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Finding patterns and learning words: Infant phonotactic knowledge is associated with vocabulary size

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ABSTRACT

Native language statistical regularities about allowable phoneme combinations (i.e., phonotactic patterns) may provide learners with cues to support word learning. The current research investigated the association between infants' native language phonotactic knowledge and their word learning progress, as measured by vocabulary size. In the experiment, 19-month-old infants listened to a corpus of nonce words that contained novel phonotactic patterns. All words began with "illegal" consonant clusters that cannot occur in native (English) words. The rationale for the task was that infants with fragile phonotactic knowledge should exhibit stronger learning of the novel illegal phonotactic patterns than infants with robust phonotactic knowledge. We found that infants with smaller vocabularies showed stronger phonotactic learning than infants with larger vocabularies even after accounting for general cognition. We propose that learning about native language structure may promote vocabulary development by providing a foundation for word learning; infants with smaller vocabularies may have weaker support from phonotactics than infants with larger vocabularies. Furthermore, stored vocabulary knowledge may promote the detection of phonotactic patterns even during infancy.

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Introduction

Experience shapes learning across development. It promotes specialization for processing the information present in one's own environment, yielding efficient and robust learning and information processing systems. For example, in language acquisition experience underpins infants' tuning to native phoneme categories (e.g., Werker & Lalonde, 1988; Werker & Tees, 1984) and the development of object name learning biases (Byers-Heinlein & Werker, 2013; Smith, Jones, Landau, Gershkoff-Stowe, & Samuelson, 2002). The current research investigated another crucial process in infants' language specialization—learning how sounds are used in words (Saffran & Graf Estes, 2006; Werker & Yeung, 2005).

One aspect of the native language sound system that infants must acquire is phonotactic information, which refers to the constraints on phoneme combinations in a given language as well as the probabilities with which phonemes and phoneme combinations occur. A key component of a language's phonotactic inventory is the distinction between those sound combinations that are attested in the words of the language (i.e., phonotactically legal sequences) and those sound combinations that are unattested (i.e., phonotactically illegal). At a young age, infants distinguish between phonotactically legal and illegal sound sequences. When presented with lists of novel words that consist of phonotactically legal or illegal word forms, 9-month-old infants listen longer to the legal word forms (Friederici & Wessels, 1993; Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993; Sebastián-Gallés & Bosch, 2002). Also at 9 months of age, infants can make an even more fine-grained distinction between two types of word forms that are phonotactically legal—those that consist of high-frequency phonemes and phoneme combinations versus those that consist of low-frequency phonemes and phoneme combinations (Jusczyk, Luce, & Charles-Luce, 1994; Nazzi, Bertoncini, & Bijeljac-Babic, 2009; see also Zamuner, 2006). Some experiments have demonstrated increasing sensitivity to native language phonotactics from 6 to 9 months of age (Jusczyk et al., 1993), indicating that phonotactic knowledge develops over time and with increased linguistic experience.

Infants' learning of phonotactic information has great potential to affect language acquisition, particularly vocabulary development. One possible point of influence is on the process of detecting individual words within the fluent stream of speech. Phonotactic patterns provide cues to word boundaries. For example, phonotactic patterns can aid in word segmentation when English speakers hear a phrase such as "give to" (/gIv tu/) because phonotactic constraints indicate that the sequence /vt/ does not tend to occur within words. Accordingly, phonotactic patterns suggest that the appropriate parsing is (/gIv tu/) rather than /gIvt u/ or /gI vtu/. Mattys and Jusczyk (2001) reported that infants can make use of such segmentation cues (see also Mattys, Jusczyk, Luce, & Morgan, 1999). They presented 9-month-olds with target nonce words embedded in phrases with phonotactic cues for segmentation. That is, the phoneme combinations surrounding the target word's onset and offset formed phoneme combinations that frequently occur across word boundaries but not within native language (English) words. Infants displayed evidence of segmenting and recognizing the novel words when good phonotactic cues were present but not when they were absent. This work demonstrates that well before infants amass large vocabularies, their early learning about sound combinations has potential to shape lexical development and contribute to the development of the protolexicon.

Graf Estes (2014) explicitly tested how infants use early phonotactic cues to support the process of linking new word forms with meanings during lexical acquisition. In the experiment, 14-month-old infants listened to passages containing two target words. The target words were embedded in either sentences that contained phonotactic segmentation cues to the target words' locations or sentences that lacked phonotactic segmentation cues (similar to Mattys & Jusczyk, 2001). The infants subsequently participated in a task where the target words were used as object labels; the labels were presented in isolated repetitions, not in fluent speech. The infants exploited phonotactic word segmentation cues to detect words and subsequently associate them with referents. Infants successfully associated the target words with objects only when they had initially heard the words embedded in sentences containing phonotactic segmentation cues to the target words' locations. When the same target words were initially presented in passages without phonotactic segmentation cues, infants failed to learn the object labels. Thus, one mechanism by which early phonotactic knowledge may

affect vocabulary development is through helping infants to discover word forms within continuous speech, thereby making words available to be associated with meanings and added to the lexicon.

Another process by which phonotactic knowledge may promote vocabulary development is by shaping infants' expectations about the forms that words can take, thus constraining word learning. To test the effects of phonotactic patterns on label learning, Graf Estes, Edwards, and Saffran (2011) presented infants around 19 months of age with object labels that were either phonotactically legal or illegal in English. Overall, infants learned the legal labels but not the illegal labels (see MacKenzie, Curtin, & Graham, 2012, for evidence with younger infants; see Nazzi & Bertoncini, 2009, for alternative findings). However, there were also differences in learning associated with vocabulary size. Infants with larger vocabularies showed stronger phonotactic constraints on label learning; they showed greater differentiation of legal versus illegal labels than infants with smaller vocabularies. In related work, Storkel (2001) found that preschool-aged children learned high phonotactic probability more readily than low-probability words. Children with larger vocabularies showed stronger phonotactic effects than children with smaller vocabularies; they had a greater advantage for high-probability labels than for low-probability labels. Taken together, these findings suggest that with vocabulary development, young learners may develop more stringent criteria for the sound sequences that are possible word forms, thereby constraining the search for words to link with meanings. This selectivity may promote efficient lexical acquisition in two ways. First, infants will avoid wasting cognitive resources entertaining illegal word forms as labels for concepts. Second, successful learning of new legal or canonical words may strengthen emerging representations of the phonotactic constraints and probabilistic patterns present in the ambient language (Beckman & Edwards, 2000; Edwards, Beckman, & Munson, 2004).

