

Nature and origins of the lexicon in 6-mo-olds

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Recent research reported the surprising finding that even 6-mo-olds understand common nouns [Bergelson E, Swingle D (2012) *Proc Natl Acad Sci USA* 109:3253–3258]. However, is their early lexicon structured and acquired like older learners? We test 6-mo-olds for a hallmark of the mature lexicon: cross-word relations. We also examine whether properties of the home environment that have been linked with lexical knowledge in older children are detectable in the initial stage of comprehension. We use a new dataset, which includes in-lab comprehension and home measures from the same infants. We find evidence for cross-word structure: On seeing two images of common nouns, infants looked significantly more at named target images when the competitor images were semantically unrelated (e.g., milk and foot) than when they were related (e.g., milk and juice), just as older learners do. We further find initial evidence for home-lab links: common noun “copresence” (i.e., whether words’ referents were present and attended to in home recordings) correlated with in-lab comprehension. These findings suggest that, even in neophyte word learners, cross-word relations are formed early and the home learning environment measurably helps shape the lexicon from the outset.

word learning | lexicon | cognitive development | language acquisition | environmental effects

To learn words, infants integrate their linguistic experiences with word forms and the conceptual categories to which they refer. They do this fast: A growing literature demonstrates that, by around 6 mo, infants have begun understanding nouns (1–5), suggesting they form word-referent links from their environment in the first half-year.

The speech–sound learning trajectory in year one is relatively well-established (6): Infants’ language-specific sensitivity emerges around 6 mo for vowels, and 12 mo for consonants (7, 8). Indeed, by 12 mo, infants reveal robust phonetic representations for common words (9–11), and fine-grained knowledge of native language speech–sound combinatorics (12). Before this, their sensitivity to phonemic and talker-specific differences can be fragile (3, 13).

In contrast, early meaning is understudied: It’s not clear what makes the first words infants understand learnable, or what aspects of meaning infants initially represent. This is partly because meaning components are not straightforward. While phonetic features (e.g., voicing) let us readily quantify speech–sound differences, characterizing meaning is harder; consider describing or comparing how “dog” and “log” sound versus what they mean. While toddlers are sensitive to visual similarity, shape, and semantic category (14–17), little is known about nascent semantic representations.

Regarding early semantics, Arias-Trejo and Plunkett (18) find that both visual similarity and category membership contribute to semantic competition: For toddlers, understanding “shoe” in the context of a boot and a shoe was harder than when shoe appeared with a hat or bin instead. Thus, even in seasoned word learners, certain visual contexts make it harder to ascertain a spoken word’s referent.

Bergelson and Aslin (19) provide further data on early meanings. They find that, over 12 mo to 20 mo, infants’ semantic specificity increases: Although younger infants looked at a named

target to similar degrees whether hearing an appropriate or a related label (e.g., “cookie” or “banana” to label a cookie), older infants did so less. This suggests that 1-y-olds have immature extensions for words they know something about (i.e., “banana” could refer to a cookie), but leaves open whether younger infants are already sensitive to words’ relatedness (i.e., banana’s and cookie’s shared meaning).

Despite the relative dearth of infant work, a large literature on adults’ single-word representations (20) reveals sensitivity to context and meaning. Adults consider semantic and perceptual relations among words in both the visual world paradigm (21, 22) and lexical decision tasks (20). Taken together, previous work with children and adults suggests that knowledge of how words are related goes hand in hand with knowledge of what words mean. Here we ask whether this is true for infants’ earliest words, or whether initial words are more like “islands,” unrelated to other emerging lexical entries.

Although lab studies provide controlled assessments of children’s knowledge, their natural habitats are far more complex. Corpus research has been crucial for establishing what children may learn from in their daily environments. Such data have been used to unpack both linguistic and nonlinguistic aspects of the input (12, 23–27); they may also prove critical for understanding early lexical development.

