Lexical-Processing Efficiency Leverages Novel Word Learning in Infants and Toddlers

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Research Highlights

- Two experiments revealed an association between infants' and young children's online lexical-processing skills and their performance on controlled word-learning tasks.
- The data suggest that children's skill in lexical recognition may be especially important to learning novel words under challenging circumstances.
- These findings contribute to an understanding of how children's speech-processing skills may be linked to language development at a mechanistic level.

Abstract

Children who rapidly recognize and interpret familiar words typically have accelerated lexical growth, providing indirect evidence that lexical processing efficiency (LPE) is related to word-learning ability. Here we directly tested whether children with better LPE are better able to learn novel words. In Experiment 1, 17- and 30-month-olds' were tested on an LPE task and on a simple word-learning task. The 17-month-olds' LPE scores predicted word learning in a regression model, and only those with relatively good LPE showed evidence of learning. The 30-month-olds learned novel words quite well regardless of LPE, but in a more difficult word-learning task (Experiment 2), their LPE predicted word-learning ability. These findings suggest that LPE supports word-learning processes, especially when learning is difficult.

Early language development is highly variable, with some children producing their first words at 8 months, and others just beginning to talk a year later (Fenson et al., 1994). At 24 months, toddlers in the lowest portion of this distribution are at higher risk of experiencing language difficulties that persist through early childhood into their school-aged years (e.g., Rescorla, 2002). Children who struggle with oral language are also are at risk for developing poorer literacy and academic skills, as well as socio-behavioral issues (Duncan et al., 2007; Hooper et al., 2003; 2010). These findings underscore the real-world consequences of persistent delays in language development.

Given the importance of children's language skills, many researchers have focused on identifying the underlying causes of language delays and disorders. It is clear from decades of research that children's language development is associated with a constellation of environmental and cognitive factors. Of particular interest in the current work is evidence that infants and children who rapidly encode and interpret speech also tend to have better language skills throughout childhood (Fernald & Marchman, 2008; Fernald et al., 2006; Marchman & Fernald, 2008). We refer to rapid and accurate lexical recognition as lexical-processing efficiency, or LPE.

Evidence that individual differences in LPE predict language development is consistent with the possibility that skill in language processing may support lexical development at a mechanistic level (Fernald et al., 2006). However, we lack direct evidence that individual differences in LPE are linked to word-learning processes. The current work was thus designed to test whether LPE is related to word-learning ability. Before describing our specific approach, we first carefully consider the task used to assess LPE, and the existing evidence on its relation to language-learning ability.

Lexical Processing Efficiency (LPE)

LPE is typically tested by presenting a familiar "target" word embedded within a sentence (e.g., "Find the doggie!") in conjunction with a picture array containing the target referent (i.e., a dog) and a distractor (e.g., a baby or a shoe). Performance on lexical recognition tasks is most often assessed in terms of the speed with which an individual locates the target picture upon hearing the label (i.e., lexical processing efficiency, or LPE). Fluent speech unfolds very rapidly, with rates of 10 to 15 phonemes per second typical of casual conversation (Cole & Jakimik, 1980), and adults encode it incrementally, even using the first phoneme of a word to initiate a correct look if it disambiguates which picture is being referred to (Marslen-Wilson & Zwisterlood, 1989), and their comprehension is resilient in the face of competing noise (Warren, 1970). This rapid and robust lexical recognition is an achievement gained across development, as infants and children are relatively slow to interpret spoken language, and more prone to comprehension errors (Fernald et al., 1998). For example, at 15 months infants typically do not initiate a gaze shift to a named object until after the entire word has unfolded, if at all (Fernald et al., 1998). However, by 18-24 months infants are much more likely to fixate on the correct referent, and often do not need to hear an entire word to do so (Fernald et al., 1998; 2001).

Older infants' superior performance on lexical recognition tasks clearly reflects their better knowledge of the word-referent associations being tested. However, performance on these tasks is also influenced by how target words are presented. For example, 18 month-olds are quicker to identify the referent of a word like "doggie" when it is presented in an ostensive labeling context than when it is presented in a more minimal speech context. In other words, they are faster to find a picture of a dog when hearing "Look at the doggie" than when hearing "Doggie!" or even "Look, doggie" (Fernald & Hurtado, 2006, see also Kedar et al., 2006). Likewise, 18-24-month-olds are faster to recognize "dog" when it is preceded by a token of "the" that contains coarticulatory cues vs. a token does not (Mahr et al., 2015). These findings suggest that speech belonging to the same intonational phrase as the target label facilitates encoding and interpreting the target word.

Infants may also encode and interpret names presented in fluent speech more rapidly because such contexts allow them to capitalize on predictable sentence structure leading up to the noun. Children learning French and Spanish can use the grammatical gender of a determiner to help identify the referent of an upcoming noun by 18 months (Cauvet et al., 2014; Lew-Williams & Fernald, 2007; VanHuegten & Shi, 2009). Likewise, English-learning children can use prenominal adjectives, such as color terms, to facilitate recognition (Fernald et al. 2010).

Finally, it is important to consider that LPE tasks are also visual in nature. While the pictured referents are chosen to be readily identifiable (i.e., "doggie" and a picture of a stereotypical dog), differences in how quickly and consistently children look to target pictures may reflect differences in the accuracy or generalizability of children's visuo-semantic representations. Children are also slower to find target pictures like "dog" when perceptually and semantically similar distractors are present (Arias-Trejo & Plunkett, 2010). Altogether then, LPE tasks typically used with children measure both how quickly they identify spoken word forms within fluent speech, and how readily they can pick out their visual referents.

Relations Between LPE and Language Learning

LPE clearly reflects infants' growing familiarity with their native language, but it may also be related to their language learning ability (Fernald et al., 2006). Indirect evidence for the hypothesis that LPE plays an active role in word learning comes from findings that it predicts subsequent growth in the lexicon, even when accounting for concurrent vocabulary size as infants approach age 2. For example, Fernald & Marchman (2012) found that in a group of late-talking 18-month-olds, who by definition have small vocabularies, individuals with better

LPE experienced more pronounced growth in their lexicons, and were more likely to have vocabulary sizes in the typical range at 24 months.

Critically, the possibility that children with good LPE have a word-learning advantage has not yet been directly tested, and the results of such a test are not a foregone conclusion. One the one hand, it is easy to see how LPE might support word learning. Infants and children build up lexical knowledge from repeated encounters with labels used in context. Infants who have better LPE may activate information about partially-learned words more readily, and thus they may better capitalize on each successive exposure to build robust and accurate lexical representations. Likewise, lexical processing skill may promote encoding the sentence contexts surrounding novel words, which often provide strong cues to their meanings (Fernald et al., 2006).

Nonethleless, it is possible that LPE is not causally related to language development, but rather is a proxy for other factors that are more relevant to mechanistic accounts of language development, such as the quantity and quality of language that infants hear. This possibility is particularly difficult to rule out because most work in this area has used parent report measures of vocabulary size rather than assessing word-learning ability directly. A notable exception is a study by Law and Edwards (2014), which revealed that preschoolers with larger vocabularies tend to look at an unfamiliar picture more quickly when hearing an unfamiliar word. However, the study stopped short of testing whether such children actually learned the novel word-referent mappings.

The goal of the current work was to directly test whether children who encode familiar words from their native language more rapidly (or who have better LPE) are better able to learn novel words in the laboratory, where children's experience with new words could be tightly controlled. If efficient processing of familiar words is a reflection of experience or familiarity with specific words and phrases, rather than learning ability, then we should find that children with better LPE are no better at learning new words than children with poorer LPE when they are given matched experience with those words. In contrast, a finding that LPE is correlated with word-learning skill under these conditions would be consistent with the hypothesis that LPE is related to learning processes.

