Jusczyk, 2003; Walley, 1987; Zamuner, 2006). Although some of the work above shows appropriate encoding of both word-initial and -final contrasts in infants (Jusczyk, 1977; Swingley, 2009), most results show that in a direct comparison word-initial contrasts are better discriminated than word-final ones during the first year of life (e.g., Hayes & Slater, 2008; Swingley, 2005; Zamuner, 2006). For example, Dutch 10-month-olds discriminated word-initial consonant contrasts but failed to do so in word-final position (Zamuner, 2006). It is only in the first half of the second year that infants appear to become sensitive to phonological information in word-final positions (Langeslag, Altwater-Mackensen, & Fikkert, 2008; Levelt, 2012; Swingley, 2009; Zamuner, 2006). Table 1 gives a summary of this research on the perception of word-initial and final segments. Although this body of research lends support to the view that word-initial position attracts more attention or is easier to discriminate than word-final position, none of these studies provides a direct answer to the question of whether there is an asymmetry in the learning of phonotactics in onset and coda position, for the following reasons.

First, all the studies mentioned above and shown in Table 1 examined either infants’ preference/sensitivity to different groups of sounds in word-initial and -final positions, (e.g., Hayes & Slater, 2008; Jusczyk et al., 1999; Jusczyk & Thompson, 1978; Tincoff & Jusczyk, 2003; Zamuner, 2006), or infants’ behavior in word recognition tasks (Cole, 1981; Fais, Kajikawa, Amano, & Werker, 2009; Fernald & Swingley, 2001; Swingley, 2005, 2009; Walley, 1987). Thus, these studies primarily investigated infants’ sensitivity to segment contrasts as well as their representation of known words, rather than explored how their ability to learn phonotactics was constrained by positional effects.

Second, most studies above have confounded word position (final/initial) with syllable position (codas/onsets) (e.g., Fernald & Swingley, 2001; Hayes & Slater, 2008; Jusczyk et al., 1999;
TABLE 1
Summary of Previous Research in Infant Onset and Coda Perception

<table>
<thead>
<tr>
<th>Authors</th>
<th>Method</th>
<th>Stimuli</th>
<th>Feature</th>
<th>Age</th>
<th>ONSET</th>
<th>CODA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Juczyk (1977)</td>
<td>HAS</td>
<td>bad/bag synthetic</td>
<td>stops</td>
<td>2m</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Jusczyk and Thompson (1978)</td>
<td>HAS</td>
<td>bada/gada daga/daga</td>
<td>stops</td>
<td>2m</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Karzon (1985)</td>
<td>HAS</td>
<td>ra/la</td>
<td></td>
<td>1-4m</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Hayes and Slater (2008)</td>
<td>HPP</td>
<td>CVC alliteration lists vs. control list</td>
<td></td>
<td>3m</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Tincoff and Jusczyk (1996)</td>
<td>HPP</td>
<td>baik/baik fit/fit</td>
<td>stops</td>
<td>7.5m</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Jusczyk,Goodman, and Baumann (1999)</td>
<td>HPP</td>
<td>CVC nonwords</td>
<td>shared manner, POA rime</td>
<td>9m</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Zamuner (2006)</td>
<td>HPP</td>
<td>CVC nonwords</td>
<td>voicing</td>
<td>9m</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Habitation CVC nonwords</td>
<td>Voicing POA</td>
<td>10m</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Habitation CVC nonwords</td>
<td>Voicing POA</td>
<td>10m</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Swingley (2005)</td>
<td>HPP</td>
<td>CVC real words, nonwords, and mispronunciations</td>
<td>POA</td>
<td>11m</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Langeslag, Altvater-Mackensen, and Fikkert (2008)</td>
<td>Switch paradigm</td>
<td>CVC real words</td>
<td>Manner (Stop-fricative) contrast</td>
<td>14m</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Swingley (2009)</td>
<td>Visual fixation Task</td>
<td>CVC real words</td>
<td>POA, voicing</td>
<td>14-22m (M=17)</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Levelt (2012)</td>
<td>Habituation</td>
<td>Real words pat/pa pas/pa pak/pa</td>
<td>voiceless</td>
<td>14m</td>
<td>N</td>
<td>Y</td>
</tr>
</tbody>
</table>

Y: infants succeeded in the task; N: infants failed in the task.

