Do Infants Learn Words from Statistics? Evidence from English-Learning Infants Hearing Italian

Amber Shoaib[1], Tianlin Wang[1], Jessica F. Hay[2], & Jill Lany[1]

University of Notre Dame, Department of Psychology[1]

University of Tennessee, Knoxville, Department of Psychology[2]

Author address:

Department of Psychology
390 Corbett Family Hall
University of Notre Dame
Notre Dame, IN 46556

Author note: The first two authors share first-author status.

Address correspondence to Jill Lany via email at jlany@nd.edu

Keywords: language learning; statistical Learning; word learning; word segmentation; referential support; infant language development

Abstract

Infants are sensitive to statistical regularities (i.e., transitional probabilities, or TPs) relevant to segmenting words in fluent speech. However, there is debate about whether tracking TPs results in representations of possible words. Infants show preferential learning of sequences with high TPs (HTPs) as object labels relative to those with low TPs (LTPs). Such findings could mean that only the HTP sequences have a word-like status, and are more readily mapped to a referent for that reason. But these findings could also suggest that HTP sequences are easier to encode, just like any other predictable sequence. Here we aimed to distinguish between these explanations. To do so, we built on findings that infants become resistant to learning labels that are not typical of their native language as they approach two years of age and add words to their lexicons. If tracking TPs in speech results in identifying candidate words, at this age TPs may have reduced power to confer lexical status when they yield a unit that is very dissimilar to word forms that are typical of infants' native language. Indeed, we found that at 20 months, English-learning infants with relatively small vocabularies learned HTP Italian words (but not LTP words) as object labels, while infants with larger vocabularies resisted learning HTP Italian words. These findings suggest that the HTP sequences may be represented as candidate words, and more broadly, that TP statistics are relevant to word learning.

A key task facing infants is identifying important units of language, such as the words upon which symbolic meaning is ultimately built, within the speech around them. From an acoustic perspective, there are no obvious cues indicating where individual words begin and end (Brent & Cartwright, 1996; van de Weijer, 1998). Before they are a year of age, however, infants can identify words from their language within continuous speech (e.g., Jusczyk & Aslin, 1995; Mandel, Jusczyk, & Pisoni, 1995; Singh, Morgan, & White, 2004), and a central question is how they do so. One possibility is that infants track statistical regularities within speech, and particularly the regularity with which syllables co-occur, to find words. Consistent with this idea, sequential relations between syllables, typically referred to as transitional probabilities (TPs), tend to be higher within words than they are across word boundaries (Swingley, 2005)[1].

It is well-accepted that infants are influenced by TPs in laboratory settings, showing evidence of distinguishing between high TP (or HTP) and low TP (or LTP) sequences in preferential listening tasks (e.g., Aslin, Saffran & Newport, 1998; Pelucchi, Hay, & Saffran, 2009a,b; Saffran, Aslin, & Newport, 1996). However, the relevance of these findings to real-world language development has been questioned (e.g., Endress & Mehler, 2009; Johnson & Tyler, 2010). In particular, evidence that infants can distinguish between speech sequences on the basis of co-occurrence statistics does not tell us whether infants represent high TP sequences as potential word forms, versus as predictable but generic sequences. Infants also track TPs in nonspeech materials, such as co-occurrences between tones, and in visual materials such as unfamiliar

[1] Our description of TPs characterizes information in the environment. See Thiessen (2017) for a discussion of the mechanisms (e.g., chunking vs boundary-finding models of learning) by which infants may be learning TPs.

shapes (Kirkham, Slemmer & Johnson, 2002), and it is unlikely that they consider all of these HTP sequences to be potential words. Thus, simply registering a sequence as having a relatively high TP, or having high internal coherence, may not necessarily render it a potential “word” in the infant’s mind.

However, the fact that TPs are relevant to learning outside the realm of language does not preclude the possibility that they are also relevant to learning words. Indeed, infants learning French distinguish between sequences composed of syllables that co-occur frequently vs. infrequently in their native language by 11 months (Ngon, Martin, Dupoux, Dutat, & Pepperkamp, 2013). There is also evidence that tracking TPs in speech can support word learning. For example, 17-month-old infants who listened to an artificial language in which TPs were the only cue to word boundaries went on to learn HTP sequences, but not those with LTPs, as labels for objects (Graf Estes, Evans, Alibali, & Saffran, 2007). Likewise, after listening to a corpus of Italian sentences containing both HTP and LTP sequences, 17-month-old English-learning infants also selectively learned the HTP sequences as labels (Hay, Pelucchi, Graf Estes, & Saffran, 2011). Still, these HTP sequences might not be learned as labels because they are represented as possible words. Rather they may simply be relatively generic sequences that are easy to encode because of their predictable internal structure, and thus more readily mapped to referents.

In the current work, we sought to differentiate between these two possibilities; HTP sequences as candidate words versus HTP sequences as units that are coherent but that nonetheless lack word-like status. Our approach was informed by evidence that infants are initially quite flexible about the forms that they learn as labels, but become increasingly selective between 18 and 24 months of age. For example, before 18 months of age, infants learn both words and nonwords like squeaks, whistles, or manual gestures as labels when presented by an experimenter with a clear intention to label (i.e., by using them in ostensive labeling frames while looking at an object, cues that are commonly referred to as “referential support”; Namy & Waxman, 1998; Woodward & Hoyne, 1999). However, by 20-24 months infants selectively learn spoken words as labels, especially when cues providing referential support are stripped away (e.g., when potential labels are presented in isolation rather than in fluent speech, and via a loudspeaker rather than a live experimenter (Namy & Waxman, 1998; Namy & Waxman, 2000; Woodward & Hoyne, 1999). Moreover, they even become resistant to learning spoken word forms that violate the phonology of their native language at similar ages (Graf Estes, Edwards, & Saffran, 2011; Hay, Graf Estes, Wang, & Saffran, 2015; see Mackenzie, Graham, & Curtin, 2011 for evidence with even younger infants).