Early in development, detecting native language phonotactic patterns may play a key role in lexical acquisition and, therefore, may be associated with vocabulary development. There are findings regarding the development of phoneme perception that inform this prediction about phonotactic knowledge. Kuhl, Conboy, Padden, Nelson, and Pruitt (2005) investigated the association between native and non-native phoneme perception and language skills. They measured 7-month-olds' perception of native and non-native phoneme distinctions and found that infants who performed well on a native (English) contrast performed poorly on a non-native (Mandarin Chinese) contrast. In addition, native contrast discrimination correlated positively with productive vocabulary size and utterance complexity more than 10 months later. In contrast, non-native contrast discrimination correlated negatively with later vocabulary size and complexity. Infants with more language-specific phoneme perception displayed more sophisticated language skills than infants who remained open to non-native phoneme discrimination. Kuhl and colleagues proposed that the developmental pattern observed here reflects neural commitment to native language structure and that neural commitment provides a foundation for further acquisition of linguistic structure. It is possible that the general principle of language-specific commitment applies to aspects of language development beyond phoneme perception. It may apply to learning phonotactic patterns as well.

Given the potential for phonotactic patterns to affect lexical acquisition through the processes of word segmentation and constraining potential word forms, early knowledge of phonotactic patterns may be connected to vocabulary size. There may be a complex relation between the two. First, infants who do not show strong native language-specific processing may be at a disadvantage in vocabulary development. Furthermore, the influence is likely to be bidirectional; extracting phonotactic information from the ambient language may facilitate vocabulary acquisition, and accumulating vocabulary knowledge may facilitate the discovery of phonotactic patterns and broadly strengthen phonological representations. In the current research, we took an essential step toward understanding these proposed relations by investigating whether an association between phonotactic knowledge and vocabulary knowledge exists during infancy.

In addressing the connection between phonotactic and vocabulary knowledge, an ancillary goal was to rule out potential confounds and examine the specificity of the proposed relation. As discussed previously, there is prior evidence with infants (Graf Estes et al., 2011) and young children (Storkel, 2001) that phonotactic knowledge is associated with vocabulary size in label mapping tasks, but the methods used in prior research incorporated both the demands of processing word forms that varied in phonotactic patterns and the demands of associating word forms with referents. The demands

of the tasks may have affected learners' interpretation of the sound sequences. Infants have been found to treat sound sequences differently in perceptually-based tasks versus mapping tasks (e.g., Stager & Werker, 1997). In tasks that are designed to measure perception rather than mapping, infants may attend more closely to the details of sound sequences. In the current task, we removed the label mapping demands to focus on how learners process phonotactic patterns. Therefore, any association between phonotactic and vocabulary knowledge that is detected cannot be attributed to general facility with learning sound–meaning mappings.

In addition, when investigating correlations between learning measures, it is important to examine whether the associations are specific or whether they can be attributed to nonspecific cognitive processing abilities. For example, Newman, Ratner, Jusczyk, Jusczyk, and Dow (2006) found that infants' word segmentation performance was selectively associated with later language skills and not with a measure of general cognition. Here, we have proposed a specific association between phonotactic and vocabulary knowledge. It is also possible that infants who are skilled in phonotactics processing tasks in the lab are skilled in vocabulary development as well as in general information processing abilities that are not particular to language. Infants with large vocabularies may be at an advantage in the phonotactics task because they are cognitively advanced across the board and, therefore, underlying general cognitive skills could explain the association we aim to detect. We sought to examine the association between phonotactic and vocabulary knowledge in a way that minimizes the potential for underlying mechanisms of general cognition to drive the effect.

To investigate the relation between infant phonotactic knowledge and vocabulary knowledge, we incorporated two important design elements. First, we collected a measure of general cognition that is largely separated from linguistic knowledge (Cognitive scale, Bayley Scales of Infant and Toddler Development–Third Edition; Bayley, 2006) in order to statistically control for general cognition while examining the association between performance on the phonotactics task and vocabulary size. We predicted that vocabulary size would predict phonotactics task performance even after accounting for the effects of general cognition. Second, we designed a phonotactic learning task in which prior knowledge of native language (English) phonotactics should interfere with successful performance. Therefore, as discussed in detail below, infants with larger vocabularies should be at a disadvantage in the phonotactics task. This design disrupts the process in which good learners are good learners regardless of the task presented to them. It allows us to focus on the specific connection between vocabulary size and what infants know about native language phonotactics.

In the experiment, we tested 18- and 19-month-old infants because by this age reliable measures of vocabulary size can be collected and there is wide variation in vocabulary size to be explored (Fenson et al., 2000). Emerging language delays in young children (i.e., late talkers) also start to be identified around this age (Hawa & Spanoudis, 2014; Rescorla & Achenbach, 2002; Thal & Bates, 1988). If phonotactic knowledge plays an important role in word learning, infants who lack phonotactic knowledge may be at a disadvantage in vocabulary development. Testing infants at around 19 months of age allowed us to examine a range of productive vocabulary sizes and the association with phonotactic learning performance. The participants' age range also overlaps with the age ranges of prior research investigating the development of early phonological representations (Graf Estes et al., 2011; Hay, Graf Estes, Wang, & Saffran, 2015; Mulak, Best, Tyler, Kitamura, & Irwin, 2013; White & Aslin, 2011).