Jusczyk & Thompson, 1978; Karzon, 1985; Swingley, 2005, 2009; Walley, 1987; Zamuner, 2006), and thus it is not possible to separate out effects of word position from effects of syllable position. From discrimination studies, there is ample evidence showing that word-edge onsets and codas are processed differently from word-medial ones (Karzon, 1985; Redford & Diehl, 1999, Walley, 1987). For example, Karzon (1985) found that although 1- to 4-month-old infants failed to show discrimination of [marana] vs. [malana], they did discriminate the [ra] vs. [la] contrast. This may be because word-edge units are acoustically more salient than word-medial ones. This is in line with Endress and Mehler’s (2010) recent experimental study in which they found that adults learned phonotactic regularities better in word edge positions than in word-medial positions. More specifically, participants in their study learned that word-edge consonants (C₁
and \( C_2 \) came from distinct sets in structures such as \( C_1 VccVC_2 \), but they failed to learn this constraint in words of the form \( cVC_1C_2Vc \), where the target consonants were in word-medial position. Therefore, conservatively we may conclude that for infants, word-initial sounds may be easier to perceive than word-final ones, but it would be premature to conclude anything about the learnability of phonotactic patterns in onsets and codas based on these data.

Finally, the asymmetry we see in the perception of onsets and codas in previous studies may originate from acoustic differences of target segments in word-initial and word-final positions. There is an abundance of work suggesting that acoustic saliency differs as a function of word position. For example, in English, word-final stops are acoustically less salient than word-initial stops, due to a tendency for final stops to be produced with an unreleased burst (Denes, 1955). Given that most of the previous studies cited have used stops as the target segments (e.g., Jusczyk et al., 1999; Levelt, 2012; Zamuner, 2006), the acoustic differences between word-initial and word-final positions may have impacted the results. Indeed, when Jusczyk (1977) used synthetic released stops, 2-month-olds discriminated segmental contrasts even in word-final position. Thus, whether infants can learn phonotactic patterns in word-initial and word-final positions may vary depending on the acoustic saliency of segments involved and the interaction of acoustics with position.

As noted above, discrimination studies have often provided evidence for asymmetrical perception. However, in order to gain phonotactic knowledge, infants must not only be able to notice subtle changes in a highly constant stream (as in discrimination), but also track regularities across many different utterances that contain a large degree of variability and store and generalize those patterns in the input. Before turning to the question of whether infants’ phonotactic learning is asymmetrical in onset and coda positions, we should review work showing that infants have some ability to learn phonotactic patterns. Previous studies have suggested that young infants can learn and generalize both natural and unnatural phonotactic patterns after brief exposure (Chambers, Onishi, & Fisher, 2003, 2011; Saffran & Thiessen, 2003; Seidl & Buckley, 2005; Seidl, Cristià, Bernard, & Onishi, 2009); however, none of these studies has directly compared phonotactic learning in word-initial and -final positions, let alone in word-medial onset and coda positions. For example, Seidl et al. (2009) find that 4-month-old infants can learn word-final unnatural phonotactics; however, they did not investigate infants’ learning of word-initial phonotactics. Thus, this study does not tell us whether there is an asymmetry in ease of learning as a function of syllable/word position. In another artificial grammar learning study, Chambers et al. (2003) familiarized 16.5-month-olds with consonant-vowel-consonant \((C_1VC_2)\) syllables in which particular consonants were restricted to either word-initial \((C_1: \text{/b, k, m, t, f/})\) or -final \((C_2: \text{/p, g, n, t, ñ, s/})\) position (e.g., /baep/, not /pæb/, i.e., /b/ could only occur in onset position, but not in coda position; /p/ could only occur in coda position, but not in onset position). At test, 16.5-month-olds listened longer to new \( C_1VC_2 \) syllables that violated the familiarized phonotactic constraints than to those that satisfied the familiarized constraints. While at first glance this study seems to address our question of positional effects, notice that although Chambers et al. (2003) used both word-initial and word-final restrictions in their study, they did not systematically vary the location of the pattern. Thus, we still do not know whether infants’ preferences in their work were due to the fact that they learned the phonotactic regularity in both word-initial and word-final positions, or they learned the pattern only in one position.

Thus, the goal of the present study was to explore specifically whether there is an asymmetry in infants’ learning of a novel phonotactic pattern in word-medial onset and coda positions.
Specifically, using the Headturn Preference Procedure (HPP: Jusczyk & Aslin, 1995), we tested English-learning infants’ phonotactic learning in word-medial onset and coda positions. Naturally spoken CVC.CVC nonsense words were presented in the experiment, with target segments \{v, z, ʒ, ð\} restricted either to word-medial onset or word-medial coda positions. Later, infants were tested with novel bisyllabic nonsense words either consistent with the experimental patterns or violating them.

