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Phonotactic constraints on infant word learning

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Abstract

How do infants use their knowledge of native language sound patterns when learning words? There is ample evidence of infants' precocious acquisition of native language sound structure during the first years of life, but much less evidence concerning how they apply this knowledge to the task of associating sounds with meanings in word learning. To address this question, 18-month-olds were presented with two phonotactically legal object labels (containing sound sequences that occur frequently in English) or two phonotactically illegal object labels (containing sound sequences that never occur in English), paired with novel objects. Infants were then tested using a looking-while-listening measure. The results revealed that infants looked at the correct objects after hearing the legal labels, but not the illegal labels. Furthermore, vocabulary size was related to performance. Infants with larger receptive vocabularies displayed greater differences between learning of legal and illegal labels than infants with smaller vocabularies. These findings provide evidence that infants' knowledge of native language sound patterns influences their word learning.

Keywords

language acquisition; speech perception; word learning

At its foundation, word learning requires mapping between sounds and meanings. To acquire a new lexical item, learners must associate a sound sequence representation with a meaning representation. Studies conducted over the past four decades have revealed that young infants possess remarkable speech perception skills, and become attuned to the sound structure of their native language very early in life (for a review, see Saffran, Werker, & Werner, 2006). A separate body of work investigating children's learning of word meaning has demonstrated that children possess a wide range of strategies and biases that allow them to access the appropriate meanings of new words (for a review, see Waxman & Lidz, 2006). However, the relationship between these two key aspects of language acquisition has only recently received attention (e.g., Fennell, Byers-Heinlein, & Werker, 2007; Mani & Plunkett, 2008; Stager & Werker, 1997; see also Saffran & Graf Estes, 2006 for a review).

Before infants produce their first words, they gather a great deal of information about the sound system of the ambient language. At 6 to 8 months of age, infants discriminate many native and non-native language phoneme distinctions, but by 12 months, infants' discrimination is focused on contrasts that are relevant in their native language (e.g., Werker & Tees, 1984). Infants also learn about distributional patterns in the sound combinations of their native language. By 9 months of age, infants discriminate sound sequences that occur

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in their native language from sequences that do not occur; they prefer to listen to phoneme combinations present in the language (Friederici & Wessels, 1993; Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993). Nine-month-olds also distinguish between words containing frequently occurring native language sound sequences from words containing infrequent sequences (Jusczyk, Luce, & Charles-Luce, 1994). These studies show that infants develop early sensitivity to native language phonotactic patterns: the constraints on and likelihood of occurrence of phonemes and phoneme combinations within a given language (see also Mattys & Jusczyk, 2001; Mattys, Jusczyk, Luce, & Morgan, 1999).

Phonotactic patterns also affect language processing in children and adults. Adults judge nonwords as more wordlike when they contain sound sequences that occur in many words in the ambient language and judge nonwords as less wordlike when they contain sound sequences that occur in few or no words of the language (e.g., Coleman & Pierrehumbert, 1997; Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997). In nonword repetition tasks, in which participants are asked to repeat novel sound sequences, both children and adults are faster and more accurate to repeat frequently occurring sound sequences relative to infrequent sound sequences (Coady & Aslin, 2004; Edwards, Beckman, & Munson, 2004; Gathercole, 1995; Vitevitch & Luce, 1998, 2005; Zamuner, Gerken, & Hammond, 2004). Adults also have better recognition memory for nonwords containing high-frequency phonemes and phoneme sequences (Frisch, Large, & Pisoni, 2000). There is a processing advantage for high-frequency sound sequences, sequences that both children and adults have had the most practice perceiving and producing.

There is ample evidence that infants and children, as well as adults, detect distributional patterns in the sound combinations of the ambient language. However, the role that phonotactic patterns might play in language acquisition is less well established. One of the crucial tasks in language acquisition is word learning, a process that is based on associating sound sequence representations with meaning representations. Does learning about native-language sound patterns affect the process of mapping sounds to meaning?

For preschool-age children, there is evidence that phonotactic knowledge affects word learning. Storkel (2001; see also Storkel, 2003, 2004; Storkel, Armbrüster, & Hogan, 2006) presented children (ages 3 to 6 years) with object labels consisting of high phonotactic probability sound sequences and labels consisting of low probability sequences. The label probabilities were based on phoneme frequencies at specific word positions and biphone frequencies in English words. Children learned the high probability labels with fewer exposures and retained them with better accuracy than low probability sequences. Label comprehension also correlated with vocabulary size; children with larger receptive vocabularies showed a greater advantage for high probability sequences over low probability sequences. As Storkel suggests, amassing a large lexicon may allow children to detect the phonotactic patterns. This phonotactic knowledge is then available to influence new learning.

Preschool-age children, of the age that Storkel (2001) tested, are likely to know several thousand words in receptive and productive vocabulary. It is not yet clear how much vocabulary knowledge or language experience learners must accumulate for phonotactic patterns to affect word learning. Infants detect phonotactic patterns in their native languages, but does phonotactic knowledge affect word learning early in vocabulary development? Extensive exposure to linguistic input in infancy, combined with early vocabulary knowledge, may be sufficient for native-language phonotactic patterns to affect how infants link the sound sequences of new words with their meanings. Even young word learners may bring prior knowledge of native language sound structure to the task of lexical acquisition. Furthermore, there is wide variation in vocabulary size in early language development, even for typically developing children (e.g., Fenson, Bates, Dale, Goodman, Reznik, & Thal, 2000). At 24 months, so-called “late talkers” may have fewer than 50 words in their expressive vocabularies, while so-called “precocious talkers” may have as many as 650 words. Like older preschool-aged children, individual differences in vocabulary size in young children may already be associated with individual differences in using phonotactic information to facilitate word learning. Infants with larger vocabularies may show a stronger distinction between words that differ in phonotactic patterns. Alternatively, it is possible that infants' phonotactic knowledge is not yet sufficiently robust to affect word learning.