Overall, these findings suggest that infants’ accumulating knowledge about the morphology and contextual usage of words in their language influences their tendency to learn novel sound sequences as labels: Speech sequences that are dissimilar to words in their native language on one or more of these dimensions are less readily learned as labels. Interestingly, this loss of symbolic flexibility does not seem to be directly linked to specific advances in the ability to encode or discriminate these dimensions. For example, infants can distinguish between many speech and nonspeech stimuli at birth, and by 9 months of age they show evidence of distinguishing between native and non-native speech sequences on the basis of learned phonological patterns, months before there is evidence of narrowing on the basis of these qualities (Vouloumanos & Werker, 2007; Jusczyk, Friederici, Wessels, Svenkerd, & Jusczyk, 1993). Rather, loss of symbolic flexibility appears to be related to age, as described above, as well as to vocabulary size. For example, at 19-months, infants who know more English words are more resistant to learning novel words that violate English phonotactic regularities than infants with smaller vocabularies (Graf Estes et al., 2011).

We used these findings to design a test of whether sequences with HTPs are more readily learned as labels than LTP sequences because they are represented as candidate words, or instead because they are simply more coherent (but still generic) sequences. In particular, the work on loss of symbolic flexibility suggests that if tracking TPs in speech is used to help identify *candidate words*, as infants get older and learn more about their native language, TPs may have reduced power to confer lexical status when they yield a unit that is very dissimilar to native language word forms. In contrast, if novel speech sequences with high TPs are better learned as labels simply because they are *generic sequences* that are more readily encoded and recognized (i.e., sequences that are primarily distinguished from LTP sequences because they are more coherent and predictable, but no different from musical sequences, or other sound sequences), then they should always have an advantage over LTP sequences in a lab-based mapping task, regardless of how much an individual has learned about her native language.

We aimed to distinguish between these explanations – the word candidate vs. generic sequence accounts – by testing whether infants who are learning English as their native language show selective learning of HTP sequences when they come from an unfamiliar natural language – Italian – at the age when they typically show a loss of symbolic flexibility. Prior work has shown that English-learning infants can track TPs within a corpus of Italian sentences by 8 months (Pelucchi et al., 2009a,b), and selectively learn HTP sequences within the corpus as labels at 17 months (Hay et al., 2011). Here we familiarized 20-month-old infants with a corpus of Italian sentences from Hay et al. (2011) containing both HTP and LTP words. We tested 20-month-olds because prior research has established that by this age infants, especially those with larger vocabularies, are becoming selective in mapping speech sequences to referents when they are presented without referential cues (Graf Estes et al., 2011; Hay et al. 2015; Woodward & Hoyne, 1999). Thus, if sensitivity to TPs leads to the identification of *potential word forms*, at 20-months infants with larger English vocabularies should be more resistant to learning Italian HTP words (Graf Estes et al., 2011). However, if HTP sequences are more readily mapped to objects because they are easier to encode, infants should continue to selectively learn them as labels, even as they gain proficiency with their native language.

In sum, on the word candidate account, infants with smaller English vocabularies should be more likely to learn HTP words (i.e., performance should be negatively related to vocabulary size), while infants should fail learn LTP words regardless of their English vocabulary size. On the sequence learning account, HTP and LTP sequences would not be represented as word candidates, but HTP words should thus be more readily mapped to referents than LTP words by virtue of being more coherent. On this account, performance on neither HTP nor LTP words would be related to native language vocabulary size[2].

Methods

Participants

Participants were healthy, monolingual English-learning infants (N = 37; 18 female) aged between 20.07 to 20.96 months. Participants were randomly assigned to one of two language conditions, which differed in their TP statistics. The languages are described in more detail below. Exclusionary criteria included: infants born before 35 weeks gestation, birth weights of less than five pounds and eight ounces, five or more ear infections in the past year, exposure to Italian, and 15 or more hours of weekly exposure to a language other than English. Infants were recruited at community events. An additional 17 infants were tested but their data were excluded because of fussiness or inattention (12), parental interference (1), equipment failure (3), and for having a vocabulary size more than 3SD above the mean score (1).

Materials and Procedure

[2] Note that even on a sequence learning account, some resistance to mapping both HTP and LTP sequences might remain due to the relatively unfamiliar phonological properties of Italian, even if they are not represented as words. If so, then we might find a negative association between English vocabulary size and performance both HTP and LTP words – though with LTP words still being learned more poorly overall. We thank an anonymous reviewer for pointing out this possibility.

We used Italian speech materials that were based on Hay et al (2011) to test whether HTP sequences are considered as possible words. Italian is well-suited for use in such a test for several reasons. First, we needed a natural language that would clearly sound non-native to English-learning infants, and prosodic differences between English and Italian are both perceptible and salient to infants from early in the first year of life (Mehler et al., 1988). Second, English and Italian also differ in their phonology in ways that are likely to be apparent by the second year. For example, the phoneme inventories of English and Italian are only partially overlapping (see the phoneme inventory table of Italian in Keren-Portnoy, Majorano, & Vihman, 2009; for English phonemes, see Rogers, 2014). The phonotactic patterns of the two languages also differ (e.g., word-initial and word-final consonant clusters are more common in English than in Italian; Barca, Burani, & Arduino, 2002). Thus, Italian should sound non-native to English-learning infants.

However, English and Italian are also similar in some important ways. For example, there is overlap in their lexical stress patterns, with most disyllabic words in both languages realized as trochees (i.e., stress falls on the first syllable; Bortolini & Leonard, 2000). Furthermore, some words in Italian and English share characteristic phonological patterns (i.e., CVCV patterns). We note this because under some circumstances sensitivity to native-language metrical and phonotactic patterns can interfere with tracking TPs in novel language materials. For example, by 9 months, English-learning infants, for whom most words follow a trochaic stress pattern (i.e., with stress falling on word-initial syllables) appear to have a difficult time segmenting HTP sequences when they follow an iambic pattern (i.e., with stress falling on word-final syllables; Thiessen &

Saffran, 2003). Both 19-month-olds and adults fail to use TPs to segment potential words in an artificial language when HTP sequences contain violations of phonotactic patterns in their native language (Finn & Hudson Kam, 2012; Graf Estes, Gluck, & Grimm, 2016; Toro, Pons, Bion, & Sebastian-Galles, 2011). Critically, because the metrical and phonotactic properties of Italian do not violate those of English, English-learning infants should not be prohibited from tracking TPs in Italian. Indeed, English-learning infants show evidence of tracking TPs within fluent Italian speech across a wide age range, including infants younger (Karaman & Hay, 2018; Hay et al., 2011; Pelucchi et al., 2009a,b) and older (Hay et al., 2017; in prep) than those tested here.