The motivation for testing English-learning infants was twofold. First, we wanted to minimize the confounding of language-specific phonotactics with language-general knowledge. Typological investigations regarding cross-language syllable structures (Blevins, 1995; Clements & Keyser, 1983) indicate that onset-nucleus (CV) is the only prosodic structure that is allowed in all of the world’s languages; in contrast, many languages do not allow codas (e.g., Hawaiian, Maori). However, English is a language known to allow many phonemes/phoneme sequences in both onset and coda positions. For example, voiced fricatives \{v, z, ʒ, ð\} occur in both onset and coda positions. Second, fricatives occur frequently in both word-medial onset and coda positions. Previous research has suggested that the frequency of phonological patterns in the input may influence many levels of linguistic representation (Levelt, Schiller, & Levelt, 2000; Zamuner, Gerken, & Hammond, 2004a). However, our corpus analyses reveal that, in English, the log frequency of word-medial voiceless singleton fricatives is comparable in onset (5.66) and coda (4.55) positions (CELEX; Baayen, Piepenbrock, & Gulikers, 1995). The log frequencies is a commonly used transform for frequency data (e.g., Edwards & Beckman, 2008; Zamuner, Gerken, & Hammond, 2004b) and is shown to better approximate human perception than raw frequency. It effectively weights the change at the low-frequency end more heavily than at the high-frequency end.¹ Thus, we speculate that English-learning infants should not, a priori, show a strong bias for either pattern based on the input. Therefore, it will be revealing to examine the development of phonotactic knowledge related to syllable structure in these infants.

**EXPERIMENT 1**

In Experiment 1, we focus on 8- and 12-month-olds because infants from the age of 9 months are becoming more closely attuned to the phonotactic patterns of their native language (Friederici & Wessels, 1993; Jusczyk, Luce, & Charles-Luce, 1994; Seidl et al., 2009). Thus, 8-month-olds, who are still learning native phonotactics, may be less affected by the input in the ambient language and their behavior may reflect more language-general knowledge than the behavior of older infants. However, given previous phonotactic work only focused on word-initial and -final positions, it may prove more challenging for 8-month-olds to learn word-medial phonotactic restrictions since we know it is more difficult to learn word-medial phonotactics (e.g., Endress & Mehler, 2010). Specifically, we ask: Do 8- and 12-month-olds learn both a phonotactic restriction in onset and coda, or are they able to learn the experimental phonotactics only in one position?

---

¹ Though infant-directed corpora may provide more reliable approximation of infants’ input, the lack of large English IDS corpora with mothers’ speech transcribed and tagged in a way similar to CELEX prevents us from easily investigating the distribution of fricatives in IDS.
Method

Participants

Twenty-four 8- and 24 12-month-old infants from monolingual English-speaking homes were tested. The 8-month-olds (12 females) were between the ages of 7.40 and 8.72 months (\(M = 7.88, SD = 0.37\)). The 12-month-olds (8 females) were between 11.38 and 12.53 months (\(M = 11.95, SD = 0.39\)). The participants were recruited from a midwestern town. They were healthy full-term infants with typical development and no known history of hearing impairment. An additional 21 infants were tested whose results were not reported for the following reasons: 13 for fussing or crying, 2 for experimenter error, and 6 for having looking times with difference scores (legal-illegal) more than 2.5 standard deviations (SD) off the overall mean. Infants were compensated with a book or a toy for their participation.

Stimuli

Two different types of nonsense bisyllabic words with CVC.CVC syllable structure were created for this experiment: CVC.FVC (Onset condition) and CVF.CVC (Coda condition).\(^2\)\(^3\)\(^{4}\) F was the critical consonant from a class of voiced fricatives \{v, z, ʒ, ʃ\}, C was a filler consonant from the group \{l, m, n, r, b, d, g\}, and V was a member of a small set of vowels \{a, i, æ, u\}. These two word types differed in their phonotactic pattern: For CVC.FVC, the critical consonant was restricted to voiced fricatives in word-medial onset position (e.g., /gæbil.zær/, /bægil.zær/); for CVF.CVC, the critical consonant was restricted to voiced fricatives in word-medial coda position (e.g., /luæ.zær/, /riv.næl/).

The nonsense words for the experiment were produced by a young female native speaker of American English in an infant-directed register. The speaker had received training in phonetics and had experience in recording stimuli for previous infant studies. Before recording, she was informed that the study was an infant study and was provided word lists with each word marked with syllable boundaries. She was informed that all the nonsense words on the list were trochaic words with a CVC.CVC structure, and was asked to produce the word lists in her happiest infant-directed speech.\(^2\)\(^3\) The stimuli were recorded using a wireless Lavalier microphone (AKG WMS40) in a sound-shielded booth recorded with a Marantz Professional Solid State Recorder (PMD660ENG). Experimental stimuli were selected based on their acoustic clarity and their similarity to the acoustic characteristics of English. The stimuli were digitized at a sampling rate of 44.1 kHz and normalized to \(\sim 72\)dB in Praat (Boersma & Weenink, 2011).