To investigate the effects of native language phonotactic patterns on the acquisition of new lexical items, we presented 18-month-old English-learning infants with two novel object labels. For one group of infants, the labels were phonotactically legal, containing only sound sequences consistent with English phonotactic patterns. For a second group of infants, the labels were phonotactically illegal, containing sound sequences that do not occur in English. We also examined the potential relationship between early vocabulary knowledge and learning of phonotactically legal and illegal words. Infants who are good at learning words in their natural environments may be good at learning labels in laboratory tasks, regardless of the phonotactic properties of the labels. If so, we would expect to see a positive correlation between vocabulary size and learning of both legal and illegal labels. Alternatively, infants who have larger vocabularies may have greater knowledge of the native-language phonotactic patterns. We predict that compared to infants with smaller vocabularies, infants with larger vocabularies will be less likely to learn phonotactically illegal labels that violate these patterns.

Method

Participants

Seventy 17- to 20-month-old infants (mean age 18.6 months, SD = .84; range 17.1 to 20.2 months) participated. An additional 22 infants were excluded from analyses because of fussiness, crying, or inattentiveness (n = 12), parental interference (n = 1), and experimenter or equipment error (n = 9). Infants were randomly assigned to the either the Legal Labels condition or the Illegal Labels condition. Forty-five of the infants were tested at University X (Legal Labels condition n = 23; Illegal Labels condition n = 22), and 25 were tested at University Y (Legal Labels condition n = 11; Illegal Labels condition n = 14). Testing procedures and equipment were nearly identical in the two locations, and the first author oversaw data collection and coding in both locations. Descriptive information for participants in both conditions is shown in Table 1. Infants in the Legal and Illegal Labels conditions did not differ in age, words produced, or words understood, based on the MacArthur-Bates Communicative Development Inventory (two-tailed independent samples t-tests, all $p > .10$).

Stimuli

Objects—Infants were shown pictures of two novel objects (see Figure 1) and two familiar objects: a ball and a shoe. The familiar items were included during label teaching and test trials to add variety to the task, and to provide infants with a familiar context for the labeling. During teaching trials, a single object moved from left to right in a small arc on the left or right side of the screen while the object was labeled. The motion was not tied to the timing of the labeling. During testing, two stationary objects (in yoked pairs, either both novel or both familiar) were positioned on the left and right sides of the screen while a request to look at one object was presented. On each test trial, one object served as the target test object and the other served as the non-target.

Auditory stimuli—Infants in the Legal Labels condition heard two phonotactically legal labels for the two novel objects. Infants in the Illegal Labels condition heard two phonotactically illegal labels for the objects. The legal and illegal labels were designed to be close phonetic matches: in the Legal Labels condition, *dref* and *sloob;* in the Illegal Labels condition, **dlef* and **sroob*. The final vowel-consonant sequences were the same across conditions, and the word-initial consonant clusters swapped second consonants to form the legal versus illegal labels. The objects associated with the labels were consistent across conditions. Object 1 (see Figure 1) was labeled *dref* or **dlef* and Object 2 was labeled *sloob* or **sroob*.

A female speaker recorded the teaching and test phrases in an infant-directed speaking style. Three different tokens of each target word were used across the teaching and testing phrases. During the teaching phase, the novel objects were introduced in carrier phrases: “Look at the [*target*]! It's a [*target*]!” The familiar objects were also introduced in carrier phrases: “See the [*target*]? That's a [*target*]!” During the test phase, each novel object was requested in the carrier phrases “Where's the [*target*]? Do you like it?” and each familiar object was requested in the carrier phrases “Where's the [*target*]? Can you find it?” The same token of “Where's the” was used for all novel object test trials to prevent the use of coarticulatory cues to the identity of the target word.

The duration, average fundamental frequency (F0), and F0 range of the tokens used in teaching and testing are presented in Table 2. The acoustic characteristics of the carrier phrases and the labels *dref* and **dlef* were closely matched, as were *sloob* and **sroob*.

Procedure

Testing took place in a sound-attenuated booth. Images were projected onto a large screen via an LCD projector with a loudspeaker located approximately 1 foot below the center of the screen, or on a 42” LCD television with integrated speakers. A video camera, connected to a monitor and digital video recorder located outside the booth, was mounted below the center of the screen to record infants' faces. Throughout the session, the infant sat approximately 3 feet from the screen on a parents' lap or in a booster seat next to a parent. The parent listened to music over sound-blocking headphones to minimize the potential for bias. Infants' looking behavior was digitally recorded at 30 frames per second and coded offline by trained coders who were naïve to the nature of the stimuli being presented. Visual fixation locations (left object, right object, transitioning between objects, or looking away) were coded frame-by-frame (see Fernald, Zangl, Portillo, & Marchman, 2008, for additional information).