Given the age of the participants, it was not appropriate to present a phonotactic discrimination task similar to previous research (e.g., Friederici & Wessels, 1993; Jusczyk et al., 1993). In these tasks, infants differentiate legal versus illegal, or common versus rare, sound sequences by 9 months of age or even younger (e.g., Archer & Curtin, 2011). Therefore, by 18 or 19 months of age, when there is ample variation in vocabulary size, there is likely to be little variation in infants' abilities to differentiate between sound sequences that vary in phonotactics. Accordingly, we designed a phonotactics task to tap learning at a point in development where no other measures of native phonotactic knowledge exist and a task geared toward detecting individual differences in performance.

The infants participated in a phonotactic learning task that was modeled on previous work by Chambers, Onishi, and Fisher (2003, 2011), who presented infants with phonotactic patterns (that did not violate native phonotactics) during a brief listening phase. They heard CVC (consonant–vow el–consonant) novel words with constraints on the identity of word-initial and word-final consonants.

Chambers and colleagues found that infants rapidly learned the novel phonotactic patterns, demonstrating the power of infants' ability to learn from patterns present in linguistic input (see also Cristia & Seidl, 2008; Saffran & Thiessen, 2003; Seidl & Buckley, 2005; Seidl, Cristia, Bernard, & Onishi, 2009; Seidl, Cristia, & Onishi, 2014; Wang & Seidl, 2014). Our task was not intended to measure basic pattern detection skills and their association with vocabulary (an interesting independent question); rather, we exploited the paradigm to tap native phonotactic knowledge. Previous research has shown that infants' emerging native language knowledge affects how they learn novel phonotactics. Seidl and colleagues (2009) found that younger English-learning infants (4-month-olds) were open to learning novel phonotactic patterns that incorporated vowel distinctions that are allophonic in English but phonemic in French (oral vs. nasal vowels). Younger infants behaved similarly to 11-month-old French infants. In contrast, 11-month-old English-learning infants did not learn the patterns because they relied on non-phonemic distinctions. Thus, phonotactic learning tasks show promise as a means to tap native language processing.

In the current phonotactic learning task, infants listened to lists of novel words that violated English phonotactics. The words all began with consonant clusters that do not occur word-initially in English (e.g., *tlan, psoog, fwote, shnim*). Evidence from listening time (Archer & Curtin, 2011; Sebastián-Gallés & Bosch, 2002) and label learning tasks (Graf Estes et al., 2011) has shown that infants across a broad age range perceive sufficient detail to detect illegal phonotactics in consonant clusters, thereby indicating that cluster misperception is unlikely to limit performance in the current task. We predicted that infants' learning would be challenged by the presence of the illegal word-initial consonant clusters because existing knowledge of English phonotactics should interfere with learning the structures. This prediction is linked to the concept of proactive interference, where past learning interferes with new learning. In these circumstances, new learning may require overriding current expectations or inhibiting prior knowledge. Such interference effects have been demonstrated in a wide range of learning and memory tasks (reviewed in Kahana, 2012) as well as in language transfer during second language acquisition (reviewed in Jarvis & Pavlenko, 2008; Odlin, 1989). In an experimental task with adults, Finn and Hudson Kam (2008) found that learners had difficulty in learning novel syllable co-occurrence patterns when they contained consonant clusters that conflicted with native language (English) phonotactics. Similarly, we expected that illegal consonant clusters should be difficult to learn because they violate the patterns in which learners are immersed. However, we did not expect the phonotactics to be *uniformly* difficult for infants to learn. Rather, we predicted that infants with smaller vocabularies would have weaker language-specific specialization and, therefore, would show stronger learning of the novel phonotactic patterns than infants with larger vocabularies.

The measure of infants' learning was based on their listening time. After listening to the training with the novel word lists, the infants heard test items that were either consistent (e.g., *tleeb, shnef, psav, fwid*) or inconsistent with the training phonotactics (e.g., *tsud, fneek, pwope, shluk*), but all of the items violated English phonotactics. If infants learned the phonotactics from the training, they should listen longer to the items that violated training. We predicted that infants with smaller vocabularies would show a stronger listening preference for the violation test items than infants with larger vocabularies (consistent with Chambers et al., 2003), thereby demonstrating greater openness to non-native phonotactics than infants with larger vocabularies.

Method

Participants

The participants were 58 infants (31 female and 27 male) aged 18 or 19 months (M = 19.3 months, range = 18.2–19.9). All infants were born full term and had no history of vision or hearing impairments or chronic ear infections. All infants were from English-speaking households, and 11 infants had some exposure to a second language at home or in child care (M = 3.5 h/week, SD = 2.4, range = 1–8). The pattern of results is the same with these infants excluded from the sample. Additional infants who participated were excluded from analyses because of fussiness (e.g., crying, squirming; n = 26), excessive movement that prevented coding (n = 10), reaching maximum listening time on 7 of 8 test trials (n = 2), not returning the vocabulary inventory or returning for the cognitive assessment (n = 9),

equipment or experimenter error ($n = 4$), and parent interference ($n = 3$). At the first session, infants participated in the phonotactic learning task and parents received a vocabulary inventory to complete at home. Infants returned to the lab for a second visit to complete the cognitive assessment.