However, there are exceedingly few available corpora of young infants, fewer yet with video, and none linking to comprehension measures in those same children. Here we begin to address these gaps by gathering real-time processing data for words within and across semantic categories, and investigating how infants’ home experiences with concrete nouns may influence their overall early comprehension. We ask the following: (i) Does semantic relatedness between visually available referents influence word

Significance

Infants start understanding words at 6 mo, when they also excel at subtle speech–sound distinctions and simple multi-modal associations, but don’t yet talk, walk, or point. However, true word learning requires integrating the speech stream with the world and learning how words interrelate. Using eye tracking, we show that neophyte word learners already represent the semantic relations between words. We further show that these same infants’ word learning has ties to their environment: The more they hear labels for what they’re looking at and attending to, the stronger their overall comprehension. These results provide an integrative approach for investigating home environment effects on early language and suggest that language delays could be detected in early infancy for possible remediation.

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comprehension in novice word learners? (ii) Do readily measurable aspects of infants' home life account for those same infants' variability in word comprehension?

We answer these questions through in-lab eye tracking and home recordings. The eye-tracking experiment addressed question i: We presented infants with image pairs that were either semantically related or unrelated (e.g., car–stroller or car–juice); then, one image was named aloud (e.g., “car”). By hypothesis, if young infants are influenced by semantic relatedness (as toddlers and adults are), we predict better performance in the unrelated trials. That is, in the context of two semantically unrelated images, we predict stronger comprehension than in the context of two related images.

Our home environment analysis addressed question ii: We gathered daylong audio and hour-long video recordings from infants in their homes, and examined just those time slices when concrete nouns were directed to the infant. We then derived measures of quantity, talker variability, utterance type, and situational context, and explored how they might be related to performance on the eye-tracking task.

Previous research with older infants suggests that hearing more words strengthens the early vocabulary whether in daily interactions (24), or in shared reading (28, 29). In the lab, talker variability aids word learning (30). For utterance type, words said in short phrases (i.e., alone or at utterance edges) are proposed to be learned more readily (31, 32). Relatedly, syntactic diversity (i.e., hearing a word across more sentence structures) has been shown to aid word learning (25).

Finally, we examined referential transparency (i.e., whether parents talk about observable referents), which is suggested to facilitate language learning (33–35). Notably, previous research examining why infants learn common nonnouns (e.g., “hi,” “eat”) later than common nouns found that visual copresence varied across word class (36). Nonnouns were more likely to be said when the referent event was not occurring (i.e., “hi” said with no one entering the scene) vis-à-vis nouns, which were generally proximally present when named. If such referential transparency were a basic feature that boosts learnability, then here too we would expect that the degree of “object copresence” in infants' experience would map onto early comprehension, which has not previously been shown within infants, or within nouns.

Results

Data processing and annotation information, and in-house scripts are available on our OSF lab wiki and github repository (<https://github.com/SeedlingsBabylab/>). Raw home-recording data (audio and video) are available through HomeBank and Databrary; see details in *Materials and Methods*; clips are available in *Supporting Information*.

Eye-Tracking Results. Eye-tracking data were processed in R 3.3.1 to determine where the child was looking for each 20-ms bin during the test trials: the target or distractor interest areas (an invisible 620 × 620 pixel rectangle around each image), or neither. Eye movement data were time-aligned to parents' target word utterances (noted by experimenter key press).

These data were then aggregated across two time windows: a pretarget baseline from trial start to target word onset and a posttarget window from 367 ms to trial end, i.e., 5,000 ms after target onset. Given the longitudinal home-and-lab design of this data collection, we exclude at the trial level rather than the infant level, where possible. Trials were excluded if infants did not look at either image for at least 1/3 of the target window (367 ms to 5,000 ms), if no looking was recording in the pretarget baseline window, or if the trial was never displayed due to experiment termination for infant fussiness; see *Supporting Information*.

We used the standard baseline-corrected target looking metric, which calculates the proportion of target looking [target/

(target+distractor)] in the posttarget window, and subtracts this same proportion from the baseline window. Visual inspection of subject means revealed one outlier (>5 SD above the mean). Once this outlier was removed, this outcome measure did not differ from a normal distribution (Shapiro–Wilk test, $P = 0.93$).