Infants were exposed to one of two Languages from the corpora developed by Hay et al. (2011). The full set of Language materials is included in the Appendix. In Language 1 (from Experiment 1 of Hay et al., 2011) there were 4 target words (*casa*, *bici*, *fuga*, and *melo*). These words were all phonotactically permissible in English, although their phonological realization was non-native for English listeners. They were embedded in a set of 12 Italian sentences that were semantically meaningful and grammatically correct. Each target word appeared six times within each passage. Two of the target words served as HTP words (TP = 1.0 in both the forward and backward direction). The syllables that comprised the HTP words did not appear anywhere else in the familiarization sentences. The other two target words served as low TP words, where the forward internal TP was reduced to 0.33 because the initial syllables of these words occurred 12 additional times within the sentences. These words are referred to here as LTPf. Note, however, that the backward TPs in these words was high (TP = 1.0), and that at 17 months infants learned these sequences as labels as well as they learned words with HTPs in the forward and backward directions (Hay et al., 2011).

In Language 2 (from Experiment 3 in Hay et al., 2011) the same 4 target words were embedded 6 times each in a different set of 12 Italian sentences. As in Language 1, two of the target words served as HTP-words (TP = 1.0 in both the forward and backward direction). The other two target words served as low TP words (or LTP words), where the internal TP in both the forward and backward direction was reduced to 0.33 because both the initial and final syllables occurred 12 additional times within the passage. At 17-months, infants failed to map these types of LTP words to objects (Hay et al., 2011).

There were two sets of sentences (A and B) within both Language 1 and Language 2, across which the specific words that served as HTP and LTP targets were counterbalanced. In Language 1A and 2A, *casa* and *bici* served as the LTP-words and *melo* and *fuga* served as the HTP-words. In Languages 1B and 2B, the HTP and LTP words were switched (i.e., here *casa* and *bici* served as the HTP words). This ensured that any differences in learning of HTP versus LTP words was due to their TPs, rather than to differences in their phonological properties. A native female speaker of Italian from Milan, who was unaware of the purpose of the study, recorded the audio stimuli. She was asked to speak in an animated voice, as though she were talking to an infant. These recordings were edited to create the four familiarization languages (i.e., Languages 1A, 1B, 2A, and 2B). During the *Auditory Familiarization* phase, infants listened to one of these languages while playing quietly on the floor in a soundproof room. The full set of sentences was presented three times, for a total duration of approximately 2 mins 45 secs for Language 1, and 3 mins 15 secs for Language 2.

During the *Referent Training* phase, infants were seated on a caregiver's lap while viewing four animal pictures whose labels are typically unfamiliar to children at this age (an armadillo, axolotl, platypus, and ring-tailed lemur; See Figure 1). These pictures were paired with the four target words (*bici, casa, melo,* and *fuga*) heard in the *Auditory Familiarization* phase. On each trial, one animal picture was presented on either the left or right corner of the screen for a total 8 seconds. The first two seconds of each trial were silent, giving infants a chance to view the pictures before the label was presented. After two seconds a phrase containing the target word was presented. In these phrases, each target word was said twice and then said following one of two uninformative Italian words (*comunque* or *modem*) used as an exclamation. Thus, on a given trial an infant might see a picture of an armadillo and hear, "*Casa, casa, comunque Casa!*" or "*Casa, casa, modem casa!".* We explain the rationale for presenting the target words in these contexts below. Note, though, that these particular uninformative exclamation words were chosen because they do not contain gender markings that could provide an early cue to the identity of the target word (this was especially relevant during the subsequent test phase). Each target was paired equally often with both exclamations, and side of presentation was counterbalanced. There were eight training trials per target word for a total of 32 training trials. After every fourth trial, infants saw an animated attention getter.

The *Test* phase immediately followed the *Referent Training* phase and assessed whether infants had learned the label-referent mappings. Two pictures from the *Referent Training* phase appeared simultaneously on the lower left and right corners of the screen in silence for two seconds. Next a labeling phrase containing one of the uninformative exclamations followed by an HTP or LTP label for one of the pictures was played (e.g., *Modem, casa!* or *Comunque, bici!*). Each test trial was approximately 7 seconds long. There were four trials per target word and after every fourth trial, we presented an animated attention getter to capture and/or sustain attention. The target pictures appeared equally often across the left and right positions of the screen and were counterbalanced across trials in appearing as targets or distractors. Each target word also occurred equally often with both exclamations.

We embedded the HTP and LTP/LTPf labels in longer streams of speech so that the structure of labeling and test events more closely matched the Auditory Familiarization, in which infants did not hear words in isolation but rather within sentences. In particular, we wanted infants to be able to connect the speech heard during the Auditory Familiarization with the Referent Training and Test phases. Note, however, that other than presenting infants with fluent Italian sentences, we did not include social cues indicating that this was a referential task.

Infants at this age have already begun to show a reduced tendency to map word forms that do not conform to the phonological patterns of their native language when referential support is low (Graf Estes et al., 2011; Hay et al., 2015) especially those with larger native-language vocabularies (Graf Estes et al., 2011). Based on these findings, the word candidate account predicts that 20-month-olds should segment HTP words from both Languages 1 and 2, but fail to map them to referents, especially those with relatively large English vocabularies. Recall that Hay et al. (2011) found that 17-month-olds learned LTPf words as well as HTP words, suggesting that their high backward TPs may have supported word learning. If this is the case, then it is possible that this negative relation with vocabulary size would hold for LTPf words in Language 1 since those items have high backward TPs, but it should not hold in Language 2, in which TPs in LTP words were low in both the forward and backward directions. The sequence learning account would predict better learning of HTP over LTP words in L1, though perhaps not L2, and no relation to vocabulary size for any of the word types[3].