Materials

Bayley Scales of Infant and Toddler Development–Third Edition

Infants received a standardized assessment of general cognitive development using the Cognitive scale on the Bayley Scales of Infant and Toddler Development–Third Edition (Bayley-III; Bayley, 2006), which is normed for use with 1- to 42-month-olds. A trained research assistant administered the Cognitive scale, including measures of object permanence, tool use, imitation, and puzzle solution. Although verbal mediation likely plays a role in some tasks (e.g., following instructions), confirmatory factor analyses support the validity of the Cognitive scale that is differentiated from the Language and Motor scales of the full measure (Bayley, 2006). The Bayley-III was revised from previous editions of the Bayley to support greater separation of the language and cognitive measures. Thus, although it might not provide a "pure" measure of nonverbal cognition, the Cognitive scale can be considered to primarily tap general or nonverbal cognitive skills and has been applied accordingly in recent research (e.g., Kover & Ellis Weismer, 2014). In the current sample, we found no significant correlation between infants' cognitive scores and vocabulary sizes ($r = .194$, $p = .145$) (vocabulary measurement is discussed below). Table 1 presents infants' standardized cognitive composite scores. The task was designed with a mean standard score of 100 ($SD = 15$); the standardization accounts for the infant's age.

Language Development Inventory

Parents completed the MacArthur–Bates Communicative Development Inventory (MCDI), Word and Sentences form, a popular parental report measure of infant and toddler language skills (Fenson et al., 2007). The inventory includes a checklist of 680 productive vocabulary items as well as items about early grammatical productions. Because our predictions are specific to vocabulary knowledge, we examined data from the vocabulary sections only. The MCDI has been used in several previous investigations of the association between lab-based language processing tasks and vocabulary development (Benasich & Tallal, 2002; Kuhl et al., 2005; Newman et al., 2006; Singh, Reznick, & Xuehua, 2012; Werker, Fennell, Corcoran, & Stager, 2002). Table 1 presents infants' standardized vocabulary percentile scores, which account for age and sex.

Stimuli

Phonotactics training phase

Infants listened to a list of novel words incorporating phoneme clusters that violated English phonotactic patterns. To control for arbitrary listening preferences and prevent specific clusters from driving any learning effects, we created two training conditions. The items in both conditions are listed in Table 2. Infants were randomly assigned to listen to one condition. In Condition A, the illegal consonant clusters at the word onsets were /tl, ps, fw, ʃn/. In Condition B, the clusters contained the same consonants in different combinations: /ts, pw, fn, ʃl/. The clusters were selected to meet the following criteria: To create well-balanced training conditions, the consonants must recombine to form two versions of illegal consonant clusters with the same onsets; the clusters must be pronounceable without epenthetic vowels; and each consonant must occur in only one cluster per condition. In addition, whereas the clusters are illegal in word onsets in English (although not in other word positions), they are legal in word onsets in other languages. For example, /ʃn, ʃl, ps/ occur in German, /fw/ and /pw/ occur in Spanish, /fn/ occurs in Danish, /tl/ occurs in Hebrew, and /ts/ occurs in Greek.[3] Although some of the clusters occur in words borrowed from other languages (e.g., *pueblo*), the clusters are likely to have very low frequency in English infant-directed speech.

[3] The sequence /ts/ is generally interpreted as an affricate consonant rather than a consonant cluster in Greek. In the current experiment, if the English-learning infants interpreted /ts/ as an affricate rather than a cluster, it does not affect our key predictions. Neither occurs word-initially in English, and both represent phonotactically illegal word onsets.

Table 1
Infants' mean (and standard deviation) ages, Cognitive scale scores, and productive vocabulary scores.

	n	Age (months)	Cognitive scale	Productive vocabulary percentile
All infants (*N*)	58	19.3 (0.47)	108.2 (10.2)	51.8 (27.1)
Vocabulary size groups				
Small vocabulary	19	19.1 (0.58)	108.2 (9.9)	19.5 (11.7)
Medium vocabulary	19	19.5 (0.27)	103.9 (9.9)	54.1 (8.5)
Large vocabulary	20	19.3 (0.46)	112.3 (9.5)	80.3 (9.9)

Note. The Cognitive scale represents the cognitive composite score, a standardized measure from the Bayley-III (Bayley, 2006). The productive vocabulary percentile is based on the MCDI (Fenson et al., 2007).

Table 2
Training sets for Conditions A and B.

Condition A words				Condition B words			
fwæz	psɛb	ʃnal	tlæn	fneɪd	pwag	ʃlæt	tsæl
fwas	psɪl	ʃnap	tleɪv	fnaɪz	pwis	ʃlaɪg	tsab
fwaɪs	psof	ʃnaɪz	tlig	fnob	pwɪf	ʃlɛz	tsam
fwuz	psag	ʃnɪm	tlok	fnup	pwod	ʃlɪb	tseɪp
fwot	psug	ʃnɪl	tluf	fnuv	pwun	ʃloz	tsɛg
fwug	psum	ʃnos	tlʌd	fnʌl	pwut	ʃlʌn	tsub

Note. Each word was repeated four times in the training corpus. The words were presented in a pseudo-random order.

Table 3
Mean (and standard deviation) duration and pitch (fundamental frequency) for the training and test items sets.

	Duration (ms)	Pitch (Hz)
Training sets		
Condition A words	983 (159)	227 (17)
Condition B words	949 (117)	225 (28)
Test items		
Condition A consistent/Condition B violation	994 (113)	226 (24)
Condition B consistent/Condition A violation	992 (78)	229 (20)

To create the novel words for training, each onset cluster was paired with six distinct CV word endings, creating a set of 24 words per condition, listed in Table 2. The word endings were assigned with the constraint that the words not form phonological neighbors with words highly likely to be familiar to infants. To create the full training corpus, each word occurred four times in a pseudo-random order, with the constraint that no more than two words in a row started with the same cluster. Two randomizations were created; infants were randomly assigned to each order. The full duration of the 94-item training corpus was 3 min 15 s in Condition A and 3 min 10 s in Condition B.

A female native English speaker was trained to produce illegal phonotactic clusters fluently and without introducing pauses, phoneme deletions, or epenthetic vowels between the consonants of the illegal clusters (see Davidson, 2006, for a discussion of the corrections speakers make when producing non-native sequences). We examined waveforms and spectrograms of the speech samples to confirm that the clusters were produced as intended. The mean duration and fundamental frequency (F0, a measure of pitch) of the items are shown in Table 3. The speaker produced the words in citation form with a moderately infant-directed speaking style. The words were played with a 1-s silence between each item. The stimuli were analyzed and equalized for volume in Praat (Boersma & Weenink, 2010). They were played at approximately 65 dB at infants' head level.