To that end, in two Experiments we tested whether lexical processing skill predicts infants' and children's word-learning performance. The first Experiment used a relatively simple task in which both the word form and referent were presented in simple, supportive contexts. We tested 17- and 30-month-olds, expecting that the task would be hardest for the younger group, and that LPE would matter most for their word learning. We also tested older children on a task that was more challenging, expecting that relations between LPE and word learning would emerge at this age for this difficult task.

The two experiments employed a correlational design, as we measured rather than manipulated LPE. Thus, they are subject to the same limitations on causal interpretations as all correlational work. However, this approach provides traction in determining the role of LPE in language development in two important ways. First, in the current work we tested word-learning directly. Second, beyond testing whether LPE is related to word-learning ability, we also tested how that relationship is manifested over the course of early language development. This allows us to provide more precise insights into how LPE affects language-learning ability.

Experiment 1

In Experiment 1, we tested 17- and 30-month-olds on their lexical-processing efficiency, and on their ability to learn novel words in the laboratory. The word-learning task was designed to tap the ability to learn and briefly remember arbitrary associations between novel, nonsense word forms and referents. By 30 months, children are accomplished word learners, readily learning novel words from just a few exposures, but are still relative novices at 17 months of age (see Bloom, 2002 for a review). Thus, we expected that the task would be much more difficult for the 17-month-olds. We tested whether individual differences in lexical processing skill predicted word learning performance in participants at both ages.

Methods

Participants. Participants were 35 17-month-old infants (the range was 16.13 to 18.66; 24 female) and 31 children 30 months of age (the range was 29.34 to 30.32; 12 female). Participants were born at least 37 weeks gestation, and were free from hearing or vision difficulties, serious cognitive delays or disorders according to parental report. The sample was 81% Caucasian, 5% African American, and the remainder were mixed race. As described in more detail below, participants were generally growing up monolingual in highly educated families, with most mothers having a college or graduate degree. Caregivers of 8 infants reported minimal exposure to a language other than English. Of those infants, there was a range of 1 to 8 hours of exposure to another language weekly. An additional 29 participants were tested but their data are not included here because of parent or sibling interference (N=7), equipment failure (N=2), insufficient attention (N=2), and excessive fussiness (N=17), and more than 15% exposure to a language other than English (N=1).

Materials and Procedure. Participants were tested in a small, sound attenuated room in which a 60” LCD monitor sat on a stand centered on one wall. Parents sat in a chair at a distance of approximately 3 feet from the monitor. Children sat on the parent's lap. A digital video camera was mounted flush with the bottom of the LCD screen, and was used to record children’s faces during the word-learning and LPE tasks. Children first completed the Novel Word-Learning task, which took between 9 and 10 minutes. After a 5-10 minute break, they completed the lexical recognition task, which took at most just over 6 minutes. Thus, the procedure lasted about 30 minutes on average.

Novel Word-Learning Task. Children were presented with four disyllabic nonsense words that words conformed to the phonotactic structure of English; *splicket, hazzle, jecter, and dravain.* During training, participants heard each word embedded in the English sentence frames “Look, it’s a ____!”, “Wow, it’s a ____!”, “Wow, look at the ____.”, “I found the ____.”, and “I see a ____.”. The sentences were naturally produced by a female native English speaker in a child-directed register, and recorded in digital format. The best token of each sentence was selected and edited for volume.

During training, the nonsense words were paired with images of colorful objects, such as pieces of abstract art (see Supplementary Materials) that were unlikely to be familiar to children. On each trial, children viewed an object on the LCD screen for 7 seconds and heard a sentence containing its label. Object images were centered in a grey box in the lower left- or right-hand corner, and slowly moved up and down within the box as it was labeled (e.g., “Look, it’s a dravain!”). The 4 novel words were presented in each of the 5 sentence frames twice over the course of training, for a total of 40 training trials,10 per word. Trial order was randomized, and after every 4 training trials, we inserted a “Whoopee” trial, which consisted of a gif of a cartoon-style animal paired with classical music designed to maintain children’s attention.

Training was followed immediately by a test phase. Each test trial consisted of two of the trained images, one in the lower left and one in the lower right corner of the screen. The objects remained static for the duration of the trial. After a 3 second silent baseline, the phrase “Find the ____!” directed children to look at one of the images. This phrase had not been heard during training, but should be quite familiar to participants at both ages tested. Furthermore, all of the target words were preceded by "the" during Training. Each word-object association served as the Target 6 times, for a total of 24 test trails. Trial order was randomized, and the left-right position of each image was counterbalanced, both when serving as the Target and when serving as a foil. Each test trial lasted 7 seconds, and every 4th trial was followed by a Whoopee trial. A sample test trial can be found in the Supplementary Materials.

Lexical-Processing Efficiency (LPE) Task. The LPE task tested children's ability to find the referents of 10 early-learned English words (*baby*, *doggie, kitty*, *birdie*, *ball*, *shoe*, *tree*, *flower, monkey*, and *cow*; see Fernald et al., 2008 for a review). On each trial two images were presented for 8 seconds, one in the lower left and one in the lower right corner of the screen. After a 2 second silent baseline, children were directed to find one of them (e.g., *Find the doggie*!). Side of image presentation was counterbalanced. The labeling phrases were naturally produced sentences generated by a female whose native language was English.

Each item was tested 4 times, for a total of 40 trials. As in the Novel Word-Learning task, every 4th trial was followed by a Whoopee trial.

Native Language Vocabulary Size. Caregivers filled out a MacArthur-Bates Communicative Development Inventory (MCDI) within a week of their child's participation. The MCDI is a parent-report measure of language development that assesses aspects of lexical and grammatical development. We used the Words and Sentences form, which is normed for infants 16 to 30 months of age, to assess vocabulary size. This aspect of the measure consists of a list of words that are typically learned within the first few years, and caregivers indicate whether or not their child has begun to produce each word on the list.

Maternal Education. A child’s language development is related to his or her family’s socio-economic status (SES) and thus we wanted to include this factor in our analyses. We asked about maternal level of education, which is one of the primary components of SES, on an optional questionnaire that included other questions about the child’s health and family background. Our sample consisted of 16 mother's who had attained less than a college degree, 27 a bachelor's, and 24 who had completed a master's degree or higher. Thus, while we were able to include maternal education as a factor in our analyses, our sample was generally highly educated.

Visual Reaction Time (VRT). It is possible that children's performance on both the Novel Word-Learning task and the LPE task is affected by shared factors that are incidental to the primary measures of interest. For example, children who move their eyes slowly, or who are sleepy or unwell might perform poorly on both tasks because of globally slow responding or reduced attentiveness. To address this possibility, we used a portion of the trials in the Training phase of the Novel Word Learning task to calculate a measure of simple visual reaction time (VRT). In particular, every fifth trial of the Training phase consisted of a “Whoopee trial” in which a colorful stimulus appeared in the center of the screen. Following offset of the central stimulus, a picture appeared abruptly on either left or right side of the screen, and was the only stimulus on the screen for the duration of the training trial. For trials on which children were attending to the central stimulus at the offset of the Whoopee trial, we calculated their latency to shift their gaze to the picture that subsequently appeared in one of the corners.

Results and Discussion

Data Preparation. In both the LPE task and the test portion of the Novel Word-Learning task, videos of children's looking behavior were viewed frame-by-frame by trained coders naïve to the content of the trials. Using the custom software iCoder, coders indicated whether a child was looking to the left or right picture, transitioning between pictures, or looking somewhere other than at the display (see Fernald et al., 2008 for more details on iCoder and the coding procedure).