We predicted that, if infants' comprehension is affected by semantic relatedness, performance on related trials would be worse than on unrelated trials. Indeed, performance was significantly above chance on unrelated trials [$t(50) = 2.91$, $P = 0.005$, by two-tailed one-sample t test], at chance on related trials [$t(50) = -0.64$, $P = 0.524$, by two-tailed one-sample t test], and significantly different between the two [$t(50) = 2.22$, $P = 0.031$, by two-tailed paired t test]. That is, infants looked more at the labeled image on unrelated trials than on related trials. Over subjects, 36/51 infants attained positive subject means for the unrelated trial type ($M = 0.044$, $SD = 0.108$, $P = 0.005$ by binomial test), while only 26/51 did so for related trials ($M = -0.013$, $SD = 0.15$, $P = 1$ by binomial test). Over items, infants showed the same numeric pattern as over subjects, i.e., the item mean was higher for unrelated items than related items ($M = 0.035$, $SD = 0.081$ and $M = 0.003$, $SD = 0.067$, respectively), and item means were positive for most items in the unrelated condition, but not the related condition; with only 16 items, item-level effects were not different from chance ($P > 0.05$). Summarily, in the related condition but not in the unrelated condition, performance was positive over most infants and most items; see Fig. 1 and Figs. S1 and S2.

Home-Recording Results. After preprocessing (see *Materials and Methods*), annotators marked each object word (i.e., concrete noun) in the recordings along with three properties: utterance type, object copresence, and speaker. Each word's utterance type was classified by its syntactic and prosodic features into seven categories: declaratives, questions, imperatives, short phrases, reading, singing, and unclear. Object copresence was coded “yes,” “no,” and “unclear” based on whether the annotator felt that the object corresponding to the word being annotated was present and attended to by the child. For videos, this was generally visually appreciable; for audio files, annotators used their impression from the context (e.g., generally, in “here's your spoon!” spoon

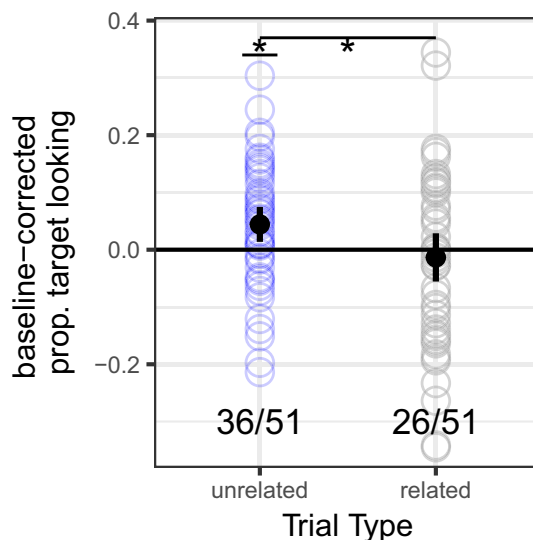


Fig. 1. Comprehension by trial type. Dots represent each infant's baseline-corrected proportion of target looking, per trial type (unrelated, related). Mean and 95% CIs are in black. Asterisk indicates $P < 0.05$ for the unrelated and related trial types; the fraction indicates the proportion of infants with positive trial-type means.

Table 1. Home-recording descriptive statistics

	No. tokens		No. types		No. speakers		Prop mat input		Prop obj.cop.		Utt type ent		Prop short phrase	
Rec type	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)
Aud	74 to 1,619	714.5 (355.7)	39 to 375	184.5 (64.9)	2 to 16	6.5 (3.4)	0.2 to 1	0.6 (0.2)	0.1 to 0.7	0.5 (0.2)	1.3 to 2.4	1.9 (0.3)	0 to 0.2	0.1 (0.05)
Vid	30 to 635	171.5 (120.9)	13 to 169	58.3 (34.4)	1 to 6	2.9 (1.2)	0 to 1	0.7 (0.3)	0.1 to 0.9	0.6 (0.2)	1.2 to 2.5	1.9 (0.3)	0 to 0.5	0.1 (0.1)

Aud, audio; ent, entropy; mat, maternal; obj.cop., object copresence; Prop, proportion; Rec, recording; Utt, utterance; Vid, video.

was coded “yes” for object copresence, while in “twinkle little star,” star was coded “no”). Interrater reliability was high [computed for 10% of annotations for utterance type: 89% agreement, Cohen’s (K) = 0.8; object copresence: 85% agreement, Cohen’s (K) = 0.7]. We then derived token counts for the various forms a word occurred in (e.g., “tooth,” “tootheroo,” “teeth”), and type counts for the lemma (e.g., “tooth”).