Table 4
Test items for Conditions A and B.

Condition A consistent/Condition B violation				Condition B consistent/Condition A violation			
fwæn	psæb	ʃnæf	tlib	fnæk	pwaz	ʃlad	tsiv
fwib	psav	ʃnid	tlaɪp	fneɪs	pweɪm	ʃlim	tsaɪf
fwaɪk	pseɪt	ʃnaɪd	tlɛn	fnɛd	pwaɪv	ʃlip	tsɛm
fwɪd	psɛk	ʃnɛf	tlɪs	fnik	pwop	ʃlɪn	tsud
fwʌm	psʌt	ʃnʌz	tlov	fnʌb	pweɪg	ʃluk	tsʌf

Note. In each trial, infants heard one word representing each cluster (four words per trial). The four words were repeated in an order randomized by blocks.

Test phase

During testing, infants listened to new word lists presented in two types of test trials. During the *consistent* test trials, the test items began with the consonant clusters from the training phase paired with previously unused VC endings. During the *violation* test trials, infants heard words that violated the trained phonotactics and also included novel VC endings. The violation trials were created so that the initial consonants were consistent with training, but the second consonants were swapped across the clusters. For example, during training in Condition A, infants heard words such as *psoog* /psug/, *fwote* /fwot/, *shnil* /ʃnɪl/, and *tleeg* /tlig/; during violation test trials, they heard *pwope* /pwop/, *shleem* /ʃlim/, *fnub* /fnʌb/, and *tsem* /tsɛm/. Conditions A and B were designed so that the same test items could be used for all infants. As shown in Table 4, words that were consistent test items in Condition A were violation items in Condition B and vice versa. In both conditions, the consistent and violation test items differed in critical but subtle ways. Both test item types violated English phonotactics and contained novel word endings, and they shared consonants. However, only the violation test items were inconsistent with infants' prior phonotactic training.

We created a test pool of 20 consistent test items and 20 violation test items. In the pool, each onset cluster was paired with five distinct word endings. During testing, each infant heard four consistent trials and four violation trials. Each trial included four distinct words, one representing each of the four onset clusters. The words were repeated in an order randomized by blocks to create a maximum trial length of 20 s. There was 1 s of silence between each word. Test trials were presented in one of eight randomized orders.

Each auditory test sequence was paired with a visual animation of a green crescent rotating in a circle. The animation was the same for all test trials. The duration of attention to the audiovisual stimulus was used to measure infants' listening time to the test items.

Procedure

During training, the infant and a parent played quietly in a sound-attenuated booth. The parent was instructed to talk as little as possible and not to refer to the experimental stimuli. Following training, the infant and parent moved to the test booth. The infant sat on the parent's lap. The parent heard brief reminder instructions before testing started. Because of this delay, infants heard an additional 30 s of the training corpus, accompanied by a soundless cartoon, before the test trials started. The parent listened to music on headphones to prevent biasing the infant's responses.

In the test booth, the infant sat approximately 3.5 feet from a television with integrated speakers. A camera mounted below the screen displayed a video image of the infant's face to a monitor for the experimenter to observe. The program Habit X (Cohen, Atkinson, & Chaput, 2004) was used to present the test stimuli and to record infants' responses. The experimenter was blind to the identity of the stimuli being presented.

We used an infant-controlled auditory preference procedure to measure infants' attention to the two types of test trials. Each trial began with an attention-getting cartoon. When the infant looked at the screen, the experimenter triggered the presentation of a test trial consisting of a visual animation paired with novel words that were consistent with or violated the trained phonotactics. The trial

continued to play until the infant looked away for at least 1 s or looked for a maximum of 20 s. The experimenter monitored how long the infant attended to the audiovisual item and recorded responses using a button press on the computer running Habit X.

The dependent variable was calculated as a listening time difference score: listening time to violation test items minus consistent test items. We predicted that if infants learned the phonotactic patterns during training, they would attend longer to the test items that violated the trained phonotactic patterns (i.e., a positive listening time difference score). We predicted the novelty preference for violation items based on the pattern of preference in several prior phonotactics training experiments (Chambers et al., 2003; Chambers, Onishi, & Fisher, 2011, Experiment 1; Seidl & Buckley, 2005; Seidl et al., 2009, Experiment 1; Seidl et al., 2014).

Results

Preliminary tests indicated that there were no significant differences in listening time difference scores between infants who heard Condition A ($M = -0.23$, $SD = 2.73$) and those who heard Condition B ($M = 0.26$, $SD = 3.02$), $t(56) = 0.644$, $p = .522$, $d = 0.17$. Therefore, we collapsed across conditions in subsequent analyses. We also examined whether, overall, infants learned the illegal phonotactic patterns. We performed a single-sample *t*-test comparing infants' listening time difference scores against chance level (0), indicating no preference for violation or consistent test items. Infants' performance did not differ from zero ($M = 0.04$, $SD = 2.88$), $t(57) = 0.106$, $p = .916$, $d = 0.02$, suggesting that, as a full group, they did not show evidence of learning the patterns.

We predicted that infants with smaller vocabularies would show greater flexibility in learning novel phonotactic patterns that conflict with native language sound patterns and that infants with larger vocabularies would show greater language-specific specialization. To test this prediction, we performed a hierarchical regression analysis predicting infants' listening time difference scores to violation test items minus consistent test items. The correlations between looking time difference scores and vocabulary size and cognitive scores are illustrated in Figs. 1 and 2.