Design

Participants in each age group were randomly assigned to two conditions. Each infant participated in both a familiarization phase and a test phase. Infants in the Onset condition were familiarized with CVC.FVC words and tested on CVC.FVC (legal) and CVF.CVC (illegal)

\(^2\) However, we cannot be sure how infants in our study have interpreted the stimuli. It is possible that they may also have interpreted the stimuli as compound or two-word sequences, given consonant clusters are either phonotactically illegal in English or were of low frequency word-medially.
words; infants in the Coda condition listened to CVF.CVC words during familiarization, and tested on CVF.CVC (legal) and CVC.FVC (illegal) words. Thus, for each infant, the legal test words shared the same phonotactic pattern as the familiarized pattern, and the illegal test words violated the familiarized pattern. The stimuli used in familiarization and test phases are shown in Appendix A.

The familiarization word list consisted of 60 words with either CVC.FVC or CVF.CVC structure in a random order with .65s pauses in between words. The test list consisted of four legal trials and four illegal trials, each containing a randomly ordered sequence of 12 words with .65s pauses in between words. Crucially, the test words were not presented in the familiarization phase. The average duration of the familiarization stimuli was 85.76 s (SD = .45); the average duration of each test trial was 19.18 s (SD = .13). The first segment of each test trial began with a different consonant, thereby eliminating the possibility of a bias resulting from a preference for the first sound heard. Each word occurred only once in the familiarization and test phase. Test trial order was randomized following the constraint that the first two trials always included a legal and an illegal trial, and at most two trials of the same type occurred in a row.

**Procedure**

A modified version of the Headturn Preference Procedure (Jusczyk & Aslin, 1995) was used in the present experiment. Each infant was seated on their caregiver’s lap in the middle of a three-sided booth. The experimenter was seated behind the booth and observed the infant through a video camera which recorded the infant’s orientation during the experiment. Both the experimenter and the caregiver wore headphones (Peltor Aviation headset 7050) which played a combination of white noise and continuous music to mask the stimuli. The booth was quiet and comfortable and consisted of three panels: a center panel with a green light and two side panels each with a red light. An overhead light was dimed to make the panel lights more salient. Each trial began with the blinking of the green light on the center panel. When the infant looked at the green light, the light was extinguished and one of the two red lights would begin to blink. A computer program randomly chose which red light began to blink. When the infant oriented at least 30° in the direction of the red light, the stimuli for that trial began to play. The stimuli played until either the infant looked away for two consecutive seconds or the stimuli file was complete. At this point, the red light was extinguished and the sound was stopped. Then the center green light began to blink in preparation for the next trial. The computer recorded the amount of time the infant spent looking at the red light. If the infant turned away from the target by 30° for less than two seconds, that time was not included in the orientation time, although the light did not extinguish.

During the familiarization phase, infants listened to the words from the familiarization list, which were presented continuously and simultaneously from both side speakers. Sound files were

---

3 It should be noted that for illegal lists, we chose either CVF.CVC (for condition Onset) or CVC.FVC (for condition Coda) rather than CVC.CVC for both groups because we would like to make sure infants’ preference, if any, for legal or illegal lists in Test phase is not confounded by segmental difference. Were we use CVC.CVC for illegal lists, even if infants’ show preference for legal lists, we still do not know whether they prefer the familiarized phonotactic pattern per se, or they just prefer words with more fricatives.
initiated by the initial orientation toward one of the flashing side lights and played continuously until the familiarization time criterion was reached. During familiarization, only lights, but not sounds were contingent on the infants’ orientation. The test phase began immediately after the familiarization phase. During the test phase, the lights and sounds were contingent upon infant looking. At test, infants heard four legal trials containing words with the same phonotactic pattern as those presented in the familiarization phase and four illegal trials containing words that violated the familiarized phonotactic pattern. Test trials were presented in a random order. The dependent measure was the average orientation time across trials to each stimulus type. A Macintosh computer controlled the presentation of the stimuli and recorded the experimenter’s coding of infants’ orientation via a button box. The audio output was fed to two Cambridge Soundworks Ensemble II speakers.

Results

Mean orientation times to the legal and illegal lists were calculated for each infant. For 8-month-olds, the average looking times to legal and illegal trials were 8.72 s ($SD = 1.10$) and 9.48 s ($SD = 1.04$) in the Onset condition, and 7.45 s ($SD = 1.10$) and 7.41 s ($SD = 1.00$) in the Coda condition. For 12-month-olds, looking times were 11.17 s ($SD = 1.90$) to legal and 8.84 s ($SD = 1.49$) to illegal in the Onset condition, and were 7.30 ($SD = 0.54$) to legal and 8.79 s ($SD = 1.09$) to illegal in the Coda condition.