Reliability measures reflect the percentage of coded frames on which the two coders agreed, allowing for deviation of a single frame for gaze shifts. A quarter of the trials from 25% of the participants were recoded to assess reliability using a comparison function built into iCoder, and the resulting agreement across frames was 99% across all coded frames, and was 94% over more selected regions of trials where gaze shifts occurred (shift-specific reliability), which is similar to levels reported by other researchers using this task (e.g., Fernald et al. 2006).

To assess performance on the Novel Word-Learning task, we first used the coded data to determine the proportion of trials on which a child was looking to the target on each video frame. We computed looking to the target picture during the silent baseline to ensure that it did not differ from chance. It did not for either age group (17-month-olds $M = .49$, $SE = .01$; $t(35) = -1.15$, $p = .26$), and 30-month-olds $M = .52$, $SE = .01$; $t(30) = 1.48$, $p = .15$). We also calculated the average proportion of trials on which he or she was looking to the target across each frame of the Target Window. This window started at 300ms after label onset to account for the time required to initiate an eye-movement in response to the label, and ended at 1800 ms, a standard window for these tasks (see Fernald et al., 2008). We refer to this measure as Mean Accuracy. Mean Accuracy scores above .5 indicate levels of target looking that are greater than chance, and higher Mean Accuracy scores generally indicate more rapid and robust looking to the target picture, consistent with stronger learning of the word-referent associations.

The primary dependent measure for the LPE task was how quickly children identified the picture that matched the Target label they heard. Thus, we selected the trials on which infants were looking (by chance) to the distractor picture when the label began, and calculated the time it took them to shift their gaze to the Target picture. This reaction time (RT) measure reflects the time taken to initiate a shift to the correct picture. Shifts that occurred outside of the Target Window (prior to 300ms, or after 1800ms) were not included.

For both the Novel Word-Learning and LPE tasks, trials on which children were not attending to the task for at least half of the silent baseline or the Target Window were excluded from analysis. There were 2 children who did not contribute a minimum of 2 usable trials in either task, and they were excluded from the final dataset for inattention, as reported in the Participants section above. In the Novel Word-Learning task, 17-month-olds contributed an average of 12 trials with a range of 2-24, and the 30-month-olds contributed an average of 14 (range 3-24). The 17-month-olds contributed a mean of 10 trials on the LPE task, with a range of 2-20, and the 30-month-olds contributed a mean of 10 (range 3-21). If participants did not have a minimum of 2 usable trials in the VRT task, we did not include a VRT measure. The 17-month-olds contributed an average of 4.61 trials to the VRT task (2-7 range). The 30-month-olds contributed an average of 4.60 (range 2-7).

Is LPE Related to Novel Word Learning?

We used linear regression analyses to determine whether RT on the LPE task was related to Mean Accuracy on the word-learning task when accounting for other potential predictors such vocabulary size, maternal education, and simple visual reaction time (VRT). We performed these analyses separately for the 17- and 30-month-olds.

17-Month-Old Results. We first consider the relation between LPE and word learning in the 17-month-olds. Table 1 contains descriptive statistics, and Table 2 contains the Pearson correlations between the factors included in the regression models. RT on the LPE task and Mean Accuracy on the word-learning task were negatively correlated, $r(35) = -.45$, $p <.01$, such that infants who had faster LPE scores performed better on the word-learning task (see also Figure 1). None of the control factors we measured (maternal education, vocabulary size, and VRT) were correlated with word-learning performance. Nonetheless, we performed a hierarchical regression to ensure that LPE predicted unique variance in word-learning scores, even after including the control factors. The Control Model (see Table 3) which only included the three control factors was not significant ($R^2 =.06$, $F(3, 29) =.56$, $p =.65$), however adding LPE to the model (LPE + three control variables) significantly improved fit ($\Delta R^2 = .3$, $\Delta F(1, 28) = 12.82$, $p = .001$; see Table 3 for a summary table of the models). Thus, for 17-month-olds, LPE predicted performance on the word-learning task.

Table 1: Experiment 1 Descriptive Statistics for 17-Month-Olds

	Mean	***SD***	**Min**	**Max**
Maternal Education (years)	16	2.29	12	21
Words Produced	69.6	62.19	4	295
Words Produced Percentile	44.6	28.22	1	95.47
VRT (ms)	276.67	35.02	222	366.5
Word Learning Accuracy	.54	.14	.23	.88
LPE RT (ms)	839.77	194.3	490	1273

Table 2: Experiment 1 17-Month-Old Correlations

	Maternal Ed	Words Produced	VRT (ms)	Word Learning
Maternal Ed				
Words Produced	-.12			
VRT (ms)	.27	.02		
Word Learning	.14	-.12	.02	
LPE RT (ms)	-.09	.03	.12	-.45**

Note: ** p <.01; *p < .05

Table 3: Regression Model For 17-Month-Olds

Step 1 (Control Model)	***b***	***SE B***	**β**	***p***
Constant	.29	.35		.26
Maternal Ed	.01	.01	.1	.6
Words Produced	.00	.00	-.11	.57
VRT (ms)	.00	.00	.15	.44

Step 2 (LPE Model)	***b***	***SE B***	**β**	***p***
Constant	.58	.23		.02
Maternal Ed	.00	.01	.07	.69
Words Produced	.00	.00	-.08	.61
VRT (ms)	.00	.00	.22	.18
LPE RT (ms)	.00	.00	-.55	.001

To better visualize 17-month-olds' performance on the word-learning task, we used a median split on RT to classify infants as relatively Fast or Slow, and then plotted real-time looking behavior, averaged across trials (Figure 2; note that looking across the 1500ms window corresponds to Mean Accuracy on the word-learning task). One-sample *t*-tests comparing Mean Accuracy scores to chance (.5) revealed that the Fast 17-month-olds learned the novel words (M =.60, SE =.03, $t(17) = 3.75$, $p < .01$), but that the Slow 17-month-olds did not (M = .48, SE =.03, $t(17) = -.52$, $p = .6$, respectively). This suggests that infants with better LPE had a critical edge on the word-learning task.

Note that LPE was not correlated with productive vocabulary size in 17-month-olds (Table 2). While many studies have reported relations between performance on lexical recognition tasks and vocabulary size, there are studies in which this relation was not present (e.g., Arias-Trejo & Plunkett, 2010; Fernald et al., 2006; Swingley & Aslin, 2000). In this case, the issue may be with the measure of vocabulary size we used, as Fernald et al. (2006) found that LPE was related receptive vocabulary size at 15 months, but was not related to productive vocabulary size until about 2 years of age. Nonetheless, we wanted to ensure that the words we used to test LPE were truly familiar. To that end we computed a more conservative measure of LPE, which was comprised of RT on just the words that parents reported their child to understand. The results using this measure of LPE were not different: It was not correlated with productive vocabulary size (r (33) = -.05, p = .77), but it was negatively related to word learning (r (33) = -.48, p < .01).

30-Month-Old Results. We next tested whether LPE and word learning were related in the 30-month-olds. A Pearson correlation indicated that they were not, $r(30) = -.01$, $p = .90$ (see Table 4 for descriptive statistics, and Table 5 and Figure 3 for Pearson correlations). Because there was no evidence that LPE was related to word learning, we have not included a regression analysis as we did for the 17-month-olds.

Table 4: Experiment 1 Descriptive Statistics for 30-Month-Olds

	Mean	***SD***	**Min**	**Max**
Maternal Education (years)	16.7	2.34	13	21
Words Produced	507.35	127.91	204	678
Words Produced Percentile	51.77	28.24	7	99
VRT (ms)	234.78	41.45	167	380
Word Learning	.66	.16	.32	.96
LPE RT (ms)	617.9	92.58	411	831.56

Table 5: Experiment 1 30-Month-Old Correlations

	Maternal Ed.	Words Produced	VRT	Word Learning
Maternal Ed.				
Words Produced	.19			
VRT	.02	-.32		
Word Learning	-.30	-.06	.05	
LPE RT	-.29	-.41*	.29	-.02

Notes: *p < .05; Ed. = Education.