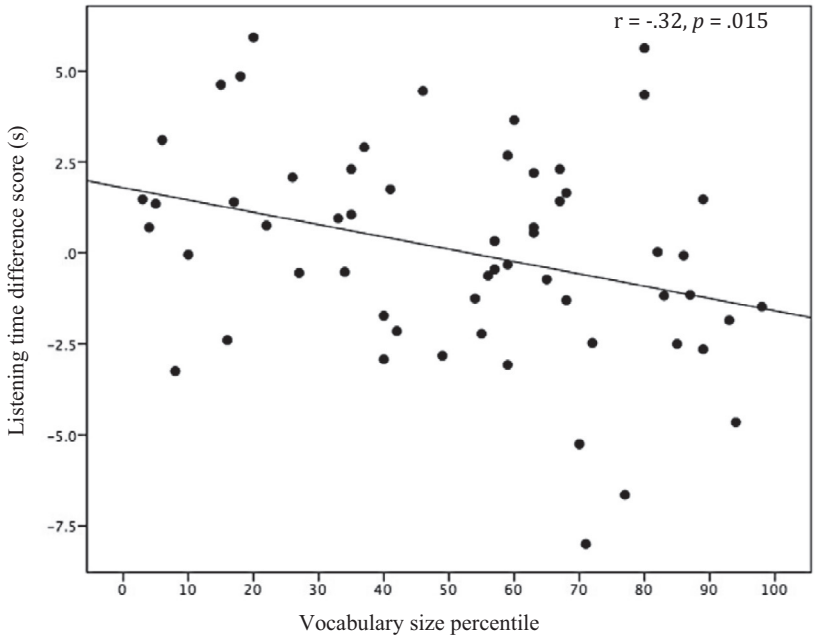

Fig. 1. Scatterplot of infants' listening time difference scores (in seconds) and vocabulary size percentiles.

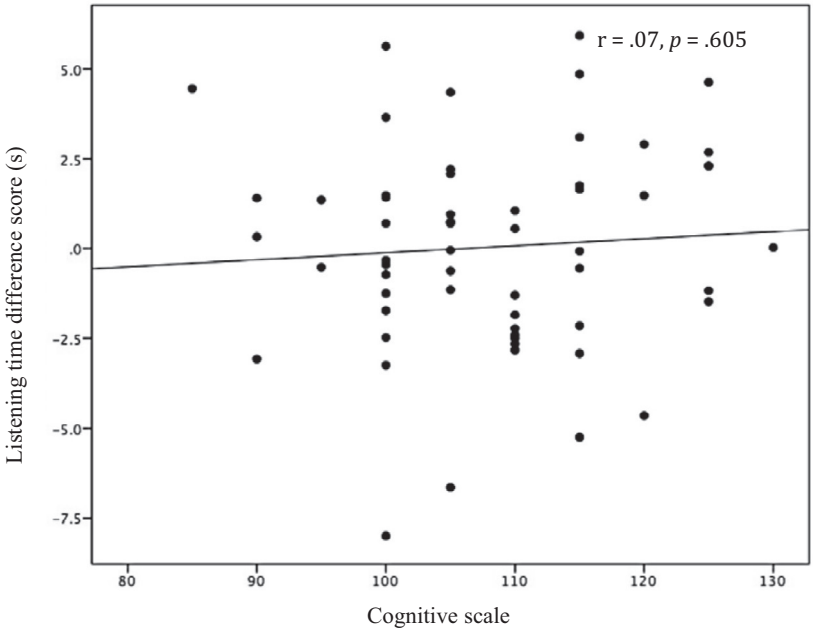

Fig. 2. Scatterplot of infants' listening time difference scores (in seconds) and Cognitive scale scores.

We entered infants' Bayley Cognitive scale scores in the first step of the hierarchical regression in order to examine whether cognitive abilities alone account for significant variance in performance. The cognitive score was not a significant predictor of infants' listening time difference scores, $\beta = .048$; it accounted for a nonsignificant 0.2% of the variance in performance on the phonotactic learning task, $R^2 = .002$, $F(1, 57) = 0.129$, $p = .721$. In the second step, we entered the cognitive score and added infants' productive vocabulary size on the MCDI. The model with both factors accounted for 11% of the variance in listening time difference scores, $R^2 = .111$, $F(2, 57) = 3.44$, $p = .039$, indicating that the model explained a statistically significant amount of variation in performance in the phonotactic learning task. In this model, the cognitive score was again not a significant predictor of performance, $\beta = .104$, $p = .423$. Vocabulary size was a significant predictor, $\beta = -.335$, $p = .012$. The direction of this pattern is that infants with smaller vocabularies showed stronger learning (i.e., larger preferences for violation test items). The model that included vocabulary size in addition to cognitive scores explained 10.9% (R^2 change = .109) more variance in performance than the model that included only the cognitive score, and this difference was statistically reliable, $F(1, 55) = 6.75$, $p = .012$. Thus, vocabulary size predicted performance in the phonotactics task above and beyond the effects of cognitive skills.

The hierarchical regression analysis showed that smaller vocabulary sizes were associated with stronger preferences for the violation test items. This result is consistent with our predictions. However, the analysis does not determine whether infants showed reliable learning of the phonotactic patterns, as evidenced by a listening time difference that is significantly different from chance. Chance performance is exhibited as a listening time difference value of zero, indicating no preference for the violation or consistent test items. To test whether infants with different vocabulary sizes showed reliable learning patterns, we divided the sample into thirds based on vocabulary size percentile. The range of scores for the small-sized vocabulary group was the 3rd to 37th percentiles ($n = 19$), the medium-sized vocabulary group ranged from the 40th to 65th percentiles ($n = 19$), and the large-sized vocabulary group ranged from the 67th to 98th percentiles ($n = 20$). Fig. 3 shows the mean listening times to the violation and consistent test trials separately for each group. For each vocabulary group, we performed a single-sample *t*-test comparing infants' listening time difference scores against