The teaching phase consisted of 12 trials in which infants heard the novel object labels (4 trials per object, 8 total label repetitions per object) and familiar object labels (2 trials per object, 4 total label repetitions per object). There were 4 pseudo-randomized teaching orders; no object was presented twice in succession, and each object was presented on the left and right sides an equal number of times. The test phase consisted of 12 trials, 4 per novel label and 2 per familiar label. There were 4 pseudorandomized test orders; each label was tested on the right and left sides an equal number of times, and no more than 3 novel label trials occurred in succession. On each test trial, the onset of the target word occurred 3.5 seconds after the test objects appeared on the screen. Between trials, a movie of a spinning pinwheel accompanied by music played to reengage infants' attention to the screen.

Seven additional infants were tested using this procedure, but were excluded from analyses (5 in the Illegal Labels condition, 2 in the Legal Labels condition) due to an extreme object bias. Object bias was evaluated by examining infants' looking performance before the onset of the label on all novel object test trials during which the infant was attending (up to 8 trials possible). An infant met the criteria for an object bias if, before the label onset, the infant looked more than 75% of the time at one object across all trials. All infants who met the object bias criteria preferred the torus-based object (Figure 1, Object 1; labeled *dref* or **dlef*). We have described this preference as an object bias because it was apparent before the target word onset and occurred in both label conditions.

Label recognition measure

To examine object label recognition, we calculated infants' proportion of fixation time to the target object as: [looking time to target] / [total looking time to target + non-target]. We examined target fixation proportion in two time windows: (1) Baseline window: fixation to each object during the 3.5 seconds that the objects were displayed before the target label onset; (2) Test window: target fixation starting at 367 ms after the target label onset and ending 2000 ms later. The test window reflects the time during which responding is most likely to be tied to the target label. It accounts for the time necessary to plan a saccade and the likely waning of attention following the initial fixation (Fernald et al., 2008). From these two values, the *corrected fixation proportion* (similar to Swingley & Aslin, 2007) was calculated trial-by-trial as: [proportion target fixation during the test window] – [proportion target fixation during the baseline window]. This correction measure allowed us to correct for trial-by-trial changes in attention to the target and non-target objects that were not motivated by the target label onset. Successful object label recognition was indicated by significant (non-zero) corrected fixation proportion; that is, a significant increase in looking at the correct object after the label was presented.[1]

Vocabulary measures

Parents were asked to complete the MacArthur-Bates Communicative Development Inventory (MCDI), Words and Sentences version, which includes a 680-word vocabulary checklist and questions about early grammatical constructions. The participants were near the bottom of the age range for the measure (normed for 16 to 30 months; Fenson et al., 2007). Therefore, we requested that parents mark the words on the inventory that their child understood in addition to the words their child understood and produced. Although this form of the MCDI is designed to test productive vocabulary, previous experiments have used similar receptive vocabulary measures with infants close to the age of our participants (e.g., Hamilton, Plunkett, & Schafer, 2000; Mani & Plunkett, 2007, Swingley & Aslin, 2007; Swingley, 2009). Because percentile scores were not available for receptive vocabulary, our analyses used raw scores. We also used raw scores for productive vocabulary to maintain consistency across analyses.

Results

To examine novel object label recognition, we performed a 2 (Label: *d-initial* versus *s-initial*; within subjects) × 2 (Group: Legal versus Illegal labels; between-subjects) mixed design ANOVA of corrected fixation proportion. There was no main effect of Label [$F(1, 68) < 1$], indicating that infants did not perform differently on the two novel object labels. Therefore, in subsequent analyses we collapsed across the labels (*d-initial* and *s-initial*) within groups. There was a significant main effect of Group [$F(1, 68) = 6.14$, $p = .016$], indicating that infants in the Legal Labels condition showed a greater corrected fixation proportion (i.e., increase in target fixation after label onset) than infants in the Illegal Labels condition (see Figure 2). The interaction of Label by Group was not significant, $F(1, 68) < 1$.

[1]Analyses of baseline looking times during the test trials indicate that infants' interest in the two objects was unequal. Overall, infants preferred the torus-based object labeled *dref* or **dlef* (Figure 1, Object 1).

The significant main effect of Group demonstrates that infants who were exposed to phonotactically legal labels showed superior label recognition over infants exposed to phonotactically illegal labels. To determine whether infants learned successfully in each condition, we performed one-sample t-tests (all tests 2-tailed) comparing corrected fixation proportion to zero. Infants in the Legal Labels condition demonstrated successful label recognition, showing a significant increase in fixation to the target objects after hearing the labels, $t(34) = 4.03$, $p < .001$. Infants in the Illegal Labels condition did not, $t(35) = .913$, $p = .368$.

These results suggest that the phonotactically legal labels facilitated mapping between labels and objects, relative to the illegal labels. However, an alternative hypothesis is that the infants who were assigned to the Legal Labels condition were superior at lexical tasks relative to infants in the Illegal Labels condition, and therefore performance differed due to participant characteristics that were independent of the label manipulation. To test this hypothesis, we performed a separate analysis of infants' recognition of the familiar words. We conducted a 2 (Label: ball versus shoe; within subjects) × 2 (Group: Legal versus Illegal labels; between subjects) mixed design ANOVA. There was no significant main effect of Label [$F(1, 63) = 3.20$, $p = .0782$] or Group [$F(1, 63) = 1.95$, $p = .168$], and no significant Group × Label interaction [$F(1, 63) < 1$]. Collapsing across familiar objects, one-sample t-tests indicated that infants in both the Legal Labels condition [corrected fixation proportion $M = .16$, $SD = .21$; $t(33) = 7.31$, $p < .001$] and the Illegal Labels condition [corrected fixation proportion $M = .23$, $SD = .18$; $t(30) = 4.183$, $p < .001$] significantly increased fixation to the familiar objects. This analysis indicates that infants in the Legal Labels condition were not overall superior language processors than infants in the Illegal Labels condition. Instead, differences in performance appear to be due to the characteristics of the novel labels.