Figure 4 depicts 30-month-olds real-time looking behavior on the word-learning task as a function of whether they were relatively Fast or Slow speech processors. The 30-month-olds performed much better overall than the 17-month olds (t (63) = 2.91, $p < .01$; see Tables 1 and 4 for Mean Accuracy on the word-learning task at each age). In addition, the 30-month-olds were successful on the task whether they were classified as relatively Fast or Slow speech processors. *M* =.69 *SE* =.03 and *M* =.63, *SE* =.05, one sample *t*s > 2.7, and *p*s <.03.

Does Vocabulary Size Moderate the Relation Between LPE and Word Learning? We found that LPE was related to word learning in the 17 month-olds, but not in the 30-month-olds. One explanation for the differential patterns across ages is that LPE is only related to word learning when the latter is challenging (the 30-month-olds learned the words much better than the 17-month-olds, apparently finding the task to be much easier).

If the relationship between LPE and word learning is stronger during more challenging tasks, we might expect vocabulary size to moderate the LPE-wording learning relationship. That is, infants' vocabulary size could be an index of how much difficulty the task would pose[1], and thus how much LPE matters for word learning[2]. Specifically, it is possible that LPE and word learning are more strongly related for infants with smaller vocabularies.

We therefore tested the possibility that vocabulary size moderates the LPE-word learning relation using the PROCESS macro for SPSS (Preacher & Hayes, 2004) with 10,000 bootstrap samples. Results revealed that the relationship was indeed stronger for 17-month-olds with small (one *SD* below the mean) and average-

[1] Word learning relies on many processes, not just LPE. Infants with smaller vocabularies may find word learning especially challenging.
[2] I thank an anonymous reviewer for this suggestion.

sized vocabularies (*t*s < - 2.12, *p*s < .05), but not those with above-average-sized vocabularies (one SD above the mean, $t = -1.32$, $p = .19$. We note, though, that the interaction between LPE and vocabulary size was not significant ($B = .000$, $t = .19$ $p = .85$). There was no evidence of moderation at 30-months, as the relation between LPE and word learning was not significant in the 30-month-olds at any level of vocabulary size (*p*s > .72).

Altogether these findings may suggest that LPE supports learning novel word-referent mappings when the word-learning task is hard. However, it is also possible that LPE is only important for word learning at the outset of language development. To provide more evidence in support of the former possibility, in Experiment 2 we tested whether 30-month-olds who process speech more quickly are better able to learn novel words in a more challenging task.

Experiment 2

The real-world scenarios in which word learning typically occurs, especially for 30-month-olds, differ substantially from those we presented in Experiment 1, both in their linguistic and their extra-linguistic properties. Thus, in Experiment 2 we again taught 30-month-olds novel words, but tried to increase the ecological validity of the task in two ways. First, we embedded the referents in a dynamic scene in which a man performed an action using an object, such as waving, or tapping. Second, we manipulated the linguistic contexts in which we presented the object labels. One label was embedded in canonical, ostensive labeling phrases (Frequent Frames), while the other was presented in contexts that are grammatical but less prototypical contexts for nouns (Infrequent Frames). Presenting novel words in a referential context in which both an object and an action were salient should encourage children to use the sentence contexts surrounding novel words to identify their referents, and to learn the mappings. Thus, we expected that children's word-learning would benefit from hearing words in Frequent Frames, and also that children with better LPE would learn the words more successfully.

Methods

Participants. Participants were 30-month-olds (range 29.96 to 30.92; N = 34, 18 of whom were female). According to parent report, 88% of children were Caucasian, an additional 6% were African American, and 6% were mixed race. Infants were monolingual, with only 6 receiving regular exposure to a language other than English, and all 6 reported that exposure was for 1 or 2 hours a week. The inclusion criteria were the same as those used in Experiment 1. An additional six children were tested but their data were not included in the analyses because of parent interference (N=1), equipment failure (N=1), excessive fussiness (N=2), and inattention (N=2).

Materials and Procedure. Participants were tested in the same room as in Experiment 1. They first completed the Novel Word-Learning Task, which took approximately 10 minutes. After a 5-10 minute break they completed the LPE task, which took at most approximately 6 minutes, in the same sound-attenuated room. Caregivers filled out a MCDI form (Level 2: Words and Sentences).

Novel Word-Learning Task. Children were first trained and then tested on two novel words, “shuffy” and zojee”, that conformed to English phonotactic regularities. Both words were first introduced using the ostensive labeling phrase “It’s a ____”. This context provides a pragmatically natural way to introduce a new object label. However, we manipulated (within participants) the remaining sentence frames in which each word was presented. One word appeared in distributional contexts that are highly characteristic of nouns, or Frequent Frames (i.e., "That’s the ____.", I see the ____.", and "Is that your ____?"). The other word occurred in contexts that are less characteristic of ostensive naming, or Infrequent Frames (e.g., "That’s his ____." "I see his ____." "Do you like ____s?"*)*. The novel words' occurrence in the two kinds of sentence frames was counterbalanced across participants. While all of the Frequent and Infrequent Frames were grammatical, there is a difference in how reliably they predict that a noun will follow (Cameron-Faulkner et al., 2003). For example, a noun is much more likely to follow “*the*” than “*his*” (consider the fact that “*his*” occurs at the end of a sentence “*That’s his.*” while “*the*” does not; e.g., Monaghan et al., 2005).

During Training, each label was paired with a video scene depicting a man performing an action on an object. The objects, a delinting bush, a lawn sprinkler, a windshield-wiper blade, and an oil guard, were chosen to be relatively unfamiliar to infants. The man performed the same action on the object each time it was labeled. The actions (waving, twirling, tapping, and plunging) were performed continuously throughout each 8 second training trial. Each infant was trained on only 2 of the objects, with assignment counterbalanced across participants. The training videos were centered on the LCD screen and played for 2 seconds before the labeling phrase began to play. The actions and their pairings with objects were also counterbalanced across participants. Each object was labeled in 4 unique phrases, with each phrase presented twice across testing, such that each object was labeled 8 times.[3]

The Test phase was designed to assess whether children learned the label-object associations. Each test trial consisted of two video scenes presented in the lower right and left corners of the LCD monitor for 8 seconds. Each video depicted the actor from the training phase performing an action on one of the trained objects. A sample video can be found in the Supplementary Materials. To ensure that children had associated the label with the object, and not with the action or something more global about the scene, the object was paired with a novel action. As a result on each test trial children saw both of the two objects that had been labeled, but each was presented within the context of a novel action. Thus, the test in Experiment 2 required generalizing object labels to a novel referential context, which can be difficult at 30 months (Childers et al., 2012).

[3] We also trained and tested these children on two novel verbs, but they failed to learn them regardless of their SPE, vocabulary size, or any of the other factors that we measured. For the sake of brevity those data are not included.

On each trial either the Frequent-Frame label or the Infrequent-Frame label was tested. Specifically, after a 2 second silent baseline, children were asked to identify one of the target objects with the phrase "Which one is a ____?". This frame was used to test both Frequent Frame and Infrequent Frame labels. In addition, Frequent Frame and Infrequent Frame labels had been preceded by "a" an equal number of times in Training, and thus the frame was not more closely associated with one label or training context vs. the other. As a result, any differences in performance should reflect differences in how well children had learned the label-object associations.

Each test video served as the target and distractor equally often, and the side of presentation was counterbalanced across the test trials. Each label was tested 4 times. After every 4^{th} trial we presented a "Whoopee" trial to maintain children's attention. The speech materials were recorded by a native English speaker and edited for volume.