We submitted the data to a repeated measures analysis of variance (ANOVA) with Legality (legal and illegal) as the within-subject factor, and with age (8 or 12 months) and Condition (Onset or Coda) as between-subject factors. Infants’ looking times to legal and illegal lists in Onset and Coda conditions are illustrated in Figure 1. There was no significant main effect of Legality, $F(1, 44) = 0.45, p = .506$, Age, $F(1, 44) = 0.50, p = .485$, or Condition, $F(1, 44) = 2.84, p = .099$. However, there was a significant Legality x Age x Condition interaction, $F(1, 44) = 4.24, p = .045, \eta^2_p = .088$. Other interactions were not significant $Fs(1, 44) < 1.81, p > .491$.

Given the interaction with Age, we further submitted the data from each age group separately to a repeated measures analysis of variance (ANOVA) with Legality (legal and illegal) as a within-subject factor, and with Legality (legal and illegal) as a within-subject factor, and Condition (Onset or Coda) as a between-subject factor. For 8-month-olds, the main factors of Legality $F(1, 22) = 0.41, p = .527$, and Condition $F(1, 22) = 1.19, p = .287$ were not significant; however, we found a significant interaction of Legality x Condition, $F(1, 22) = 8.61, p = .008, \eta^2_p = .281$. To compare infants’ looking times to legal versus illegal trials, we conducted contrast comparisons under each condition. The results indicated that 12-month-olds in the Onset condition looked significantly longer to legal than to illegal lists $F(1, 22) = 6.40, p = .019$, Cohen’s $d = 1.36$. However, orientation times to legal and illegal lists were not significantly different for the Coda condition $F(1, 22) = 2.63, p = .119$ (see Figure 1).

Discussion

While 8-month-olds failed to learn the pattern when the target segments were restricted in both onset and coda positions, 12-month-olds showed an asymmetrical learning pattern. The fact that
8-month-olds failed to show a preference in both Onset and Coda conditions may suggest that it is more challenging for them to learn word-medial phonotactic patterns. However, there are two possible interpretations of the 12-month-olds’ behavior. The first possibility is that 12-month-olds learned the phonotactic pattern only in the Onset condition where the target segments occurred only in word-medial onset positions. The second possibility is that the 12-month-olds also learned the familiarized pattern in Coda condition but were transitioning from a familiarity to a novelty preference, thus showing a null effect in the Coda condition. If this were true, then the results would suggest that patterns in the Coda condition are actually easier to learn. However, we suspect that this is not the case given the fact that transitions from familiarity to novelty preferences take place when task complexity decreases for a certain age group (e.g., Hunter & Ames, 1988; Seidl & Johnson, 2008; Thiessen, Hill, & Saffran, 2005). For example, in a word segmentation task, 11-month-olds showed a novelty preference in segmenting word-initial vowels in sentence-final position, but they displayed a familiarity preference in sentence-initial position, where the task was more difficult (Seidl & Johnson, 2008). Further, 16.5-month-old toddlers in Chambers et al.’s (2003) study displayed a preference for illegal items (a novelty preference) in phonotactic learning. Given that the phonotactic learning task in our study was very demanding, both because it was word-medial and because the participants were younger, it seems unlikely that 12-month-olds would show a novelty preference.\footnote{Furthermore, the 15-month-olds infants (in Experiment 2) showed a novelty preference in the Coda condition, thus providing us with more evidence that 12-month-olds in Experiment 1 have not learned the pattern in coda position.} Taken together, these data suggest that 12-month-olds learned phonotactic patterns only in one position and thus showed asymmetric learning patterns.

EXPERIMENT 2

Experiment 1 suggests that 12-month-olds learned the phonotactic regularities only in Onset condition. Thus, these results support the Asymmetrical Hypothesis. Nonetheless, English-learning infants need to learn phonotactic patterns when the target segments are restricted to both word-medial onset and coda positions in order to become mature language learners. Therefore, questions remain as to when infants show evidence of learning in both positions. In Experiment 2, we tested 15-month-olds’ learning of the same phonotactic pattern in the Coda condition only.

Methods

Participants

Twelve English-learning, healthy term 15-month-olds ($M = 14.98, SD = 0.41$) from the same midwestern town (5 female) were tested. Data from an additional 5 infants were excluded for the following reasons: 2 for fussing or crying, 1 for experimenter error, and 2 for having looking times for difference scores (legal-illegal) more than 2.5 standard deviations from the mean. Infants were compensated with a book or a toy for their participation.