Note that the Referent Training and Test phases differed from those used with younger infants in Hay et al. (2011). In that study, 17-month-olds were habituated to two word-referent pairings (either HTP or LTP/LTPf), and at test were presented with familiar word-object pairings and violations of those pairings using a “same/switch” paradigm. Although the “same/switch” paradigm is often used successfully with younger infants, the procedure used in the current study provides a number of benefits: It is more commonly used with older infants, it provides within-participant measures of learning HTP *and* LTP/LTPf words, and it is likely to provide a more sensitive measure of how well infants learned these two word types. Given that we used different tasks with

[3] Note that if the general unfamiliarity of Italian phonotactic patterns impedes mapping the HTP and LTP/LTPf sequences even when represented as generic sequences, as suggested by the anonymous reviewer, to the extent that there is learning for either HTP or LTP/LTPf words, both would be negatively related to vocabulary size.

different measures, our goal was not to directly compare the performance of 20-month-old infants to the 17-month-olds from they Hay et al. study. Rather, we asked whether 20-month-olds with larger English vocabularies showed less of an HTP advantage than those with smaller English vocabularies.

Vocabulary Development Assessment. Infants' native-language vocabulary size was assessed using the MacArthur-Bates Communicative Development Inventories (MCDI; Fenson, Marchman, Thal, Dale, & Reznick, 2007). We used the Words and Sentences form, which consists of a parent-report measure of infants' expressive vocabulary size. Parents indicated which words their infant says from a set of 680 words commonly known by infants and toddlers.

Results

Infants' looking behavior during the test phase was digitally captured at a rate of 30fps, and coded offline. On each frame, trained coders indicated whether the infant was looking to the picture on the left, on the right, transitioning between pictures, or off-task (see Fernald, Zangl, Portillo, & Marchman, 2008). Inter-coder reliability was assessed by randomly selecting 25% of participants to be recoded. Agreement between coders within a single frame was greater than 98%.

We assessed word learning using an accuracy score that was based on infants' looking behavior during a 1500ms target window following the onset of the HTP or LTP/LTPf word. Specifically, the proportion of time infants were looking to the target picture, beginning 300ms after the onset of the label and ending 1800ms after the onset, (the target window) was computed for each trial and averaged across trials. For each infant, Accuracy scores were calculated separately for HTP and LTP/LTPf words. Because there were two pictures, scores above 0.5 indicate greater looking to the target in response to the label. Trials during which infants were inattentive to the pictures for more than 15 frames anywhere during the target window were not included in the analyses. A total of 443 trials were included in the analyses, with each participant contributing between 8 and 16 trials, and an average of 12.0 trials per participant. There were 220 usable trials included in the HTP condition and 223 in the LTP/LTPf condition.

We used this Accuracy measure to determine whether infants' native language proficiency was related to how they utilized TP information in the word-learning task. To do so, we used a mixed-effects modeling approach (Pinheiro & Bates, 2000) using the lme4 package in R (Bates et al., 2008). For all models, participant was the random effect. The fixed effects were Language condition (Language 1 vs Language 2), and trial type (HTP vs. LTP or LTPf). Vocabulary size was included as a covariate. This model thus allowed us to test how vocabulary size was related to performance on each of the two trial types. We included the interaction between trial type and vocabulary size in the model to assess whether that relation was the same or different across the two kinds of trials. All significance tests used a two-tailed alpha set to 0.05.

First, there was a main effect of Language condition, reflecting the fact that performance was stronger in Language 1 than Language 2; F (1, 69) = 7.67, p = .007 (see Table 1 for more model parameters). Planned one-sample *t*-tests revealed that in Language 1, as a group infants showed above-chance learning of the HTP words (*M* = .578, *SE* = .034; *t* (18) = 2.340, *p* = .03; *d* = .537), and marginal learning of the LTPf words (*M* = .563, SE = .030; *t* (18) = 2.086, *p* = .05; *d* = .479), with approximately medium effect sizes for both. As a group, infants who heard Language 2 did not show evidence of learning HTP or LTP words (respectively, *M*s were .482 and .481, and *SE*s were .033 and .034; *t*s (17) < .543, *p*s > .5). This suggests that Language 1 may have been easier to learn than Language 2. It is not clear why this was the case, though Hay et al. (2011) reported similar findings.

Critically, we also found an interaction between trial type and vocabulary size *F* (1, 69) = 14.422, *p* = .0003), suggesting that vocabulary size was related to performance on the HTP and LTP/LTPf trials differently (see also Table 1). Note that this interaction held in Language 1 (*F* = 7.108, *p* = .01) and in Language 2 (*F* = 9.528, *p* = .004). Thus, we followed up this result by testing the linear relation between vocabulary size and HTP and LTP/LTPf words separately, including Language condition as a covariate (see Figure 3; Table 1 contains additional model parameters and results). Vocabulary size was negatively related to performance on HTP trials ($\boldsymbol{\beta}$ = -.492, *t* (34) = -3.526, *p* = .001, and positively related to performance on LTP trials, though the latter relation was weaker, and failed to reach significance ($\boldsymbol{\beta}$ =.276, *t* (34) = 1.748, *p* = .089). In other words, 20-month-olds with smaller English vocabularies were more likely to learn Italian HTP sequences as labels for uncommon animals than those with larger vocabularies. In contrast, 20-month-olds with larger English vocabularies were, if anything, more likely to learn the LTP/LTPf words than those with smaller vocabularies.