While input data varied by child, there was relatively high consistency in our proportional measures (Table 1). We operationalized input quantity as the number of types and tokens of each lemma. Given that the video recordings were all ~1 h, while the audio recordings varied based on the nap time of the child, we report daily audio rates and hourly video rates.

In our daylong audio recordings, infants heard ~710 object word tokens of ~180 word types, from seven speakers, on average. Sixty percent of this input came from infants’ mothers, and 50% of the time that infants heard an object word, the corresponding referent was visible and attended to (i.e., 50% object copresence). In our hour-long video recordings, infants heard ~170 tokens, from ~60 types, from three speakers. In the videos, 70% of the input came from infants’ mothers, with 60% object copresence. For both audio and video recordings, the average entropy across utterance types (i.e., the variability proportions of each utterance type in “bits”) was 1.9; short phrases were 10% of the input (Fig. 2).

Comparing the daylong audio and hour-long video recordings, we found that, although infants heard more object word input in the audio recordings in an absolute sense, they heard relatively more input in the videos. That is, infants heard only 25 to 50% fewer word tokens, word types, and speakers in the hour-long video than in the daylong audio recording (from a different day), even though the latter was ~10–11× longer than the former; we explore this in ongoing work.

Questionnaires. Vocabulary questionnaires [MacArthur-Bates Communicative Development Inventory (MCIDI)] showed that parents felt their infants understood few of our 16 tested words [M = 1.96 (3.98); R : 0 to 15; mode: 0], whereas, on Word Exposure Surveys, parents indicated that their child heard these words

daily on average (4 on a 1 to 5 scale from “never” to “several times a day”). According to parental report, 71% of infants were not yet babbling, all but one were not yet hands-and-knees crawling, and 29% were exclusively breast-fed; see [Supporting Information](#).

Home and Lab Linkages. We next examined data from the infants who provided both home and in-lab data (video and eye tracking: n = 40; audio and eye tracking: n = 41). We modeled infants’ subject means from our eye-tracking experiment as a function of the properties we had annotated (noun input, talker, utterance types, and object copresence). Given the relatively small sample size, the large number of ways one might aggregate the home data, and both predicted and unanticipated collinearity among these four preidentified properties of interest, we opted for a simple analysis approach. Namely, we tested directionally specified correlations between home environment measures found to predict lexical knowledge in previous research and infants’ in-lab comprehension. That is, if measures that predict lexical knowledge in older infants hold at 6 mo at levels our home measures can detect, we would see positive correlations between in-lab comprehension and noun input, talker variability, utterance type diversity, and object copresence. When analyzing counts, we examined audio and video data separately, since length varied substantially by recording type. When examining proportions, we averaged audio and video data. We first conducted Shapiro–Wilk Normality tests; if both variables were normally distributed, we used Pearson correlations; if one or both were not, we used Kendall correlations.

As described above, the eye-tracking results suggest that neophyte word learners are sensitive to semantic similarity. However, given that the home environment is not split into experiences relevant for our two experimental trial types, we examine how overall lab performance correlates with home measures. Notably, aggregating across trial types for each infant, performance overall was not above chance, given the relatively weak performance on related trials [$t(40)$ = 1.59, P = 0.12]. [This t test was run on the subset of infants reported above for whom there is