Stimuli, Design, and Procedure

These were identical to those in the Coda condition of Experiment 1.
Results

Mean orientation times to legal and illegal lists were calculated. Across all subjects, the average orientation time were 9.52 s (SD = 3.52) to the legal lists, and 7.62 s (SD = 2.08) to the illegal lists (Figure 1). A paired $t$-test revealed that this difference in orientation times was significant, $t(11) = 2.57, p = .026$, Cohen’s $d = 0.66$ (Figure 1). Thus, 15-month-olds listened longer to the legal lists that followed the phonotactic pattern exemplified in the familiarization phase. To examine the developmental change between 12- and 15-month-olds’ learning in the Coda condition, we further conducted a repeated measures of ANOVA with Legality (legal or illegal) as a within-subject factor, and Age (12 or 15 months) as a between-subject factor. No significant main effect of Age, $F(1, 22) = 0.26, p = .619$, or Legality $F(1, 22) = 0.12, p = .734$ was found. However, the Legality x Age interaction, $F(1, 22) = 8.34, p = .009, \eta^2_p = .275$, shows that there is a significant difference between 12- and 15-month-olds’ looking times to legal versus illegal trials in the Coda condition. This occurred because 12-month-olds failed to show a preference, $F(1, 22) = 3.24, p = .086$, while 15-month-olds showed preference for the legal test trials, $F(1, 22) = 5.22, p = .032$, Cohen’s $d = 0.66$.

Discussion

In Experiment 1, 8-month-olds failed to learn the experimental pattern in both Onset and Coda conditions, and 12-month-olds showed significant effects in the Onset condition but not in the Coda condition. In Experimental 2, 15-month-olds showed significant looking time differences in the Coda condition. These results suggest not only that the phonotactic patterns we exposed

![Figure 1](https://example.com/figure1.png)

**FIGURE 1** 8-, 12- and 15-month-olds’ looking times to legal and illegal trials in Onset and Coda condition. Error bars show standard error. *Looking times to legal and illegal trials are significantly different.
infants to in the Coda condition are learnable, but also that this learning may be delayed with respect to the phonotactic patterns presented in the Onset condition. These results support the Asymmetrical hypothesis and suggest that the learnability of phonotactic patterns varies as a function of syllable position.

GENERAL DISCUSSION

The purpose of this study was to explore whether there is an asymmetry in English infants’ learning of voiced fricatives in word-medial onset and coda positions. English-learning 8-month-olds failed to learn the experimental pattern in both conditions. Twelve-month-olds learned the phonotactic pattern in the Onset condition, but they did not learn the same regularity in the Coda condition. In contrast, English-learning 15-month-olds showed evidence of learning even in the Coda condition. These results are consistent with the Asymmetrical hypothesis and suggest that phonotactic learning varies as a function of syllable position.

The fact that infants as young as 4 months are able to learn a wide range of phonotactic patterns (e.g., Saffran & Thiessen, 2003; Seidl & Buckley, 2005; Seidl et al., 2009) may make it seem surprising that 8-month-olds failed to learn the phonotactic patterns in our study. What factors can account for 8-month-olds’ failure in learning phonotactic patterns in both onset and coda positions? There are at least three explanations we might want to take into consideration: First, the task of phonotactic learning in word-medial positions is more challenging than word-edge ones. As mentioned, we know that 1- to 4-month-olds discriminate the [ra]-[la] contrast, but fail to discriminate the [marana]-[malana] contrast (Karzon, 1985). Infants’ failure to discriminate contrasts in the second case is likely because word-medial consonants are acoustically less salient and thus are more difficult to perceive. In addition, adults learn phonotactic regularities better at edge positions than in medial positions (Endress & Mehler, 2010). Endress and Mehler (2010) suggest that this difficulty occurs because the pauses that may occur at word-edges facilitate speech processing of units at word boundaries; further, the initial and final strengthening makes these units acoustically more salient (e.g., Cooper & Paccia-Cooper, 1980; Fougeron & Keating, 1997; Keating et al., 2003; Wightman et al., 1992), thus facilitating young infants’ speech processing. Second, the segments involved in our study -fricatives, may be more difficult to process than stops (e.g., Weisler & Milekic, 1999). Specifically, several studies show that the perception of fricatives is delayed with respect to other sounds (Nittrouer & Studdert-Kennedy, 1987; Polka, Colantonio, & Sundara, 2001). This characterization is consistent with Eiler’s (1977) study showing that it is more difficult for 2- to 5-month-olds to discriminate voicing contrast between two fricatives [as] versus [az] than between two stops [at] vs. [ad]. Thus, it is possible that 8-month-olds are able to learn phonotactic patterns in word-medial positions involving other natural classes, such as stops, or nasals; however, our current data do not allow us to determine whether this is true or not. Third, some may argue that the phonotactic patterns in our current study were unfamiliar and conflict with children’s English input. Thus, perhaps these young infants were more confused than older infants and because of this showed no evidence of learning. This last argument, however, is not persuasive given that Seidl et al. (2009) found that 4-month-olds are able to learn both unnatural and natural patterns within a short period of exposure. Therefore, it is more likely that 8-month-olds’ failure in learning phonotactics is due to either the word-internal constraints and/or acoustic saliency.
The fact that 12-month-olds learned the pattern only in the Onset condition supports our hypothesis that phonotactic learning is asymmetrical. However, there are two possible interpretations of the results as to which patterns infants have learned in the Onset condition. The first possibility is that the infants have learned that “voiced fricatives only appear in onset position.” If this were true, our results may suggest that word-medial onset phonotactics are learned earlier than word-medial coda ones. The second possibility is that infants have learned the restriction that “voiced fricatives never appear in coda position.” If this were true, then our results suggest that coda restrictions are learned earlier than onset ones. Given the design of current study, we cannot adjudicate between these two possibilities; however, based on infants’ better discrimination of contrasts in word-initial position than word-final position from previous perception studies, we think it is less likely that the infants learned the restricted pattern. Further, evidence from syntactic acquisition suggests that infants do not like restrictions (Bentea & Durrleman-Tame, 2013). Specifically, in this study they tested French-speaking infants on a character selection task with structure-type, animacy, and set-restriction as variables. Results showed that infants performed better for –set-restricted object A’-dependencies than for +set-restricted ones. Thus, we speculate that infants may also be resistant to similar restrictions in phonotactic learning. Accordingly, it is most likely that infants learned that “voiced fricatives only appear in onset position” in the Onset condition, and learned that “voiced fricatives only appear in coda position” in the Coda condition.