The final set of analyses examined the relationship between novel label recognition (as indicated by corrected fixation proportion) and infants' productive and receptive vocabulary sizes and age. For infants in the Legal Labels condition, novel label recognition did not correlate with words produced on the MCDI ($r = .119$, $p = .554$) or age ($r = .286$, $p = .101$). However, there was a significant positive correlation between novel label recognition and words understood on the MCDI: $r = .405$, $p = .036$. Infants with larger receptive vocabularies showed superior recognition of the legal labels than infants with smaller vocabularies. For infants in the Illegal Labels condition, novel label recognition also did not correlate with words produced ($r = -.035$, $p = .866$) or age ($r = -.278$, $p = .100$). However there was a trend toward a negative correlation between novel label recognition and words understood: $r = -.393$, $p = .061$. That is, infants with larger receptive vocabularies showed a trend toward being *less* likely to recognize phonotactically illegal labels than infants with smaller vocabularies. These correlations are illustrated in the scatterplots shown in Figure 3. The absence of a reliable correlation with age suggests that phonotactic pattern effects on learning are more closely related to progress in language acquisition than to duration of exposure. The fact that receptive vocabulary, but not productive vocabulary is correlated with novel label recognition suggests that receptive vocabulary may be a more sensitive indicator of what infants know about their native language than productive vocabulary at this very young age.

To further explore the vocabulary findings, we examined whether the correlational findings were supported by differences in learning for groups of infants with relatively larger and

[2]The sample sizes were not identical in the novel and familiar object analyses. There were two test trials per familiar object. Most infants looked at the test objects during the windows of analysis on at least one trial per object, but some infants only looked during *ball* target object trials or *shoe* target object trials. Because of the within-subjects comparison in the ANOVA, infants' responses were excluded if they did not provide looking times to both the ball and shoe test trials. Therefore, some infants included in the novel object analyses did not contribute to the familiar object analyses.

smaller vocabulary sizes. Because of the significant correlations with receptive vocabulary size, we analyzed performance of infants above and below the median receptive vocabulary size (303 words) using a 2 (Group: Legal vs. Illegal labels) × 2 (Vocabulary size: high vs. low) between-subjects ANOVA. The main effect of Vocabulary size was not significant, $F < 1$. There was a significant main effect of Group, $F(1, 48) = 5.82$, $p = .020$. Infants in the Legal Labels condition exhibited higher recognition performance than infants in the Illegal Labels condition. However, there was also a significant interaction between Vocabulary size and Group, $F(1, 48) = 8.24$, $p = .006$. Follow-up analyses indicated that for infants with high vocabularies, recognition of legal labels was significantly better than recognition of illegal labels, $t(24)= 3.33$, $p = .006$. For infants with low vocabularies, there was no significant difference between recognition of legal versus illegal labels, $t(24)= -.375$, $p = .711$. This pattern of results is shown in Figure 4.

Discussion

We found that 18-month-old infants readily learned a pair of phonotactically legal object labels, but had difficulty learning phonotactically illegal labels. Furthermore, label learning performance correlated with receptive vocabulary size. Infants with larger vocabularies tended to be more successful at learning phonotactically *legal* labels and they showed a trend toward being less successful at learning phonotactically *illegal* labels, relative to same-age infants with smaller vocabularies. The results of this experiment provide an important new piece of evidence regarding phonotactic knowledge in infants. Previous demonstrations of phonotactic effects on word learning examined children at an age when vocabulary size typically includes thousands of words (Storkel, 2001). Our participants had a median productive vocabulary size of 65 words, and a median receptive vocabulary size of 303 words. We found that that early phonotactic knowledge affects lexical acquisition. This research demonstrates one way that infants might use prior learning about native language sound sequences—to associate the sounds of words with meanings.

The positive correlation between receptive vocabulary size and the acquisition of phonotactically legal label-object pairings could be interpreted to suggest that infants who are successful at learning words in their natural environments are also generally successful at learning words in laboratory tasks. However, the negative relationship between vocabulary size and the acquisition of phonotactically illegal label-object pairings suggests that the vocabulary size advantage does not extend to words that are inconsistent with native language phonotactic patterns. Further, the comparison of high and low vocabulary groups showed that children with smaller vocabularies did not show a significant difference between learning legal and illegal labels, but children with larger vocabularies did. It is possible that infants with smaller vocabularies did not detect the illegal sequences because they do not perceive phoneme sequences with as much detail as infants with larger vocabularies. However, even much younger infants discriminate between words with consonant clusters that are phonotactically legal versus illegal (Friederici & Wessels, 1993).