We further explored the interaction between trial type and vocabulary size by dividing participants into two groups, those with relatively small and large English vocabularies using a median split based on their vocabulary size. One-sample *t*-tests revealed that infants with small vocabularies learned the HTP words (M = .584, SE = .033; t (17) = 2.529, p = .02; d = .596) but not the LTP words (M = .483, SE = .032, t (17) = -.54, p = .6). A paired-samples *t*-test indicated that they learned HTP words better than LTP words t (17) = 2.169, p = .045; d = .511). In contrast, infants with large vocabularies showed no evidence of learning the HTP words (M = .482, SE = .033; t (18) = -.559, p = .58). Their performance on LTP words was only marginally better than chance (M = .562, SE = .032, t (18) = 1.914, p = .072, d = .439), and also only marginally better than performance on HTP trials t (18) = -1.946, p = .067; d = .45), but the effect sizes suggest that some learning occurred for LTP words.

In sum, we found that infants with smaller English vocabularies selectively learned HTP words as labels, but those with larger English vocabularies did not, if anything showing better learning of the LTP words, a finding we consider further in the Discussion. The overall pattern of findings, and particularly the finding that infants show less of an HTP advantage on a word learning task as a function of vocabulary size, is consistent with an account in which tracking TPs in speech can be used to find candidate words, and those words may or not be mapped to meaning depending on other factors (e.g., their phonology and the degree of referential support provided).

Discussion

The current study was designed to shed light on whether infants' sensitivity to TPs among syllables within speech yields word-like representations. In several prior studies, infants mapped HTP sequences, but not LTP sequences, to referents. Selective learning of HTP sequences as labels could indicate that infants perceive HTP sequences as potential word forms, but could instead reflect a more general advantage for learning associations between a cohesive but generic sequence and an object referent. These explanations make different predictions about how TPs should influence learning words from a foreign language as a function of native language knowledge. By 20 months of age, infants are becoming resistant to learning mappings between words and referents when word forms deviate from native-language norms, especially as their vocabularies grow. If TPs contribute to infants' identification of potential word forms, infants with smaller native-language vocabularies should be more likely to learn HTP sequences from a foreign language as labels than those with larger native language lexicons. However, if HTP sequences are better learned simply because they are easier to process because of their high TPs, infants should continue to show an advantage in learning them regardless of their vocabulary size. We found that the extent to which 20-month-old infants learning English as their native language showed an advantage for learning HTP vs. LTP words from Italian was related to the number of English words they know. In particular, the fewer English words infants knew, the better they learned the HTP Italian words. These results suggest that tracking TPs in speech can result in forming representations of candidate words.

The word candidate and generic sequence accounts both predict relatively poor learning of LTP words, with no relation to vocabulary size[4]. Interestingly, we found that infants with larger English vocabularies, if anything, showed a hint of learning LTP sequences. This result is most consistent with the word candidate account, which predicts that performance on HTP and LTP words will be related to vocabulary size in different ways, in that the relation between learning HTP words and vocabulary size was negative, while the weak relation between performance on LTP words and vocabulary size was in the opposite direction. We did not predict that infants with larger vocabularies would have an advantage on LTP words, but Hay et al. (2017; in prep) reported a similar finding, and thus it may reflect a genuine effect. If so, one possible explanation is that the LTP sequences were learned by these infants because they contained highly frequent syllables – one or both of them were three times as frequent as the syllables in the HTP words. Thus, it is possible that the LTP sequences were neither represented as words nor learned as referential mappings, but were instead learned by associative learning mechanisms due to the high frequency of their component syllables. Such associative learning may support word learning by allowing infants to make links between visual and auditory information even when they are not being learned as word-referent mappings. The current findings suggest that 20-month-

[4] The generic sequence account might also predict a negative relation, as previously mentioned in footnotes 2 and 3. However, it would predict relations in the same direction for HTP and LTP words, which we did not find.

olds with relatively large English vocabularies are more likely to learn these associations, and point to a potential role for this kind of learning in lexical development.

It is important, however, to consider an alternative explanation for the overall pattern findings, which is that infants who have larger English vocabularies no longer track TP statistics in Italian. If so, they could fail to show better learning for HTP vs. LTP words because they resist learning all Italian word forms, as they do not sound like English words. We think this possibility is unlikely for two reasons. First, previous studies have shown that humans can track TPs in novel language materials well into adulthood (e.g., Saffran, Newport, & Aslin, 1997) even in unfamiliar natural languages (Kittleson, Aguilar, Tokerud, Plante, & Asbjørnsen, 2010). When learners fail to use TPs for word segmentation it is generally because the HTP sequences violate some aspect of native language phonology (Finn & Hudson Kam, 2008; Toro et al., 2013). The Italian words in this study did not violate phonotactic or phonological structure in English, and thus there is no strong reason to think that the phonology of Italian would prevent infants from tracking TPs.

Second, there is evidence that even older infants continue to track TPs in this Italian corpus. Specifically, in recent work by Hay et al. (2017; in prep) when 22- to 24-month-olds were familiarized to a highly similar Italian corpus (the sentences were spoken by a different individual), they subsequently showed differential learning of HTP and LTP words when they were presented with stronger referential support (i.e., when the HTP and LTP words were presented in English carrier phrases during the referent training phase, and tested alongside familiar English words). Their results suggest that HTP words were learned due to their high internal coherence, whereas LTP words, were learned due to their high syllable frequency. Infants would have had to learn the TPs in the familiarization phase to show this effect, which contained the same statistical regularities as the Familiarization used in the current study. Given that both slightly younger and slightly older infants familiarized to the Italian sentence corpus used here show evidence of tracking TPs within it, it is likely that infants in our sample did so as well.

Finally, we think it is unlikely that infants with larger native-language vocabularies were less likely to learn HTP words simply because they were resistant to learning all Italian forms as words, regardless of their TPs. We suggest this because they were not equally resistant to learning HTP and LTP words. This suggests that the statistical structure of the Familiarization phase influenced what was learned during the referent training phase. Overall, then, we suggest that it is likely that infants in the current experiment were sensitive to the TP statistics within the corpus, but that high TPs were not potent enough, in the absence of referential support, to support mapping a non-native speech sequence to a referent.