The fact that 15-month-olds showed a preference after familiarization with the phonotactic pattern in Coda condition may suggest that developmental changes enable older infants to pay attention to coda phonotactics, but the reason is unclear. One may speculate that the increased sensitivity to codas at 15 months is due in part to a growth in morphological awareness. There is growing evidence that in the second year of life, infants begin to pay attention to sentence structures and morphology (e.g., Shady, 1996; Soderstrom, Wexler, & Jusczyk, 2002). This increasing sensitivity to morphology, for example, suffixes, may encourage language-learning infants’ growing sensitivity to codas in general. Thus, it is possible that English-learning 15-month-olds learned the phonotactic pattern in coda position because attention to morphemes in codas led them to attend to codas elsewhere. Although word-medial codas do not act as loci of morphologically rich information, infants having learned to attend to word-final codas by this age may extend this knowledge to word-medial codas (Bernard, 2011). Interestingly, if it were true that attention to codas is bootstrapped from morphology, then infants with mostly prefixal morphology in their input language may not show an ability to attend to codas until later in development. However, it is also possible that the ability to attend to codas word-medially and elsewhere is what aids in later morphological acquisition. If this were the case then this finding would not depend on the locus of morphological marking in the input language. The results from previous studies seem to favor the view that prosody constrains language learners’ perception and production of morphemes (Demuth, 2001; Song, Sundara, & Demuth, 2009; Sundara, Demuth, & Kuhl, 2011). For example, 22- and 27-month-olds are sensitive to the inflectional morpheme -s in sentence-final, but not in sentence-medial positions (Santelman & Jusczyk, 1998; Sundara, Demuth, & Kuhl, 2011). Similarly, Demuth (2001) analyzed speech production data elicited from a 20- to 21-month-old Spanish-speaking child, and found that the inclusion and omission of certain morphemes can be predicted based on children’s general prosodic knowledge. Moreover, Santelman and Jusczyk (1998) found that when presented with passages containing either a well-formed dependency between the auxiliary verb is and the verb ending -ing, or an ill-formed dependency
relation between the auxiliary verb can and -ing, but not 15-month-olds showed preference for the well-formed passages. Therefore, it may be more plausible that prosodic growth bootstraps morphological growth.

The current study is limited in several respects. First, as noted above, the frequency count of voiced fricatives in word-medial onset and coda position was taken from an adult corpus; however, IDS corpora may provide more reliable approximation of the input to infants. Second, though we speculate that infants learned phonotactics earlier in onset position based on the results from previous perception and learning studies, due to the design of our study we are not able to firmly differentiate between the explanation that infants learned that “the voiced fricatives only appear in onset position” or the explanation that infants learned that “voiced fricatives never appear in coda position.” An ideal followup would to explore these two alternatives. Finally, the stimuli included only trochees, such that the coda patterns appeared in the stressed syllable and the onset patterns appeared in the unstressed syllable of the word. Thus, there is a potential confounding of stress and syllabic position. It would be interesting for future work to replicate the present studies with other types of word forms such that the coda patterns were in the unstressed syllable and the onset patterns in the stressed syllable in order to examine interactions between syllable position and word stress.