Furthermore, investigations with older children indicate that vocabulary growth promotes the development of phonotactic knowledge (e.g., Edwards et al., 2004; Storkel, 2001). The present pattern of results suggests that the accumulation of vocabulary knowledge, and the corresponding strengthening of phonotactic knowledge, may constrain what learners treat as appropriate new lexical items. Although infants with infants with greater vocabulary knowledge would likely be able to learn phonotactically illegal labels with additional label repetitions, or in a modified task, the current results suggest that they will remain more resistant to learning illegal labels than infants with smaller vocabularies. The development of phonotactic constraints on word learning may also affect the course of vocabulary development. Infants with stronger expectations about the sound combinations that do and do not occur within native language words may be better able to focus learning on appropriate candidate words.

Nazzi and Bertoncini (2009) recently reported that 20-month-olds showed no difference in their ability to learn novel object labels that contained frequent versus infrequent phoneme combinations (see also Nazzi, Bertoncini, & Bijeljac-Babic, 2009). The experiment was designed to tap infants' attention to phonetic detail in new words at onset and coda word positions. There were several procedural differences between the present study and Nazzi and Bertoncini's task (e.g., use of an object categorization labeling task as opposed to our looking-while-listening task). However, two key differences may contribute to the contrast with our finding that phonotactic patterns affect word learning. First, the labels in Nazzi and Bertoncini's (2009) task were legal consonant-vowel-consonant sequences that varied in frequency. By contrast, our labels contained phonotactically legal versus illegal word-initial consonant-consonant sequences. We chose to use word-initial consonant-consonant sequences based on the results of previous research with preschool-aged children. Edwards et al. (2004) found a larger effect of phonotactic probability on production accuracy for word-initial consonant-consonant sequences as compared to consonant-vowel sequences. Zamuner (2009) also found a greater effect of phonotactic probability on onsets as compared to codas. More research is needed to clarify the significance of word position in label learning. Future research will also be necessary to examine whether infants distinguish between legal high-probability and low-probability labels, in addition to legal versus illegal labels. Exploring a broader range of phonotactic patterns will help to reveal whether some sound sequences are strongly dispreferred across development and even across languages. These questions are currently under investigation. Another difference is that the participants in Nazzi and Bertoncini's task were about 2 months older that the participants in the present experiment. There may be developmental changes in how phonotactic patterns affect learning, a possibility that is also under investigation. The procedural differences between our study and Nazzi and Bertoncini's study should not be discounted, as methods of measurement can have a significant impact on infants' learning patterns (e.g., MacKenzie, Curtin, & Graham, in press; Yoshida, Fennell, Swingley, & Werker, 2009). However, the comparison of findings raises intriguing questions about developmental changes in phonotactic probability effects and about how patterns of learning relate to a range of phonotactic characteristics.

The selectivity of label learning in infants with greater lexical knowledge seen in this experiment dovetails with prior demonstrations that infants become increasingly language-specific about the range of potential object labels as they accumulate native language experience. At 13 months, infants accept non-speech sounds (e.g., from a noisemaker) as labels, but not at 20 months (Woodward & Hoyne, 1999). At 18 months, infants accept gestures as object labels, but not at 26 months (Namy & Waxman, 1998). Thus, in interactive word learning tasks, infants' acceptance of object labels appears to narrow as vocabulary development progresses (but see MacKenzie et al., in press). Kuhl, Conboy, Padden, Nelson, and Pruitt (2005) reported a different type of relation between language-specific tuning and word learning: correlations between 7-month-olds' native and non-native phoneme discrimination and language development between 14 and 30 months of age. Early success at discriminating native language phonemes predicted subsequent success in vocabulary development (as well as other language measures). Conversely, infants who performed well at non-native phoneme discrimination at 7 months showed slower language development at 14 to 30 months. Infants who become focused on the sound distinctions of their native language early in development may have an advantage in word learning. The present research demonstrates how phonotactic patterns influence infant word learning and how this influence is modulated by vocabulary size. The findings suggest another example of how learning becomes increasingly tuned to and supported by the characteristics of the linguistic environment.

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References

Coady JA, Aslin RN. Young children's sensitivity to probabilistic phonotactics in the developing lexicon. Journal of Experimental Child Psychology. 2004; 89(3):183–213. [PubMed: 15501451]

Coleman, J.; Pierrehumbert, J. Proceedings of the 3rd Meeting of the ACL Special Interest Group in Computational Phonology. Somerset, NJ: Assoc. for Computational Linguistics; 1997. Stochastic phonological grammars and acceptability; p. 49-56.

Edwards J, Beckman ME, Munson B. The Interaction Between Vocabulary Size and Phonotactic Probability Effects on Children's Production Accuracy and Fluency in Nonword Repetition. Journal of Speech, Language, and Hearing Research. 2004; 47(2):421–436.

Fennell CT, Byers-Heinlein K, Werker JF. Using speech sounds to guide word learning: The case of bilingual infants. Child Development. 2007; 78(5):1510–1525. [PubMed: 17883445]

Fernald, A.; Zangl, R.; Portillo, AL.; Marchman, VA. Looking while listening: Using eye movements to monitor spoken language comprehension by infants and young children. In: Sekerina, IA.; Fernandez, EM.; Clahsen, H., editors. Developmental Psycholinguistics: On-line methods in children's language processing. Amsterdam, Netherlands: John Benjamins Publishing Company; 2008.

Fenson, L.; Marchman, VA.; Thal, DJ.; Dale, PS.; Reznick, JS.; Bates, E. MacArthur-Bates Communicative Development Inventories: Users Guide and Technical Manual. 2nd. Baltimore, MD: Brookes; 2007.