Speech-Processing Efficiency Task. The materials, design, and procedure of the LPE task were identical to Experiment 1.

Native Language Development Assessment. As in Experiment 1, caregivers filled out the MCDI: Level II (Words and Sentences) form.

Results

The data for both the Novel Word Learning and LPE tasks were coded as in Experiment 1. Reliability across trials in their entirety was greater than 98%, and shift-specific reliability was 96%. To assess word-learning, we averaged the proportion of trials on which children were looking to the Target scene in the 1500 ms beginning 300ms after the onset of the target label, the same Mean Accuracy window we used in Experiment 1. We also computed looking to the target during the silent baseline to ensure that it did not differ from chance, which it did not (Frequent Frame trials M = .47, SE = .04; t (33) = -.7, p = .48; Infrequent Frame M = .48 = SE = .03; t (33) = -.6, p = .56). Performance on the LPE task was measured in terms of RT, which was calculated as in Experiment 1.

As in Experiment 1, in both the Novel Word Learning and LPE tasks, trials on which children were not attending for at least half of the silent baseline or the Target Window were excluded, and children with fewer than 2 usable trials in either task were excluded from the final dataset for inattention. Children contributed an average of 6 trials on the word-learning task (range 2-8), and an average of 10 trials on the LPE task (range 3-17).

Is LPE Related to Novel Word Learning?

Our primary question was whether children's Mean Accuracy on the Word-Learning Task was related to their LPE. If performance on each were related at comparable levels to LPE, we would be justified in creating an average word-learning score, collapsing across the two trials. However, an ANCOVA with trial type (Frequent Frame vs. Infrequent Frame labels) as a within participant factor, and LPE as a covariate, revealed a marginal interaction between trial type and the covariate, LPE; $F(1, 32) = 3.73$, $p = .06$. This result suggests that the relation between children’s LPE and their word learning scores differed as a function of trial type. Given these findings, we examined the relations separately by trial type. Pearson correlations revealed that LPE was negatively related to performance on the Frequent Frame trials ($r(33) = -.48$, $p < .01$), suggesting that children who were faster to encode native language speech were better able to learn these labels. LPE was unrelated to performance on the Infrequent Frame trials; $r(33) = .05$, $p = .79$; see Figures 5 and 6.

To test whether LPE was selectively related to learning words presented in Frequent Frames, we performed a hierarchical regression. Table 6 contains descriptive statistics, Table 7 contains the Pearson correlations, and Table 8 contains the regression model parameters. We first entered maternal education and concurrent vocabulary size into the regression model (Control Model), but these factors did not account for significant variance in word learning scores ($R = .19$, $F(2, 31) = .59$, $p = .56$). Adding LPE significantly increased the model fit

(ΔR^2 = .16, ΔF (1, 30) = 6.14, p = .02; see also Table 8). Thus, children's online speech processing ability was related to their word-learning performance on these trials, even when accounting for other factors that might also drive performance on the word-learning task. LPE was not related to vocabulary size.

We plotted real-time looking behavior on the word-learning task as a function of LPE, using a median split to create Fast and Slow groups, to better visualize how performance was related to LPE. Note that looking across the 1500ms window corresponds to Mean Accuracy on the word-learning task. As can been seen in Figure 7, Fast children showed evidence of learning the words in Frequent Frames (Mean Accuracy *was* .58, SE = .04, t (16) = 2.13, p = .05) while Slow children did not (Mean Accuracy was .45, SE = .06, t (16) = -.80, p = .44; see Figure 7). Figure 8 shows that neither Fast nor Slow children showed evidence of learning the words presented in an Infrequent frame (Ms = .49 and .48, SEs = .06 and .08 respectively, ts (16) < .22, ps > .4). These findings suggest that learning labels in both Frequent Frames and Infrequent Frames was challenging, and further, that the extent to which children were able to learn the former was related to their LPE.

Does Vocabulary Size Moderate the Relation Between LPE and Word Learning?

In Experiment 1 we found evidence consistent with the possibility that LPE matters most for word learning when the task is difficult. Specifically, the relation was significant only for 17-month-olds, who generally struggled to learn the novel words they were trained on. Moreover, the relation was stronger for infants with below average and average-sized vocabularies, who may be especially likely to have poor word-learning skills. In the current experiment we found even stronger evidence that vocabulary size moderated the relationship between LPE and word learning. A moderation analysis (using the PROCESS macro as in Experiment 1) revealed a significant interaction between LPE and vocabulary size (B = .000, t = 2.12, p = .04). We therefore looked at the relationship between LPE and word learning in Frequent Frames for children with vocabularies at the 1 SD below the mean, at the mean, and 1 SD above it. The relationship was only significant in individuals with average and below-average vocabularies (ts < -3.5, ps < .02), but not for children with relatively large vocabularies (i.e., 1 SD above the mean; t = -.71, p = .48). We return to this issue in the General Discussion.

Table 6: Experiment 2 Descriptive Statistics

	Mean	***SD***	**Min**	**Max**
Maternal Education (years)	15.94	2.23	12	21
Words Produced	466.84	186.33	30.82	670
Words Produced Percentile	46.7	29.68	1	97
Frequent Frames Accuracy	0.52	0.21	0	1
Infrequent Frames Accuracy	.49	.28	0	1
LPE RT (ms)	671.04	150.86	433.25	1048.45

Table 7: Experiment 2 Correlations

	Maternal Ed.	Words Produced	Frequent Frames
Maternal Ed.			
Words Produced	-.14		
Frequent Frames	.14	-.11	
LPE	-.19	.04	-.48**

** *p* < .01; Ed. = Education.

Table 8: Regression Model for Frequent-Frame Analyses

Step 1 (Control Model)	***b***	***SE B***	**β**	**p**
Constant	.38	.30		.23
Maternal Ed	.00	.00	-.09	.62
Words Produced	.01	.02	.13	.48

Step 2 (LPE Model)	***b***	***SE B***	**β**	**p**
Constant	.94	.34		.01
Maternal Ed	.00	.00	-.09	.61
Words Produced	.00	.02	.04	.81
LPE RT	.00	.00	-.47	01

In sum children struggled to learn the novel word-referent associations in this experiment, perhaps because of complexity in the sentence frames in which the words were embedded, and in the referential displays in which the objects were depicted. Critically, children with better LPE were also better able to learn novel words that were presented in Frequent Frames. Moreover, LPE had the strongest beneficial effect for individuals with small- to average-sized vocabularies. However, learning words from Infrequent Frames seemed to be out of reach for the majority of the 30-month-olds, regardless of their LPE.

General Discussion

In two experiments we tested whether children who more efficiently recognized familiar words also learned novel words more readily than their peers who recognized familiar words less quickly. Moreover, we tested the conditions under which lexical-processing efficiency (LPE) is related to word-learning performance at different points in development. In Experiment 1, 17 month-olds and 30 month-olds were presented with a relatively straightforward word-learning task, in which they heard novel words used in canonical labeling phrases. The referents (images of colorful objects) were presented in isolation. A regression revealed that LPE predicted 17-month-olds' word-learning performance even when including variance related to how many words they knew, maternal education, and simple visual reaction time. Moreover, this task was challenging for 17-month-olds, and only the infants with relatively good LPE showed evidence of learning the novel words.

In contrast, the 30-month-olds performed quite well on this word-learning task regardless of their LPE. We suspected that the word-learning task was so easy at this age that LPE was not critical to performance. Thus, in Experiment 2 we tested whether 30-month-olds' LPE was related to performance on a more challenging word-learning task in which the labeled objects were embedded in a dynamic event. Furthermore, one word was presented in a highly prototypical context for object labels (a Frequent Frame), which we predicted should facilitate learning and the other word was presented in a less prototypical context (an

Infrequent Frame). LPE predicted how well children learned words that were presented in Frequent Frames, and only children with better LPE showed evidence of successful learning. However children failed to learn words presented in Infrequent Frames regardless of their LPE, suggesting that learning these words was simply too hard, even for skilled language processors.