We have demonstrated that infants’ learning of phonotactic patterns is earlier in the Onset condition than in the Coda condition. We interpret our results as showing that infants’ learning of phonotactics is asymmetric at 12 months. However, due to a growth in linguistic experience, infants begin to show less asymmetric behavior at 15 months. This finding is consistent with previous findings from infant’s perception of word-initial and -final contrasts. Furthermore, this research sheds light on how infant’s phonotactic learning patterns may be related to cross-linguistic positional patterns and how pattern learning is affected by ongoing language experience.

5 To answer the question as to whether there is any correlation between infants’ morphology and prosodic development we have been tracking 15-month-olds participants’ vocabulary development. Parents are asked to complete a MacArthur Communicative Development Inventory (CDI) – Words and Gestures when infants are 18-months-old. Twelve 15-month-olds have participated in the Coda condition; however, we were able to gather only 7 infants’ vocabulary outcome at 18-month-olds due to attrition. We conducted a bivariate correlation analysis between infant looking times and vocabulary output. The result showed that these two variables were not correlated, \( r = -0.367, p = .419 \). This data provides evidence that 15-month-olds’ learning of coda phonotactics in our study is not morphologically driven.

6 Segments in stressed syllables may have an acoustic advantage over those from unstressed syllables, and this is especially true in IDS given that prosodically salient units are exaggerated more than unstressed syllables (Wang, Cristià, & Seidl, in revision). Furthermore, this exaggeration applies to both vowels and consonants. For example, Cristià (2010) found that sibilants were enhanced in IDS as compared to ADS. In order to compare the acoustics of segments in onset and coda position, we segmented the target fricatives in Praat (Boersma & Weenink, 2011) and extracted three acoustic measurements, duration, amplitude, and fundamental frequency (F0), from the target fricatives across the familiarization (120 tokens) and test trials (96 tokens). We obtained the duration and amplitude measurements for all the target fricatives (108 tokens for onset and 108 tokens for coda); however, only 193 tokens (107 for coda, and 86 for onset) F0 measurements were obtained due to devoicing of some target segments. Analyses of variance (ANOVA) were performed on each of the measurements with two independent variables: syllable position and segment properties. Results indicate that word-medial coda fricatives were greater both in amplitude, \( F(1, 215) = 34.54, p < .0001 \), and F0, \( F(1, 192) = 20.42, p < .0001 \), than word-medial onset fricatives. However, there were no significant differences in duration \( F(1, 215) = 0.13, p = .716 \). Thus, analyses of acoustic measurements made on the target fricatives suggest that voiced fricatives are more salient in word-medial coda position than in onset position. This may result from hyperarticulation of fricatives in stressed syllables.
REFERENCES


APPENDIX

Familiarization stimuli for Onset condition: CVC.FVC


Familiarization stimuli for Coda condition: CVF:CVC


Test stimuli

CVF:CVC

1. lið.run, gæv.dub, niz.dam, nuð.lag, buэ.gan, duz.gib, mié.ðar, rié.ðæd, gæz.lib, mié.gul, raz.dun, buð.mæg
2. baэ.gam, deav.lin, raz.gun, raэ.nul, gav.bum, daэ.nib, nué.mil, gið.lub, mié.nal, raэ.ðin, mié.gar, deé.rug
3. gi₃.læb, biv.dæn, gi₀.rab, bæv.mad, ra₀.bul, liz.mag, læ₃.din, ruv.mag, di₀.ram, niv.rum, gæv.bul, bi₀.dæm
4. ma₃.rid, buv.nig, læ₃.rug, guz.dib, la₃.bug, dæz.nim, ra₃.dæb, ruz.nig, li₃.dum, lu₀.bær, gaz.mun, ræv.nid

CVC FVC

5. lum.zæl, ræn.zub, mun.₃ig, nid.var, nud.vag, mib.ðud, gæl.vad, nug.zam, bud.ðim, bar.væm, dar.ʒib, dær.zun
6. big.ðan, din.vud, bad.ʒul, mab.vul, bug.ðæm, mag.zin, nud.ðig, din.zæb, mib.ðar, gæl.vum, lær.ʒub, gim.zær
7. gæb.ðil, rib.æd, rud.ðib, lil.væd, rib.ʒæg, bid.zæl, gær.ðul, næd.zul, næg.ʒim, mil.var, rib.væl, nem.ʒur
8. mæl.zur, rød.ðin, dæg.vum, næg.zab, gin.ʒad, bug.ẓid, bim.væl, run.ʒig, gær.vin, gab.ðim, nul.zid, rug.ʒil