In sum, these findings suggest that TPs play an important role in word learning, facilitating the segmentation of potential words that are available to be mapped to meanings. As infants begin to learn more and more words in their language, TPs may become just one of many factors that influence how likely infants are to successfully form mappings between speech sequences and referents. These findings are consistent with Thiessen and Saffran (2003), who suggested that TPs may be most potent early in development, before infants have identified the language-specific features that are characteristic of words. While these findings suggest a reduced role for TPs across development, they suggest that infants do use TPs to identify possible word candidates.

References

Aslin, R. N., Saffran, J. R., & Newport, E. L. (1998). Computation of conditional probability statistics by 8-month-old infants. *Psychological Science*, *9*(4), 321-324.

Bates, D. M., Maechler, M., Dai, B., & Vasishth, S. (2008). Lme4: Linear mixed-effect models using S4 classes (R Package Version 0.999375-27) [Software]. Vienna: R Foundation for Statistical Computing.

Bortolini, U., & Leonard, L. B. (2000). Phonology and children with specific language impairment: status of structural constraints in two languages. *Journal of Communication Disorders*, *33*(2), 131-150.

Brent, M. R., & Cartwright, T. A. (1996). Distributional regularity and phonotactic constraints are useful for segmentation. *Cognition*, *61*(1), 93-125.

Endress, A. D., & Mehler, J. (2009). The surprising power of statistical learning: When fragment knowledge leads to false memories of unheard words. *Journal of Memory and Language*, *60*(3), 351-367.

Fernald, A., Zangl, R., Portillo, A. L., & Marchman, V. A. (2008). Looking while listening: Using eye movements to monitor spoken language. *Developmental psycholinguistics: On-line methods in children's language processing*, *44*, 97.

Fenson, L., Dale, P. S., Reznick, J. S., Bates, E., Thal, D. J., Pethick, S. J., ... & Stiles, J. (1994). Variability in early communicative development. *Monographs of the Society for Research in Child Development*, i-185.

Fenson, L., Bates, E., Dale, P. S., Marchman, V. A., Reznick, J. S., & Thal, D. J. (2007). *MacArthur-Bates Communicative Development Inventories*. Paul H. Brookes Publishing Company.

Finn, A. S., & Kam, C. L. H. (2008). The curse of knowledge: First language knowledge impairs adult learners' use of novel statistics for word segmentation. *Cognition*, *108*(2), 477-499.

Graf Estes, K., Evans, J. L., Alibali, M. W., & Saffran, J. R. (2007). Can infants map meaning to newly segmented words? Statistical segmentation and word learning. *Psychological Science*, *18*(3), 254-260.

Graf Estes, K., Edwards, J., & Saffran, J. R. (2011). Phonotactic constraints on infant word learning. *Infancy*, *16*(2), 180-197.

Estes, K. G., Gluck, S. C. W., & Grimm, K. J. (2016). Finding patterns and learning words: Infant phonotactic knowledge is associated with vocabulary size. *Journal of Experimental Child Psychology*, *146*, 34-49.

Hay, J. F., Moore, D., Lohman, J., Malone, G., & Lany, J. (MS in preparation). Statistical learning and referential support in word learning.

Hay, J. S., Shoaib, A., Wang, T., Moore, D., Lohman, J. & Lany, J. (2017, November). Learning words in an unfamiliar language The role of statistics and context. The 42nd Boston University Conference on Language Development, Boston, MA.

Hay, J. F., Pelucchi, B., Graf Estes, K. G., & Saffran, J. R. (2011). Linking sounds to meanings: Infant statistical learning in a natural language. *Cognitive Psychology*, *63*(2), 93-106.

Johnson, E. K., & Tyler, M. D. (2010). Testing the limits of statistical learning for word segmentation. *Developmental Science*, *13*(2), 339-345.

Jusczyk, P. W., & Aslin, R. N. (1995). Infants′ detection of the sound patterns of words in fluent speech. *Cognitive Psychology*, *29*(1), 1-23.

Jusczyk, P. W., Friederici, A. D., Wessels, J. M., Svenkerud, V. Y., & Jusczyk, A. M. (1993). Infants’ sensitivity to the sound patterns of native language words. *Journal of Memory and Language, 32*, 402–420.

Karaman, F., & Hay, J. F. (2018). The longevity of statistical learning: When infant memory decays, isolated words come to the rescue. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 44*(2), 221-232.

Keren-Portnoy, T., Majorano, M., & Vihman, M. M. (2009). From phonetics to phonology: The emergence of first words in Italian. *Journal of Child Language*, *36*(2), 235-267.

Kirkham, N. Z., Slemmer, J. A., & Johnson, S. P. (2002). Visual statistical learning in infancy: Evidence for a domain general learning mechanism. *Cognition*, *83*(2), B35-B42.

Kittleson, M. M., Aguilar, J. M., Tokerud, G. L., Plante, E., & Asbjørnsen, A. E. (2010). Implicit language learning: Adults' ability to segment words in Norwegian. *Bilingualism: Language and Cognition*, *13*(4), 513-523.

MacKenzie, H., Graham, S. A., & Curtin, S. (2011). Twelve-month-olds privilege words over other linguistic sounds in an associative learning task. *Developmental Science*, *14*(2), 249-255.

Mehler, J., Jusczyk, P., Lambertz, G., Halsted, N., Bertoncini, J., & Amiel-Tison, C. (1988). A precursor of language acquisition in young infants. *Cognition*, *29*(2), 143-178.

Namy, L. L., & Waxman, S. R. (1998). Words and gestures: Infants' interpretations of different forms of symbolic reference. *Child Development*, *69*(2), 295-308.

Namy, L. L., & Waxman, S. R. (2000). Naming and exclaiming: Infants' sensitivity to naming contexts. *Journal of Cognition and Development*, *1*(4), 405-428.