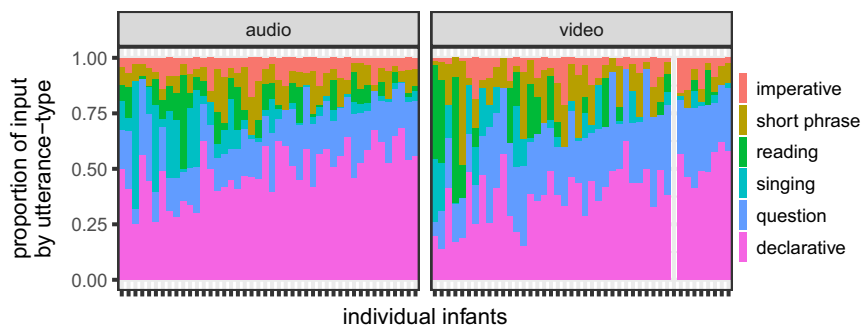


Fig. 2. Distribution of object word utterances, by infant. Color shows utterance type [daylong audio (Left) and hour-long video (Right)]. One video was lost; one word with unclear utterance type was removed. The x axes are identically ordered by each child’s overall proportion of object words in declaratives and questions.

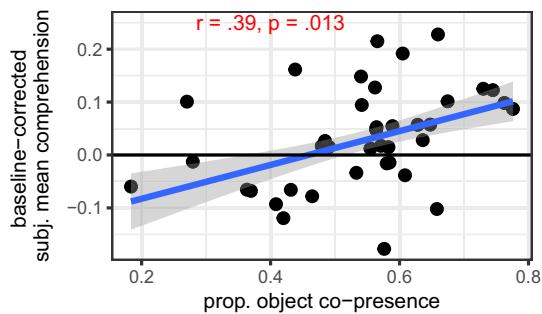


Fig. 3. In-lab comprehension by proportion of object copresence. Each point indicates a given infant's average proportion of object copresence in the audio and video home recordings (x axis) by that same infant's subject mean in the eye-tracking experiment (y axis). Line indicates robust linear fit, with 95% CI in gray.

also home-recording data ($n = 41$); the same pattern holds over all infants included in the initial analysis.]

We find a significant correlation between the proportion of object copresence and infants' overall in-lab comprehension ($r = 0.39$, $P = 0.013$) (Fig. 3). This result is consistent with a broader role for referential transparency in word learning, even among (early-learned) nouns; we return to this in *Discussion*.

We next considered four measures of object word quantity from the literature: number of types, tokens, and words read, along with type-token ratio. These variables tend to be highly correlated with each other, and, indeed, we find each of them significantly correlated with the others in both audio and video data ($|r|$ between 0.23 and 0.82; $P < 0.05$). (As expected, type-token ratio negatively correlated with quantity; all other r 's were positive.)

Given predicted correlations among quantity measures, we asked how these measures correlated with lab performance. No video quantity measures correlated significantly with in-lab comprehension. However, several quantity metrics from the audio recordings (number of types, tokens, and object word-containing reading utterances) were close to the $P < 0.05$ significance threshold [$r = 0.32$, $P = 0.047$; $r = 0.29$, $P = 0.074$; and (τ) = 0.19, $P = 0.088$, respectively]; this leaves open the possibility that an expanded home and lab sample, or other measures of word knowledge and/or input quantity, would render clearer results.

Looking at talker variability, we again did not find significant correlations with in-lab comprehension in audio or video recordings, or in the proportion of input from infants' mothers (all $P > 0.05$). Finally, looking at utterance type variability (calculated as each infant's average entropy across utterance types), we found no significant correlations with in-lab comprehension ($P = 0.58$), likely due to highly similar utterance type distributions across participants (Fig. 2). We replicated previous work reporting that infants hear $\sim 10\%$ of words in isolation (31), but this property too was not associated with in-lab comprehension ($P = 0.43$).

Thus, across the four aspects of home environment we predicted would positively correlate with in-lab comprehension, only object copresence clearly did so, although it is premature to conclude that this variable is a differentially better predictor than

the others. Given that our analyses were predicated upon directional predictions, but served as initial exploratory steps, we evaluated this correlation further by calculating bootstrapped CIs with 1,000 iterations. The 95% CI did not include 0 (0.15 to 0.62). (Audio and video object copresence were marginally correlated with each other, $r = 0.29$ and $P = 0.064$.)

Discussion

Consistent with research on adults and children, we find that 6-mo-olds understand words more readily when shown two semantically unrelated referents than when shown two related ones. We further find initial evidence that, in these same infants, in-lab word comprehension is linked with referential transparency in the home, but not with measures of talker or utterance-type, and only marginally with input quantity. These findings enrich our understanding of infants' real-time word comprehension, and the longer-scale learning environment that fuels it.