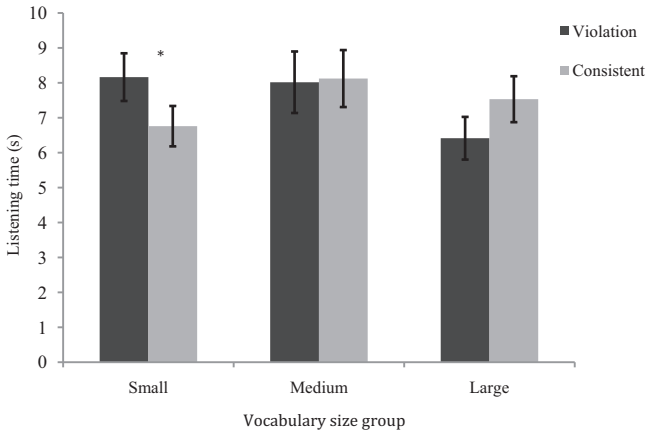

Fig. 3. Mean listening times (in seconds) to violation and consistent test trials. Error bars indicate standard errors. $^{*}p < .05$.

chance (0). Infants with the largest vocabularies did not have listening time difference scores that were significantly different from zero ($M = -1.11$, $SD = 3.44$), $t(19) = 1.45$, $p = .162$, $d = 0.32$, and neither did infants with the medium-sized vocabularies ($M = -0.11$, $SD = 2.24$), $t(18) = 0.205$, $p = .840$, $d = 0.05$. In contrast, infants with the smallest vocabularies showed listening time difference scores that were significantly above chance ($M = 1.40$, $SD = 2.31$), $t(18) = 2.65$, $p = .016$, $d = 0.61$. Thus, only infants with the smallest vocabularies showed reliable evidence of learning the phonotactic patterns, as evidenced by longer listening to the violation test items.

Figs. 1 and 3 show that at larger vocabulary sizes, there was a tendency for infants to listen longer to the consistent test items than to the violation test items (i.e., negative listening time difference scores). That is, infants with larger vocabularies tended toward a familiarity preference. According to Hunter and Ames's (1988) model of infant attention, familiarity preferences are likely to occur when infants perform difficult tasks and when learning is not yet firmly established; they attend longer to test items that are consistent with ongoing learning. In contrast, when learning is robust, infants tend to display novelty preferences, seeking out stimuli that differ from the information they have already processed thoroughly (Houston-Price & Nakai, 2004; Hunter & Ames, 1988; Hunter, Ames, & Koopman, 1983). It is possible that infants with large vocabularies are starting to show a familiarity preference, indicating emerging learning. There is evidence from prior phonotactic learning tasks that both novelty and familiarity preferences can indicate learning (Chambers et al., 2011; Saffran & Thiessen, 2003). We must be cautious in our interpretation of a potential familiarity preference because the infants with large vocabularies did not reliably differentiate the test items and, therefore, did not display reliable evidence of learning. Furthermore, the lack of a reliable preference could have occurred because of the wide spread of responses in the high-vocabulary group, contributing to the challenge of interpreting the results. However, it is clear that only the infants with the smallest vocabularies differentiated the consistent versus violation test items, exhibiting the novelty preference that is indicative of robust learning.

Discussion

We presented 19-month-old infants with a novel phonotactic learning task. It required learning four phonotactic patterns over 3.5 min of exposure. During testing, successful discrimination of the test items required detecting the difference between the trained consonant clusters and unfamiliar clusters that incorporated identical consonants in novel pairings. The findings indicate that phonotactic knowledge is tied to the lexicon early in vocabulary development. Importantly, only infants with the smallest vocabularies exhibited learning of the phonotactic patterns; infants with medium- and

large-sized vocabularies did not. Furthermore, in the hierarchical regression analysis, infant vocabulary size was associated with phonotactic learning performance such that infants with smaller vocabularies showed stronger evidence of learning illegal phonotactic patterns than infants with larger vocabularies. The effect held when controlling for general cognition; phonotactic learning performance was associated specifically with vocabulary size and not with a measure of nonverbal cognitive skills. Infants with larger vocabularies often (but not always, as discussed below) outperform infants with smaller vocabularies on a wide variety of language processing tasks, including measures of speech processing efficiency (Fernald, Perfors, & Marchman, 2006) and word learning (Bion, Borovsky, & Fernald, 2013; Mervis & Bertrand, 1994; Werker et al., 2002). However, the phonotactic patterns presented here were designed to conflict with native language sound structure. Thus, we propose that infants with larger vocabularies failed to demonstrate learning of the novel phonotactic patterns because their native language knowledge interfered. Infants with smaller vocabularies displayed greater openness in learning.

We propose that the pattern of performance in the phonotactics task reflects specialization in language processing that is akin to developmental processes that occur in perceptual narrowing for faces and phonemes (Maurer & Werker, 2014; Scott, Pascalis, & Nelson, 2007). For example, in speech perception, across the first year of life, infants transition from discriminating native and non-native phoneme contrasts to discriminating primarily those that are present in their own native languages (Best, McRoberts, LaFleur, & Silver-Isenstadt, 1995; Werker & Lalonde, 1988; Werker & Tees, 1984). The idea is that with experience, cognitive and perceptual systems are shaped by the input to promote the rapid processing that is necessary to interpret information in faces and voices. Some openness or flexibility in information processing is lost, but the benefit is the formation of a system that is adapted to process just the types of information that are prevalent in the environment.

Our findings are consistent with several other experiments showing that younger infants outperform older infants in particular types of language learning tasks. For example, younger infants more readily learn a range of sounds and gestures as object labels when the labels conflict with the forms of native language words (Hay et al., 2015; May & Werker, 2014; Namy & Waxman, 1998; Woodward & Hoyne, 1999). A commonality across these studies is that the apparent decline in performance across development reflects increasing native language sophistication and specialization. Infants may become increasingly resistant to learning new information that conflicts with their prior knowledge. A related phenomenon occurs in adults. First language knowledge can interfere with learning second language structures (Jarvis & Pavlenko, 2008; see also Finn & Hudson Kam, 2008).