The data from the two experiments are consistent with the hypothesis that children's LPE supports learning words. Furthermore, they suggest that LPE may be especially critical when learning a word poses a strong challenge. Good LPE is likely to contribute to word-learning ability in several ways. First, and perhaps most obviously, it may facilitate encoding novel word forms accurately. Second, because encoding word-forms and their referents simultaneously can be challenging (Stager & Werker, 1997) children with superior LPE may have more resources available for encoding the visual characteristics of referents. This would be relevant for both experiments, but especially Experiment 1. Finally, children with better LPE may be better able to form rich, high-quality representations of longer segments of fluent speech in real time. This would give them better access to information from the grammatical contexts of the novel words, which can provide powerful clues to their semantic properties, or likely referents. This may have been especially relevant in Experiment 2, where children seemed to benefit from hearing novel words in familiar labeling frames that provided exceptionally good cues that the novel word referred to an object.

While the results of these two experiments are consistent with the hypothesis that lexical processing skills support word learning, there are other interpretations of the data. For example, it is possible that children with good LPE also have better attention or memory capacity, and that these cognitive skills, rather than their LPE, drove their superior word-learning performance. In other words, the variance in the LPE measure could primarily reflect individual differences in nonlinguistic skills that also contribute to performance on the word-learning task. As noted in the Introduction, both lexical recognition and word-learning clearly involve processes that are not specific to language processing, such as visual encoding, memory, and categorization. However, it is unlikely that the LPE-word learning relation primarily reflects factors incidental to lexical processing because this relationship appeared to be influenced by both linguistic task demands and by children's vocabulary size. There was particularly good evidence for the importance of linguistic task demands within in Experiment 2: In group-level analyses, Fast but not Slow children showed evidence of learning words presented in Frequent Frames, while performance on Infrequent Frame trials did not differ from chance for either Fast or Slow children. The key difference between the Frequent and Infrequent Frame training contexts was linguistic (i.e., they differed only in the extent to which the novel word was preceded by frequent determiners that provided strong cues about the novel words' grammatical category). This suggests that children with better LPE were better able to capitalize on these linguistic cues to aid learning.

The finding that the relation between LPE and word-learning was moderated by vocabulary size also suggests that it reflects something about language-learning processes. Specifically, in both experiments, LPE was most strongly related to word learning in individuals with small- to average-sized vocabularies, though the moderation was only significant in Experiment 2. This suggests that LPE was particularly crucial to word-learning success in these tasks for infants and children who knew relatively few words for their age. Additional work will be necessary to determine more precisely what these relations tell us about when and how LPE makes a difference for learning words. However, one possibility is that Individuals with larger vocabularies relied on other sources of word-learning support, and thus were less affected by poor LPE.

Given these findings, we suggest that the LPE–word-learning relation does not reflect the role of general factors, such as visual attention, but rather reflects factors that are especially relevant to lexical development. However, future work should aim to more directly incorporate the current data into a more finely drawn explanatory account of early language development: We have characterized LPE as a factor that drives word learning, but it may be that experience learning words hones lexical processing by providing stronger representations of native language phonology, or by building more densely connected semantic networks. Relatedly, it may be that children who are more skilled word learners have stronger representations of the familiar words because of their superior learning skills, rather than *vice versa*. Thus, it would be informative to test interrelations between children's language input, LPE, and word-learning ability in a longitudinal design.

Despite the limitations we have noted, these findings advance our understanding of the role of LPE in language learning. For example, previous studies using correlational designs showed that LPE predicts which children with small vocabularies may catch up over time. The current work makes a critical contribution by showing that LPE is correlated with word-learning itself. Moreover, the current work suggests that once children fall behind in speech processing skills, whether due to impoverished language input or other factors, they may continue to fall behind in their lexical development because they experience greater difficulty with language learning.

Perhaps even more importantly, these data suggest that when learning words is hard, even forming a rudimentary mapping between a spoken label and a referent may be significantly impacted by speech processing skills. It also suggests that LPE is especially relevant when children are learning words under challenging circumstances, and when they know relatively few words for their age. Given that children continue to learn harder and harder words as they get older, LPE may support vocabulary development not just during the preschool years, but also well into childhood.

Finally, the data also have important implications for theories of word-learning processes. Of course children learn only the language(s) they hear, and in this way language-development is clearly shaped by experience, but the processes by which experience influences learning mechanisms are not fully understood. Building on previous work showing that language input influences outcomes by providing the material for word learning (Hart & Risley, 1995) and by supporting online lexical processing (Weisleder & Fernald, 2013), the current work provides new evidence that online processing affects word-learning ability. These data illustrate how word-learning skill may emerge from a dynamic interaction between environment and cognitive processes.

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Figure Captions

Figure 1. Experiment 1 correlation between LPE and word-learning scores for 17-Month-Olds

Figure 2. Experiment 1 Accuracy scores for 17-Month-Olds as a function of LPE

Figure 3. Experiment 1 correlation between LPE and word-learning scores for 30-Month-Olds

Figure 4. Experiment 1 Accuracy scores for 30-Month-Olds as a function of LPE.

Figure 5. Experiment 2 correlation between LPE scores and performance on the Frequent Frame Labels

Figure 6. Experiment 2 correlation between LPE scores and performance on the Infrequent Frame Labels

Figure 7. Experiment 2 Accuracy scores for Frequent Frame Labels as a function of LPE

Figure 8. Experiment 2 Accuracy scores for Infrequent Frame Labels as a function of LPE

Figure 1

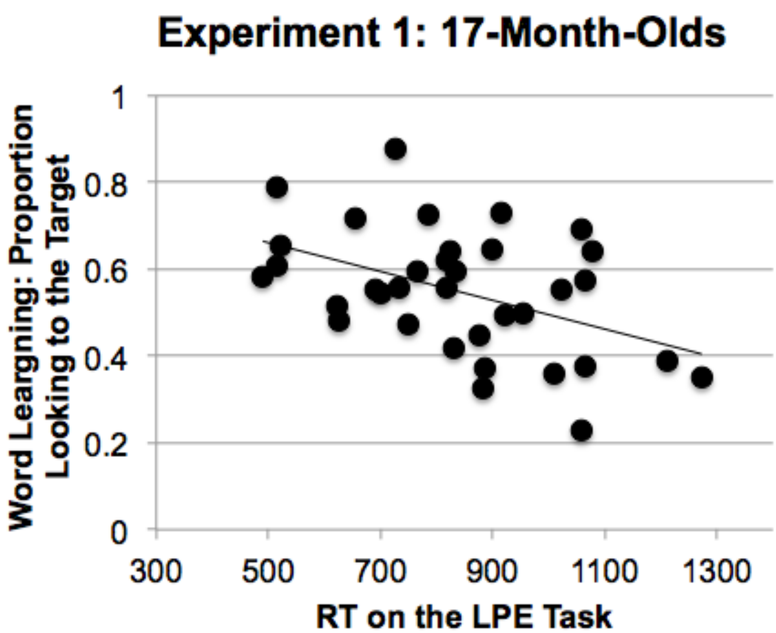

Experiment 1: 17-Month-Olds
Word Leargning: Proportion Looking to the Target
1
0.8
0.6
0.4
0.2
0
300
500
700
900
1100
1300
RT on the LPE Task