Friederici AD, Wessels JM. Phonotactic knowledge of word boundaries and its use in infant speech perception. Perception & Psychophysics. 1993; 54(3):287–295. [PubMed: 8414887]

Frisch SA, Large NR, Pisoni DB. Perception of wordlikeness: Effects of segment probability and length on the processing of nonwords. Journal of Memory and Language. 2000; 42:481–496. [PubMed: 21738287]

Gathercole SE. Is nonword repetition a test of phonological memory or long-term knowledge? It all depends on the nonwords. Memory & Cognition. 1995; 23(1):83–94.

Hamilton A, Plunkett K, Schafer G. Infant vocabulary development assessed with a British Communicative Development Inventory. Journal of Child Language. 2000; 27(3):689–705. [PubMed: 11089344]

Jusczyk PW, Friederici AD, Wessels JM, Svenkerud VY, Jusczyk AM. Infants' sensitivity to the sound patterns of native language words. Journal of Memory and Language. 1993; 32(3):402–420.

Jusczyk PW, Luce PA, Charles-Luce J. Infants' sensitivity to phonotactic patterns in the native language. Journal of Memory and Language. 1994; 33(5):630–645.

Kuhl PK, Conboy BT, Padden D, Nelson T, Pruitt J. Early speech perception and later language development: Implications for the “critical period”. Language Learning and Development. 2005; 1(3-4):237–264.

Mani N, Plunkett K. Fourteen-month-olds pay attention to vowels in novel words. Developmental Science. 2008; 11(1):53–59. [PubMed: 18171367]

MacKenzie H, Graham SA, Curtin S. 12-month-olds privilege words over other linguistic sounds in an associative learning task. Developmental Science. in press.

Mattys SL, Jusczyk PW. Phonotactic cues for segmentation of fluent speech by infants. Cognition. 2001; 78(2):91–121. [PubMed: 11074247]

Mattys SL, Jusczyk PW, Luce PA, Morgan JL. Phonotactic and prosodic effects on word segmentation in infants. Cognitive Psychology. 1999; 38(4):465–494. [PubMed: 10334878]

Namy LL, Waxman SR. Words and gestures: Infants' interpretations of different forms of symbolic reference. Child Development. 1998; 69(2):295–308. [PubMed: 9586206]

Nazzi T, Bertoncini J. Phonetic specificity in early lexical acquisition: New evidence from consonants in coda positions. Language and Speech. 2009; 52:463–480. [PubMed: 20121042]

Nazzi T, Bertoncini J, Bijeljac-Babic R. A perceptual equivalent of the labial-coronal effect in the first year of life. Journal of the Acoustical Society of America. 2009; 126:1440–1446. [PubMed: 19739757]

Saffran, JR.; Graf Estes, KM. Mapping sound to meaning: Connections between learning about sounds and learning about words. In: Kail, R., editor. Advances in Child Development and Behavior. Vol. 34. New York: Elsevier; 2006. p. 1-38.

Saffran, JR.; Werker, JF.; Werner, LA. The Infant's Auditory World: Hearing, Speech, and the Beginnings of Language. In: Damon, W.; Lerner, RM., editors; Siegler, R.; Kuhn, D., editors. Handbook of Child Psychology: Vol 2, Cognition, Perception and Language. New York: Wiley; 2006. p. 58-108.Series Eds.Vol Eds.

Stager CL, Werker JF. Infants listen for more phonetic detail in speech perception than in word-learning tasks. Nature. 1997; 388(6640):381–382. [PubMed: 9237755]

Storkel HL. Learning new words: Phonotactic probability in language development. Journal of Speech, Language, and Hearing Research. 2001; 44(6):1321–1337.

Storkel HL. Learning new words II: Phonotactic probability in verb learning. Journal of Speech, Language, and Hearing Research. 2003; 46(6):1312–1323.

Storkel HL. The emerging lexicon of children with phonological delays: Phonotactic constraints and probability in acquisition. Journal of Speech, Language, and Hearing Research. 2004; 47(5):1194–1212.

Storkel HL, Armbrüster J, Hogan TP. Differentiating phonotactic probability and neighborhood density in adult word learning. Journal of Speech, Language, and Hearing Research. 2006; 49(6): 1175–1192.

Swingley D. Onsets and codas in 1.5-year-olds' word recognition. Journal of Memory and Language. 2009; 60:252–269. [PubMed: 20126290]

Swingley D, Aslin RN. Lexical competition in young children's word learning. Cognitive Psychology. 2007; 54(2):99–132. [PubMed: 17054932]

Vitevitch MS, Luce PA, Charles-Luce J, Kemmerer D. Phonotactics and syllable stress: Implications for the processing of spoken nonsense words. Language and Speech. 1997; 40(1):47–62. [PubMed: 9230698]

Vitevitch MS, Luce PA. When words compete: Levels of processing in perception of spoken words. Psychological Science. 1998; 9(4):325–329.

Vitevitch MS, Luce PA. Increases in phonotactic probability facilitate spoken nonword repetition. Journal of Memory and Language. 2005; 52(2):193–204. [PubMed: 18797517]

Waxman, SR.; Lidz, JL. Early Word Learning. In: Damon, W.; Lerner, RM., editors; Siegler, R.; Kuhn, D., editors. Handbook of Child Psychology: Vol 2, Cognition, Perception and Language. New York: Wiley; 2006. p. 299-335.Series Eds.Vol Eds.