Ngon, C., Martin, A., Dupoux, E., Cabrol, D., Dutat, M., & Peperkamp, S. (2013). (Non) words,(non) words,(non) words: evidence for a protolexicon during the first year of life. *Developmental Science*, *16*(1), 24-34.

Pelucchi, B., Hay, J. F., & Saffran, J. R. (2009a). Statistical Learning in a Natural Language by 8-Month-Old Infants. *Child Development*, *80*(3), 674-685.

Pelucchi, B., Hay, J. F., & Saffran, J. R. (2009b). Learning in reverse: Eight-month-old infants track backward transitional probabilities. *Cognition*, *113*(2), 244-247.

Pinheiro, J. C., & Bates, D. M. (2000). Linear mixed-effects models: basic concepts and examples. *Mixed-effects models in S and S-Plus*, 3-56.

Rogers, H. (2014). *The sounds of language: An introduction to phonetics*. Routledge.

Saffran, J. R., Newport, E. L., Aslin, R. N., Tunick, R. A., & Barrueco, S. (1997). Incidental language learning: Listening (and learning) out of the corner of your ear. *Psychological Science*, *8*(2), 101-105.

Swingley, D. (2005). Statistical clustering and the contents of the infant vocabulary. *Cognitive Psychology*, *50*(1), 86-132.

Thiessen, E. D., & Saffran, J. R. (2003). When cues collide: use of stress and statistical cues to word boundaries by 7-to 9-month-old infants. *Developmental Psychology*, *39*(4), 706.

Thiessen, E. D. (2017). What's statistical about learning? Insights from modeling statistical learning as a set of memory processes. *Philisophical Transactions of the. Royal Society B*, *372*(1711), 20160056.

Toro, J. M., Pons, F., Bion, R. A., & Sebastián-Gallés, N. (2011). The contribution of language-specific knowledge in the selection of statistically-coherent word candidates. *Journal of Memory and Language*, *64*(2), 171-180.

van de Weijer, J. (1998). Language input for word discovery. Nijmegen: Max Plank Institute for Psycholinguistics.

Vouloumanos, A., & Werker, J. F. (2007). Listening to language at birth: Evidence for a bias for speech in neonates. *Developmental science*, *10*(2), 159-164.

Woodward, A. and Hoyne, K. (1999), Infants' learning about words and sounds in relation to objects. *Child Development, 70*, 65–77.

Table 1. Model parameters and results.

Multilevel Model

	β	F	p
Word Type	-0.3854	0.0786	0.7801
Vocabulary Size	-0.5003	1.9106	0.1714
Language (1 vs 2)	0.2961	7.6722	0.0072
Word Type*Vocabulary	0.6496	14.4216	0.0003

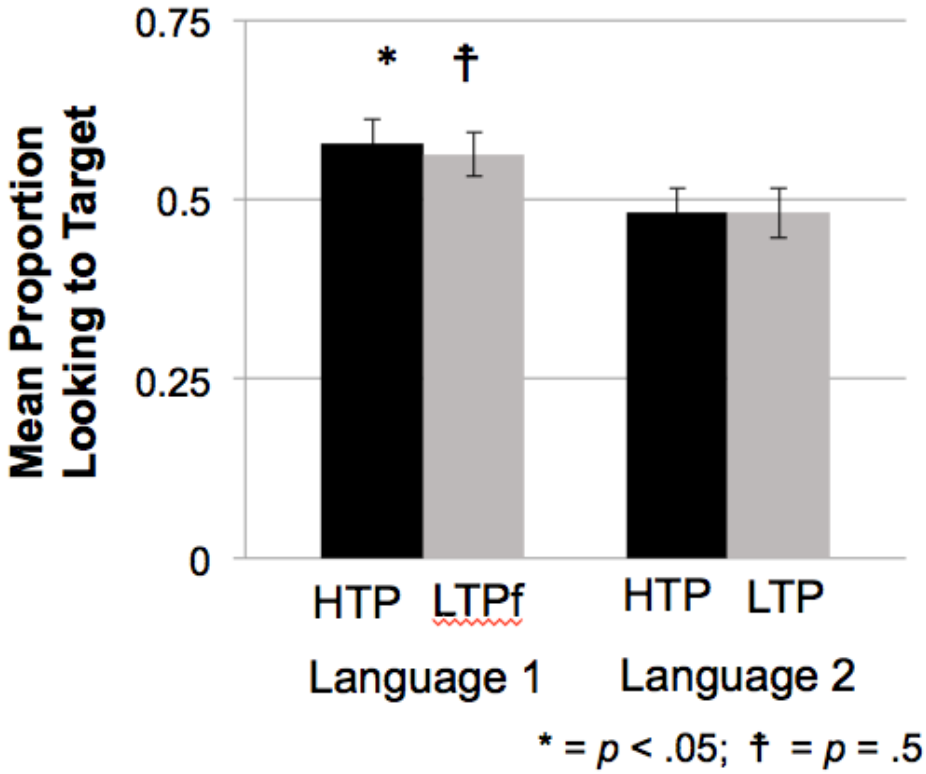
HTP linear model

	β	t	p
Vocabulary	-0.492	-3.526	0.0012
Language (1 vs 2)	0.274	1.967	0.0574
LTP linear model			
Vocabulary Size	0.2763	1.748	0.0895
Language (1 vs 2)	0.3190	2.018	0.0515