Figure 2

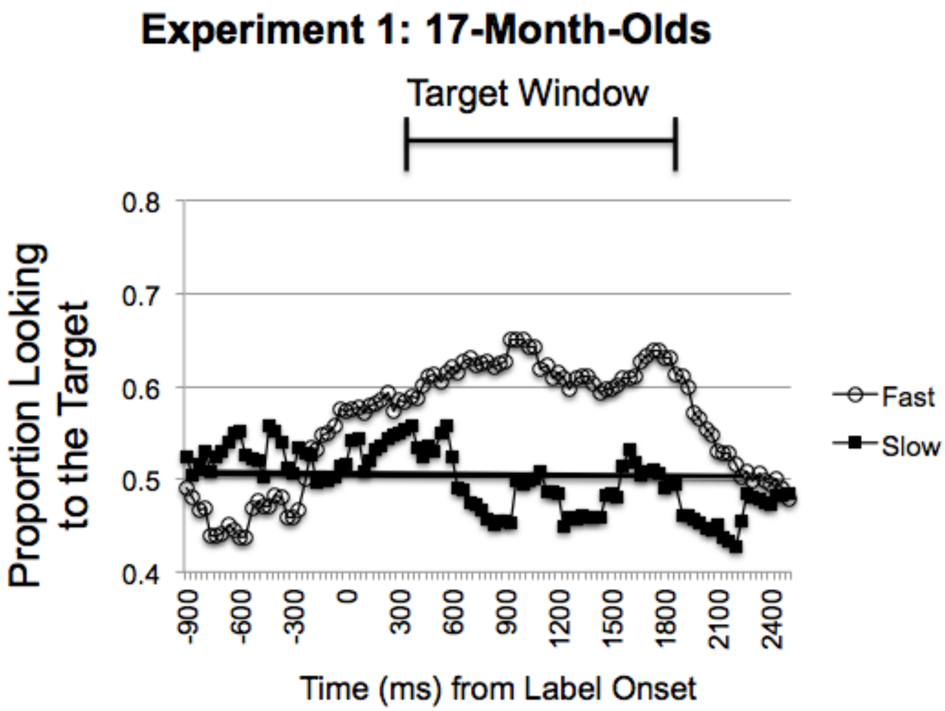
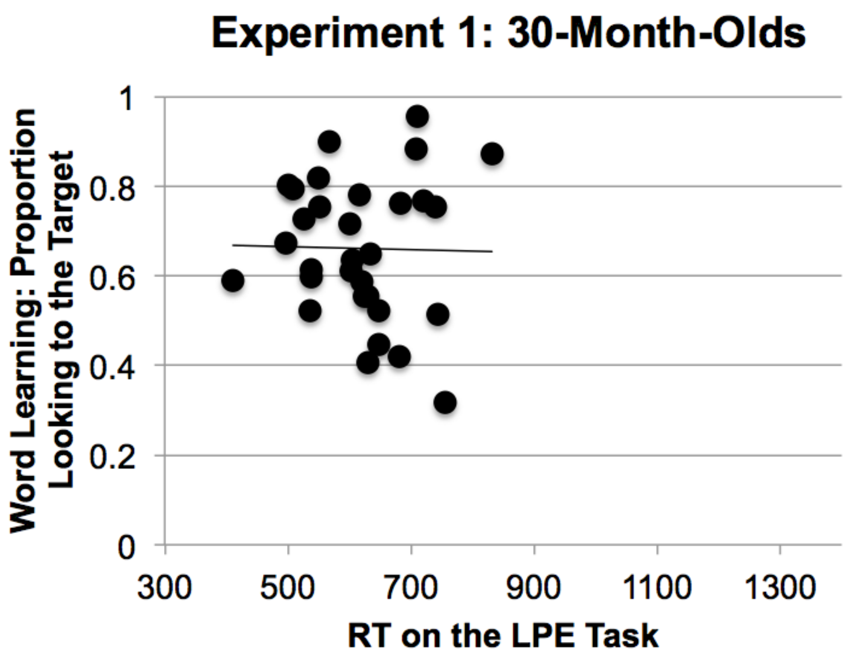

Experiment 1: 17-Month-Olds
Target Window
Proportion Looking to the Target
0.8
0.7
0.6
0.5
0.4
-900
-600
-300
0
300
600
900
1200
1500
1800
2100
2400
Time (ms) from Label Onset
Fast
Slow

Figure 3


Experiment 1: 30-Month-Olds
Word Learning: Proportion Looking to the Target
RT on the LPE Task
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0.8
0.6
0.4
0.2
0
300
500
700
900
1100
1300

Figure 4

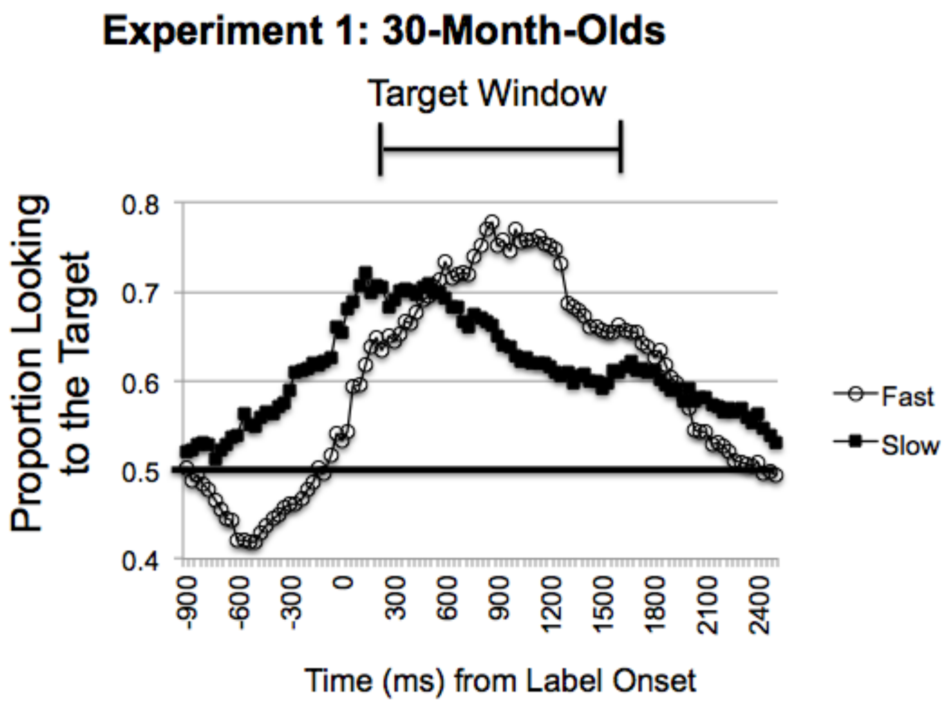
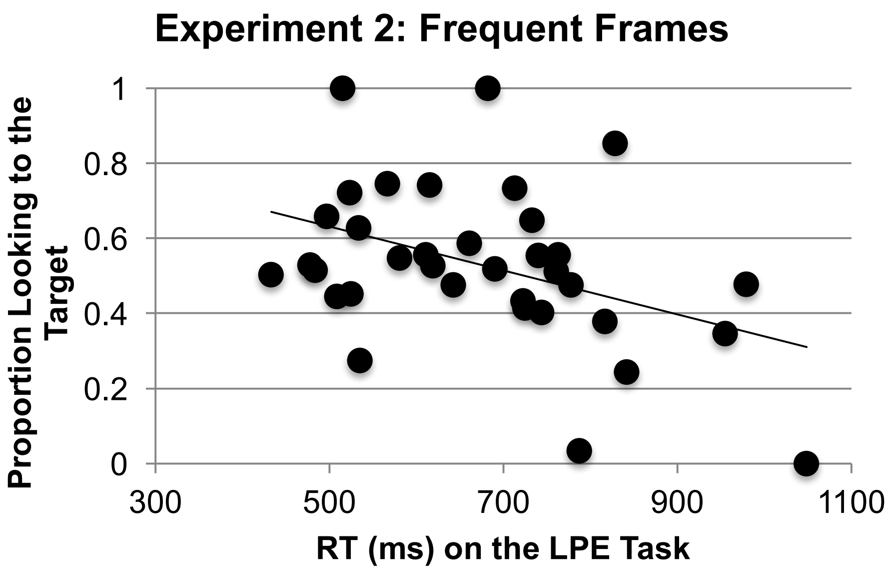