Werker JF, Tees RC. Cross-language speech perception: Evidence for perceptual reorganization during the first year of life. Infant Behavior & Development. 1984; 7(1):49–63.

Woodward AL, Hoyne KL. Infants' learning about words and sounds in relation to objects. Child Development. 1999; 70(1):65–77. [PubMed: 10191515]

Yoshida K, Fennell C, Swingley D, Werker JF. 14-month-olds learn similar-sounding words. Developmental Science. 2009; 12:412–418. [PubMed: 19371365]

Zamuner TS. Phonological probabilities at the onset of language development: Speech production and word position. Journal of Speech, Language, and Hearing Research. 2009; 52:49–60.

Zamuner TS, Gerken L, Hammond M. Phonotactic probabilities in young children's speech production. Journal of Child Language. 2004; 31(3):515–536. [PubMed: 15612388]

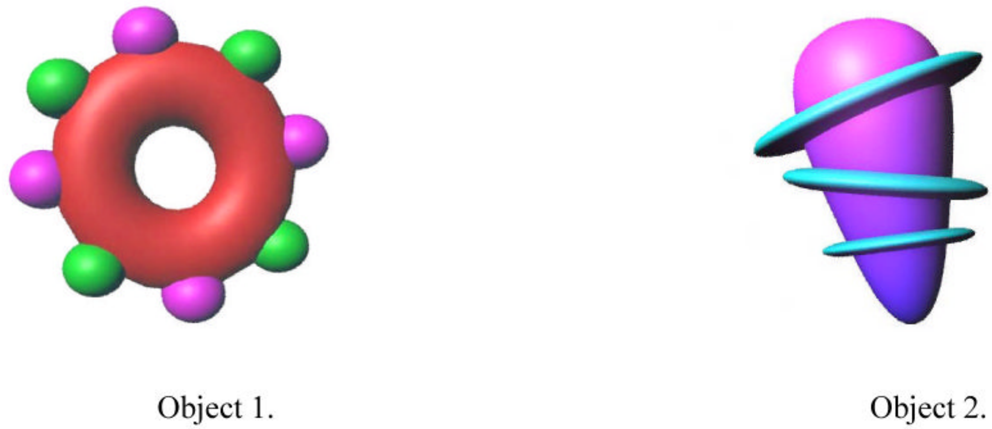

Figure 1.
Novel objects labeled with phonotactically legal and illegal object labels. Object 1 was labeled *dref* or **dlef*; Object 2 was labeled *sloob* or **sroob*.

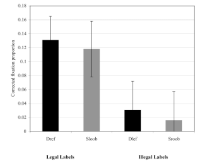

Figure 2.
Mean corrected fixation proportion (and SE) for infants presented with legal versus illegal object labels.