Figures

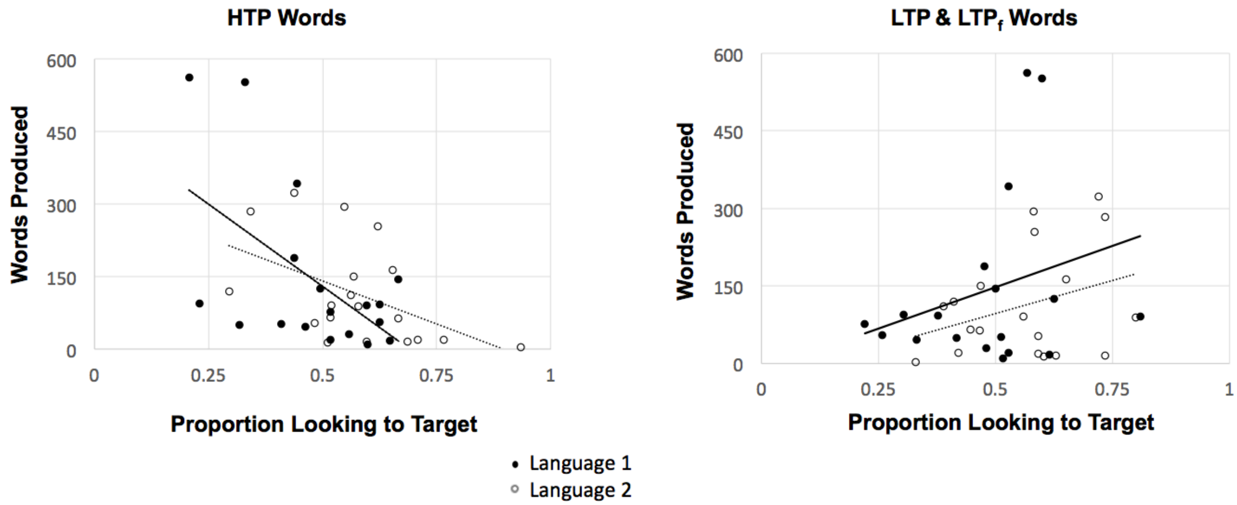
Figure 1. The four animal pictures used in the experiment.

Figure 2. Word-Learning Performance in Language 1 and Language 2



Group level performance on the two languages is depicted, with chance performance equal to 0.5.

Figure 3. Relations between Vocabulary Size and Performance on HTP and LTP/LTPf Trials.



Interaction between Word Type and Vocabulary Size: $F(1,69) = 14.42$, $p < .001$
HTP: $\beta = -.49$, $p < .01$
LTP: $\beta = .28$, $p < .1$

Plotted here are the correlations between infants' performance on the HTP and LTP/LTPf words. Performance in Language 1 (which contained LTPf words, and in Language 2 (which contained LTP words) are depicted in filled and unfilled circles respectively.

Appendix

Language 1A from Hay et al., 2011

Torno a casa con le bici cariche di frutta in bilico sulla sella.

La zia Carola si è esibita in una fuga colla bici verde.

Se porti il melo sulla bici forse cali un po' di chili.

La bici ha subito un danno dentro la casa del capo di Lara.

La cavia Bida è in fuga da casa per aver giocato con le bilie blu.

La biscia in lenta fuga dal giardino capita in casa mia.

Il tuo melo arcano fuga l'afa che debilita la folla.

Arriviamo in bici fino al bivio del grande melo con un caro amico.

Il picchio si abitua a fare la sua casa in ogni melo cavo e alto.

Gusto i bigoli dentro casa o coricata all'ombra del melo verde.

Di rado una bici in rapida fuga rincorre la moto bigia e rossa.

Per ascoltare la fuga quasi cadi sul melo e inciampi sulla biro sull'erba.

Language 1B from Hay et al., 2011

Non è da me scendere dal melo in una futile fuga dalle api.

Torno a casa dalla futa con la bici piena di mele mature.

Il melo e diverse bici furono portate presso la mescita di vino.

Zio Luigi Medo è in fuga colla bici verde.

Vi fu l'età' dei tentativi di fuga in bici verso il rifugio del melo antico.

Il fu Romero Rossi temeva di andare in gita colla bici nuova.

Dario fu l'ingenuo che portò una bici a casa il mese scorso.

Una fuga da casa è il sogno della topina Mela verso la libertà.

Il ratto Meco tentò la fuga da casa quando vi fu la tempesta.

Il micio Refuso medita in casa o dimena la coda sotto al melo ombroso.

Sui rami del melo che sembrano fusi c'è la casa del fuco solitario.

La fuga della stella cometa si è fermata sul melo che fu della zia.

Language 2A from Hay et al., 2011

Spesso Lisa capita in fuga nella casa dove giaci gracile e tesa.

Se cadi con la bici prima del bivio del melo cavo ti do dieci bigoli e una biro.

Gli amici della cavia Bida poggiano le bici in bilico presso il melo per difesa dalla biscia.

Sovente carico la spesa nel vicinato dopo una fuga con la bici nuova.

Carola si è esibita in una fuga verso il melo perché offesa dagli amici scortesi.

Se vai a casa in bici ti debiliti ma cali e non sei più obesa.

Dietro la casa del capo ho sprecato i ceci sotto al melo ombroso.

Se cuci subito sulla divisa bigia il distintivo col melo vado in casa a dormire.

Teresa si abitua alla fuga da casa con la vecchia bici senza luci posteriori.

Taci sulla fuga di Marisa con il caro lattaio.

Il bel melo sta tra la casa dei Greci e la chiesa arcana dove hai giocato con le bilie.

I soci della ditta Musa si danno alla fuga con la bici della maglia rosa.

Language 2B from Hay et al., 2011

Roméro fu coinvolto in una futile fuga in bici verso il profumo del mélo ombroso.

Il collega di Paolo Fusi trovò la bici per la fuga presso la casa del molo.

La maga tiene in casa almeno un fuco, uno squalo e una tartaruga del Nilo.

Il fuco procede parallelo alla casa sulla riga tracciata dalla cometa.

Il gattone Refuso medita sul mélo presso casa ascoltando una fuga di Verdi.

Il fu Medo Rossi ruppe la braga nella bici il mese scorso durante la gara.

Giga ogni mese paga con zelo l'affitto per la casa con il melo in fiore.

meco prega il cielo che ogni fuga da casa termini sotto melo ombroso.

Il delfino beluga si dimena tutto solo nella fuga verso il Nilo azzurro.

Un pezzo di filo si è infilato nella bici appoggiata al melo dietro la méscita.

Vi fu un tempo in cui la bici in lega non temeva il gelo del rifugio della Futa.

La strega del melo fu vista in fuga sulla bici con un chilo di rametti.