Experiment 1: 30-Month-Olds
Target Window
Proportion Looking to the Target
0.8
0.7
0.6
0.5
0.4
-900
-600
-300
0
300
600
900
1200
1500
1800
2100
2400
Time (ms) from Label Onset
Fast
Slow

Figure 5



Experiment 2: Frequent Frames
Proportion Looking to the Target
1
0.8
0.6
0.4
0.2
0
300
500
700
900
1100
RT (ms) on the LPE Task

Figure 6

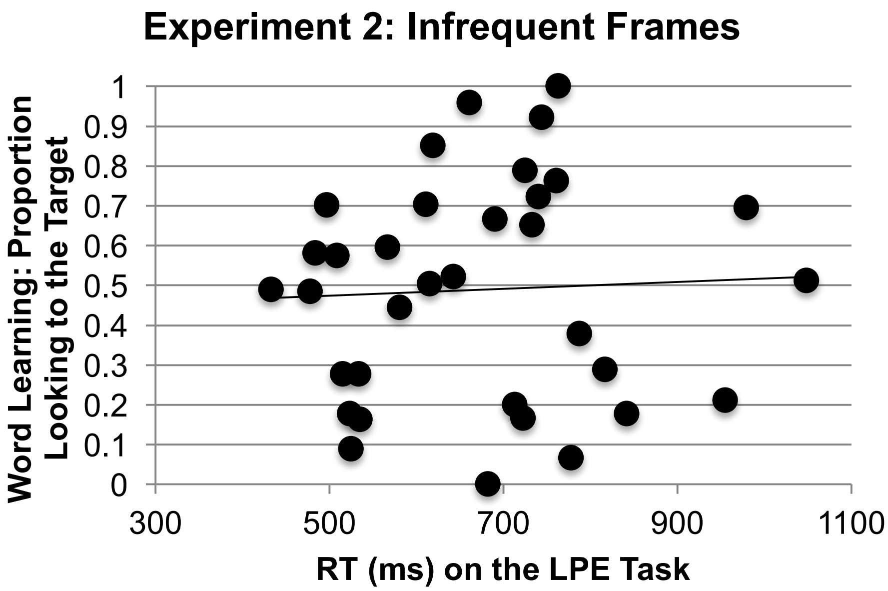

Experiment 2: Infrequent Frames
Word Learning: Proportion Looking to the Target
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
300
500
700
900
1100
RT (ms) on the LPE Task

Figure 7

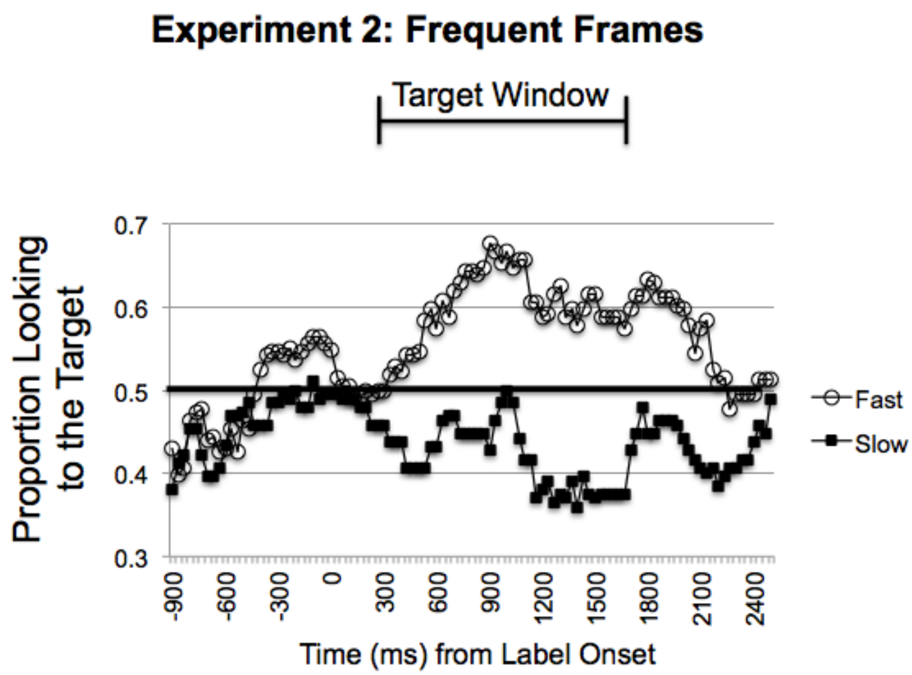
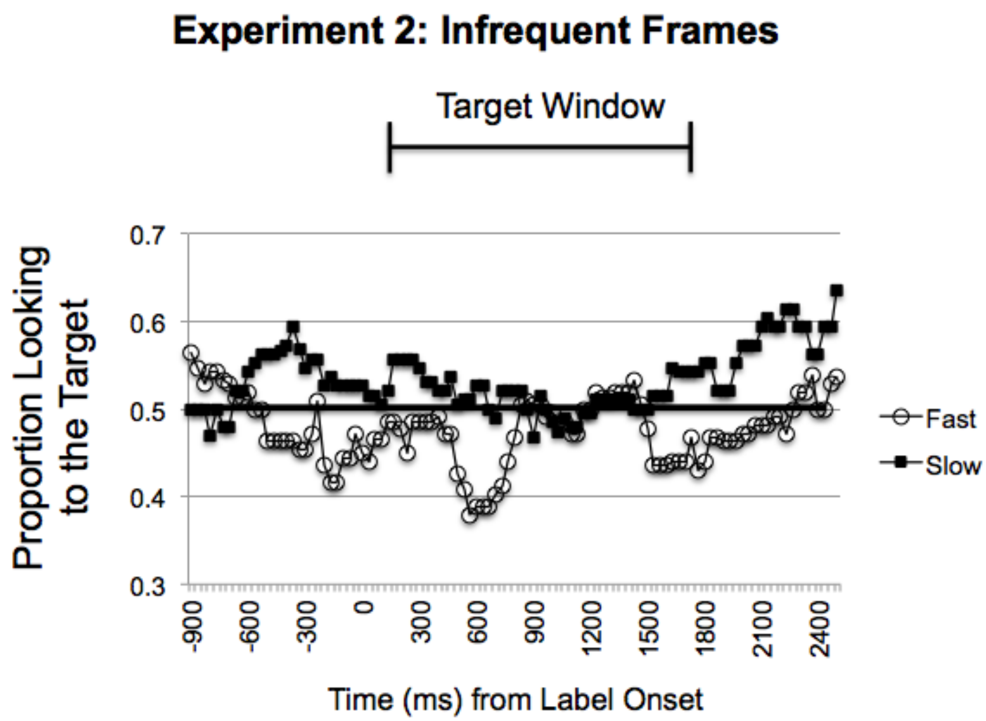

Experiment 2: Frequent Frames
Target Window
Proportion Looking to the Target
0.7
0.6
0.5
0.4
0.3
-900
-600
-300
0
300
600
900
1200
1500
1800
2100
2400
Time (ms) from Label Onset
Fast
Slow

Figure 8


Experiment 2: Infrequent Frames
Target Window
Proportion Looking to the Target
0.7
0.6
0.5
0.4
0.3
-900
-600
-300
0
300
600
900
1200
1500
1800
2100
2400
Time (ms) from Label Onset
Fast
Slow