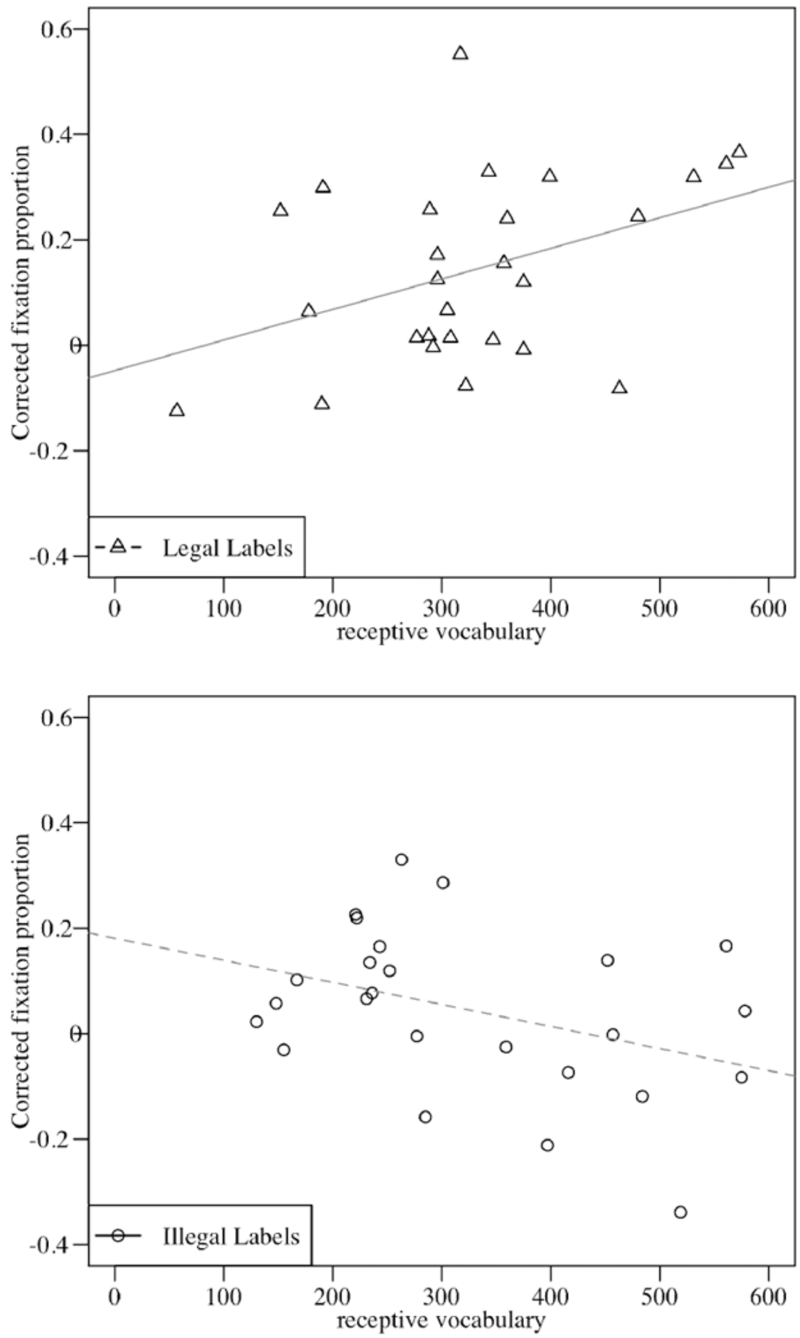

Figure 3.

Scatter plots of infants' corrected fixation proportion by receptive vocabulary size (number of words understood on MCDI) for legal (top plot) and illegal labels (bottom plot). Solid regression line shows significant correlation, while dashed regression line shows a trend towards significance.

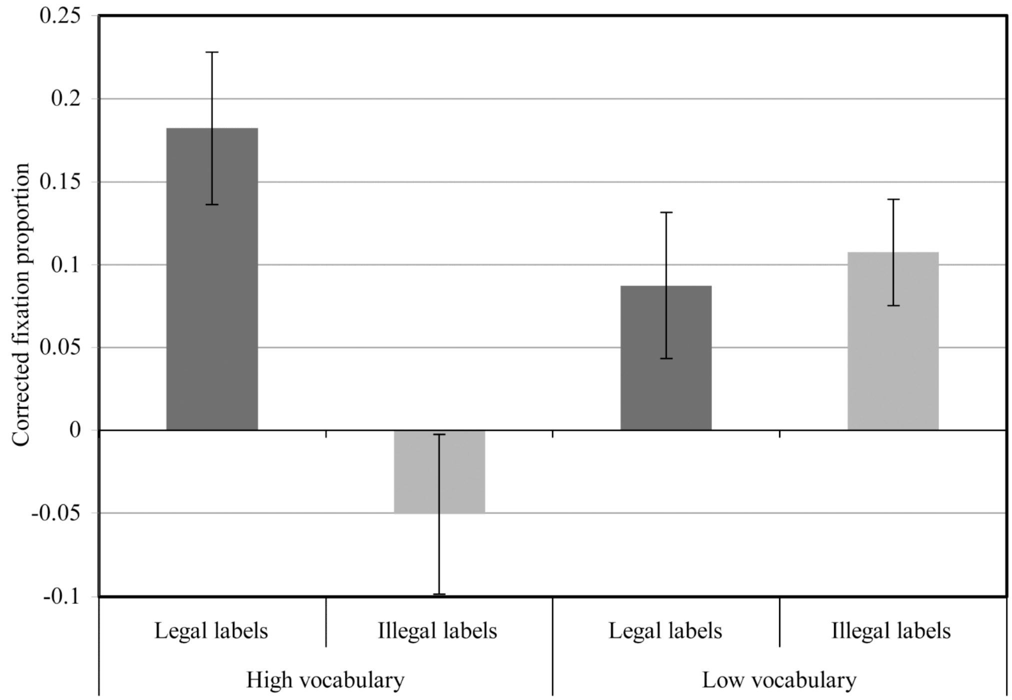

Figure 4.
Mean corrected fixation proportion (and SE) for infants presented with legal versus illegal object labels, divided by median split for receptive vocabulary size.

Table 1

Descriptive Statistics for Participant Age and Vocabulary Size

	Sex		**Age**		**Words understood**		**Words produced**	
	Male	**Female**	***M***	***SD***	***M***	***SD***	***M***	***SD***
Condition								
Legal Labels	16	18	18.6	.78	330	121	86	65
Illegal Labels	19	17	18.6	.90	327	142	109	131

Note. Parents of 28 infants in the Legal Labels condition (out of 34 total) and parents of 25 infants in the Illegal Labels condition (out of 36 total) contributed vocabulary data. One participant's vocabulary data were excluded because her Words Understood score was an outlier at over 2 standard deviations from the mean.

Table 2

Mean Duration (msec) and Fundamental Frequency (F0; in Hz) for Legal and Illegal Object Labels during Teaching and Test Trials

	Teaching trials				Test trials	
	"Look at the [*target*]"		**"It's a [*target*]"**		**"Where's the [target]"**	
	Full sentence	**Target word**	**Full sentence**	**Target word**	**Full sentence**	**Target word**
dref						
Duration	1880	1018	1819	1120	2059	1053
Average F0	315	325	296	314	324	320
Minimum F0	189	185	192	192	187	188
Maximum F0	419	419	434	434	393	393
***dlef**						
Duration	1788	963	1788	966	1982	977
Average F0	312	325	313	311	325	320
Minimum F0	201	184	202	202	100	100
Maximum F0	383	419	383	383	388	388
slub						
Duration	1948	1584	1918	1371	2177	1207
Average F0	306	305	307	317	309	292
Minimum F0	179	179	183	183	163	163
Maximum F0	405	405	436	436	388	388
***srub**						
Duration	1748	1201	2004	1434	2148	1187
Average F0	305	302	298	311	309	291
Minimum F0	175	175	172	172	161	161
Maximum F0	393	393	437	437	374	374