Our eye-tracking results suggest that even first words are not unconnected islands of meaning; they already contain semantic structure. Still, there are various interpretations of infants' relatively strong performance on unrelated trials (e.g., car-juice), versus their poor performance on related trials (e.g., car-stroller). One possibility is that infants know (something about) the tested words, but cannot overcome semantic competition on related trials, i.e., hearing "car" leads to car looking, but also activates related words, e.g., stroller, to a similar (or indistinguishable) degree.

Alternatively, infants' word knowledge may be underspecified: They may know enough about a word's meaning to tell it apart from the unrelated referent but not the related one (which, by design, has distributional, conceptual, and/or visual overlap). That is, perhaps infants know "car" cannot refer to juice, but not whether stroller is in the "car" category.

Furthermore, these options may intertwine, and, indeed, our time course data are compatible with both (Fig. S2): Infants consistently looked at the labeled target image in related trials, but shifted between the images in unrelated trials, consistent with underspecification or competition.

In studies of children and adults, these possibilities are disambiguated by both "cleaner" (i.e., less noisy, more accurate) eye movements, which reveal transient looks at the semantically related distractor, and overt (touch or click) target selection, which 6-mo-olds (who do not even point yet) cannot do. Additional infant measures (e.g., neural recordings or reaching tasks) may be promising future directions.

These results also complement previous early word comprehension research (1, 2, 4, 5). Here too, further work may elucidate how presentation method influences infants' looking behavior (e.g., video vs. photo; two-image displays vs. scenes).

Turning to the corpus results, home-lab links were relatively limited. Specifically, we did not find a relation between how infants' object word input was distributed across speakers and utterance types, and infants' comprehension of common nouns. Especially for utterance type, this may reflect the limits of analyzing only object word utterances. Similarly, input quantity measures (which are tied to toddlers' vocabulary, e.g., ref. 24) were only marginally correlated with comprehension. While these variables may matter for subsequent lexical knowledge, they did



Fig. 4. Item pairs in eye-tracking study. Infants saw each image pair twice. There were 16 trials in each trial type (related, unrelated), 32 trials total.

These results are first steps toward understanding how the initial lexicon is organized and acquired from experience by 6 mo. We find that real-time comprehension is influenced by links among words. We further find promising results tying infants' experiences with referential transparency to early word knowledge. Finally, these results suggest a combined lab-home (LH) approach can begin to reveal the range and dynamics of learner-by-environment interaction, as infants' initial understanding of words starts to give way to robust knowledge of their language.

Given unknown effect sizes for home-lab links in young infants, the target sample size was 48, i.e., $3 \times$ the standard minimum sample size ($n = 16$). We enrolled and retained 44 infants over an 8-mo enrollment window for the LH group. Once LH enrollment ended, LO did as well.

The experiment began with four “warm-ups,” in which a single image was labeled by a sentence played over speakers (e.g., “Look at the apple!”). Parents were then given a visor that blocked the screen (or closed their eyes, $n = 3$), and over-ear headphones. The experiment was also recorded by camcorder to ensure compliance and monitor the child’s state.

Visual stimuli were photos of each target and warm-up word, edited onto a gray background, displayed at 500×500 pixels on a 27.4- by 34-cm LCD 96 pixels per inch screen, at a viewing distance of 55 cm to 60 cm. Warm-up images ($n = 4$) were displayed centrally. For test trials ($n = 32$), each image was centered within the left and right half of the screen (counterbalanced across trials). Each of 16 test photos occurred four times: once as target and once as distractor in each trial type (related and unrelated; see Fig. 4).

At either the lab or home visit, parents were given a LENA (Language Environment Analysis) audio recorder ($8.6 \times 5.6 \times 1.3$ cm, 57 g) and clothing with a LENA pocket. (LENA Foundation). Parents were asked to turn the recorder on when the child awoke, and off at the end of the day or if they wanted to stop recording. Recording time ranged from 10.66 h to 16.00 h ($M = 14.37$).

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