Specialization in language-specific phonotactics is crucial preparation for becoming a native language user (see also Graf Estes & Hay, 2015; Hay et al., 2015). Our finding that infants with large- and medium-sized vocabularies failed to demonstrate learning of phonotactic patterns that violate native language phonotactics suggests that they showed stronger specialization than infants with smaller vocabularies. To further support this point, we are also beginning to examine whether there are vocabulary differences in infants' processing of native language phonotactics as well. We propose that if infants with small vocabularies have not yet developed specialization for processing native phonotactics, they may have difficulty in exploiting the ways in which phonotactic information supports language acquisition and processing. Knowledge of which consonant clusters can and cannot occur at word onsets and offsets provides cues to word boundaries, facilitating rapid word recognition in adults (McQueen, 1998) and facilitating word segmentation and word learning in infants (Graf Estes, 2014; Mattys & Jusczyk, 2001). In addition, knowledge of phonotactic patterns may help to constrain word learning by promoting infants' focus on the sound sequences that form possible words and allowing them to disregard forms that are not possible or likely to label concepts (Graf Estes et al., 2011; MacKenzie et al., 2012). Thus, developing robust phonotactic knowledge reflects adaptive language-specific specialization that supports multiple functions in acquisition and processing. Lack of support from phonotactic knowledge may put infants at a disadvantage in vocabulary acquisition.

A prediction that follows from the account that we have presented is that early phonotactic knowledge contributes to later language skills. An essential step in this line of research will be to investigate longitudinally whether infants' phonotactic knowledge predicts their language development trajectories. Several recent studies have demonstrated that early language processing skills are associated with later language outcomes, suggesting a possible causal role in development. For example, Kuhl

and colleagues (2005) reported that young infants' abilities to perceive native language phoneme contrasts were associated with strong later language abilities, but the ability to perceive non-native contrasts was associated with weaker later skills. These findings are consistent with the pattern of language specialization presented in the current research. In another example, Newman and colleagues (2006) found that word segmentation performance (using a variety of segmentation cues, including phonotactics) at 7.5 to 12 months of age was associated with vocabulary size at 24 months as well as stronger lexical and syntactic skills at 4 to 6 years of age (see also Singh et al., 2012). Segmentation performance was not associated with measures of children's nonverbal cognition. These results suggest that early sensitivity to cues to native language structure supports later development. A similar pattern may occur for phonotactic knowledge.

Although we have discussed the ways in which infants may take advantage of phonotactics to promote vocabulary development, another direction of influence is likely to occur as well. The association between vocabulary size and phonotactic representations may occur because building a vocabulary provides infants with the data necessary to detect phonotactic patterns. By 18 or 19 months of age, infants may store a sufficient inventory of word forms to generalize about the frequency of various sound combinations. Developing this inventory supports the detection of new words that fit with prior experience as well as novel sound sequences that violate the phonotactic generalizations. In considering this direction of influence, we are not arguing that rich vocabulary knowledge is the sole driver of phonotactic representations because by 9 months of age infants distinguish phonotactically legal versus illegal sequences (e.g., Jusczyk et al., 1993) and common versus rare sequences (e.g., Jusczyk et al., 1994). At these ages, infants have started to store representations of word forms and have started to comprehend words, but they do not yet have rich lexicons. The average comprehension vocabulary size is only approximately 40 words at 9 months of age (Dale & Fenson, 1996). However, the presence of early phonotactic sensitivities in infants also does not mean that phonotactic representations are fully formed during infancy. Although early representations of native phonotactics may be an important foundation for word segmentation and word learning, there is ample room for further enrichment as vocabulary acquisition promotes the strengthening of phonotactic representations and phonological representations more broadly (Beckman & Edwards, 2000; Edwards et al., 2004; Werker & Curtin, 2005).

There is substantial evidence across several lines of work that vocabulary development is closely tied to phonological development. In infants, experience with referents linked to phonological forms can enrich infants' representations of phonetic detail and allow them to attend to difficult contrasts (Thiessen, 2007; Yeung & Werker, 2009). Across a wide range of ages, vocabulary size is associated with effectiveness in processing the sounds of words. Infants with larger vocabularies show better attention to phonetic detail when learning novel words compared with infants with smaller vocabularies (Werker et al., 2002). For older children, those with larger vocabularies are more effective at recognizing words from partial information (i.e., gated word recognition) and repeating novel phoneme strings (i.e., nonword repetition) (Edwards et al., 2004; Metsala, 1999; Stokes, Moran, & George, 2013; Walley, 1993; Walley, Metsala, & Garlock, 2003). As vocabulary knowledge is stored, learners gather rich information supporting generalizations about how frequently sounds occur in the input, how frequently sounds occur together, and where those sound and sound combinations occur within words. This information is further strengthened by practice in producing those patterns. The findings regarding connections between vocabulary size and phonological development across tasks and across ages highlight the importance of conducting future research designed to tease apart the direction of influence between vocabulary knowledge and phonotactic representations across development.

Conclusions

The current research found evidence of an association between vocabulary size and infants' performance in a task designed to tap knowledge of native language phonotactics by testing learning of illegal phonotactic patterns. Only infants with small vocabularies successfully learned the patterns. We propose that they learned successfully because their knowledge of native phonotactics was sufficiently fragile to prevent interference. Lack of strong phonotactic knowledge may mean that these infants lack ready access to phonotactic word learning cues. In contrast, infants with robust phonotactic knowledge

may have greater access to cues that support word learning and vocabulary acquisition. Future investigations will be necessary to determine whether early phonotactic knowledge predicts long-term language outcomes as well as to explore the mutual influences of phonotactic and vocabulary knowledge across development. The current research takes a crucial step toward understanding the connection by demonstrating that vocabulary size is linked to phonotactic knowledge during infancy.

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