

PAPER

Interactions between statistical and semantic information in infant language development

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Abstract

Infants can use statistical regularities to form rudimentary word categories (e.g. noun, verb), and to learn the meanings common to words from those categories. Using an artificial language methodology, we probed the mechanisms by which two types of statistical cues (distributional and phonological regularities) affect word learning. Because linking distributional cues vs. phonological information to semantics make different computational demands on learners, we also tested whether their use is related to language proficiency. We found that 22-month-old infants with smaller vocabularies generalized using phonological cues; however, infants with larger vocabularies showed the opposite pattern of results, generalizing based on distributional cues. These findings suggest that both phonological and distributional cues marking word categories promote early word learning. Moreover, while correlations between these cues are important to forming word categories, we found infants' weighting of these cues in subsequent word-learning tasks changes over the course of early language development.

Introduction

The emergence of the ability to learn the meanings of words toward the end of the first year is a major milestone in language development. Over the second year, infants typically amass a lexicon of over 100 words, requiring the development and coordination of myriad underlying skills and processes. One important area of development that supports word learning involves becoming a 'native listener', or learning the acoustic and structural properties of a native language. For example, 13-month-old infants, who are still novice word learners, will accept many kinds of stimuli as labels for objects, such as gestures and mechanical sounds, in addition to spoken words. However, by 26 months of age, infants acquiring a spoken language are much more selective, preferentially associating human speech sounds with novel referents (Woodward & Hoyne, 1999; Namy & Waxman, 1998).

Beyond narrowing in on speech sounds as potential linguistic labels, infants must also learn what constitutes a typical sound sequence in their language. By 9 months of age, infants distinguish between words composed of phoneme sequences with high transitional probabilities versus words that contain either illegal or low probability sequences (Jusczyk, Friederici, Wessels, Svenkerud & Jusczyk, 1993; Jusczyk, Luce & Charles-Luce, 1994). Infants' sensitivity to statistical regularities supports segmenting words from fluent speech (Mattys & Jusczyk,

2001; Pelucchi, Hay & Saffran, 2009; Saffran, Aslin & Newport, 1996), and also lays a critical foundation for mapping sound sequences to meanings (Graf Estes, Evans, Alibali & Saffran, 2007; Graf Estes, Edwards & Saffran, 2011; Hay, Pelucchi, Graf Estes & Saffran, 2010). Experience with statistical regularities in speech may facilitate word learning by promoting more accurate processing and subsequent recall of sound sequences that must be mapped to referents.

Infants' experience with statistical regularities in the sound stream may also support vocabulary development by providing clues to words' meanings. Words from different lexical categories are correlated with different *semantic regularities*: e.g. nouns tend to refer to objects and people, adjectives to properties such as color or texture, and verbs to actions or events. Lexical categories can also be distinguished by a constellation of statistical cues, including *distributional regularities* (the sentence contexts in which words are likely to occur), and *phonological properties* including lexical stress patterns and phonotactic patterns of word onsets and offsets (e.g. Christiansen, Onnis & Hockema, 2009; Kelly, 1992; Mintz, Newport & Bever, 2002; Monaghan, Chater & Christiansen, 2005).

Even before infants begin learning the semantic properties of lexical categories, there is evidence that they may be learning the distributional and phonological properties characteristic of native-language lexical categories. For example, infants can distinguish between

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words based on their length, stress patterns, and phonotactic properties at 9 months of age, and track the distributional properties of words by 12 months (Hohle, Weissenborn, Kiefer, Schulz & Schmitz, 2004; Jusczyk, Cutler & Redanz, 1993; Mintz, 2006; Spring & Dale, 1977). Critically, by 12 months, infants can also form rudimentary word categories when they are marked by correlated distributional and phonological cues (Gómez & Lakusta, 2004; Lany & Gómez, 2008). However, when categories are marked by distributional cues alone, without reliably correlated phonological or semantic cues, infants fail to learn them (Gerken, Wilson & Lewis, 2005; Gómez & Lakusta, 2004; see also Braine, 1987, for similar findings in adults). Thus, correlations between the distributional and phonological properties of words appear to play an important role in getting category learning off the ground.

Given the findings that infants can use correlated statistical cues to form word categories, a recent study tested whether they can also capitalize on experience with such cues to learn the semantic properties of categories (Lany & Saffran, 2010). In this study, 22-month-olds first listened to an artificial language that contained words from four categories, *a*, *b*, *X* and *Y*. There were two *a*-words ('ong', 'erd') and two *b*-words ('alt', 'ush'), which were combined into phrases with a larger set of disyllabic *X* words and monosyllabic *Y* words. For infants in the Experimental group, phrases took the form *aX* and *bY*. The *X* and *Y* words differed in both their phonological properties (i.e. syllable number) and their distributional properties; the sentence contexts in which *X* words and *Y* words occurred did not overlap. Thus, membership in the *X* and *Y* categories was reliably marked by correlated phonological and distributional cues (see Table 1). For infants in the Control group, words' phonological properties did not covary with their distributional properties. Specifically, *a*-words were reliably followed by one set of *X*s and *Y*s, and *b*-words were followed by a different set. Thus, while either distributional or phonological cues alone could be used to form categories, these categories were not supported by the presence of both cues. Infants were then trained on pairings between

these phrases and pictures of unfamiliar animals and vehicles. Critically, a subset of *aX* and *bY* phrases had occurred in both the Experimental and Control languages, and for infants in both conditions, familiar *aX* phrases were paired with animal pictures, and familiar *bY* phrases were paired with vehicle pictures. Thus all infants had the same amount of experience with trained pairings in which both the distributional and phonological properties of words were correlated with their semantic properties. Even Control infants tracking just one of the cues during the initial phase should be able to learn a regular correspondence to semantic properties.

Interestingly, Lany and Saffran (2010) found that only the Experimental infants were able to learn the trained associations between phrases and pictures and successfully generalize to novel pairings: when hearing a new word with both distributional and phonological properties of other words referring to animals, they mapped the word to a novel animal over a novel vehicle. These findings are consistent with studies suggesting that the presence of correlated distributional and phonological cues is important in forming word categories from experience listening to spoken language (Gerken *et al.*, 2005; Gómez & Lakusta, 2004). Moreover, they suggest that infants' experience with such correlated cues lays an important foundation for subsequently learning the meanings of those words.

While Lany and Saffran (2010) found a linkage between experience with statistical cues to category membership and the process of mapping meanings to words and word categories, the mechanisms underlying this process remain unclear. The presence of correlated distributional and phonological cues marking word categories is clearly important both to forming categories and to word learning: when the categories are not marked by strongly correlated cues, infants fail to form categories (Gerken *et al.*, 2005; Gómez & Lakusta, 2004; Lany & Gómez, 2008) and fail to learn the meanings of words from those categories (Lany & Saffran, 2010). However, there are at least two different ways that experience with correlated cues could benefit word learning. One possibility is that infants formed a phonological template such as 'erd [disyllabic]', 'alt [monosyllabic]' based on their listening experience, and that this template facilitated learning the meanings of words, similar to the way that perceptual familiarity with phonotactic patterns may facilitate learning label-referent pairings (e.g. Graf Estes *et al.*, 2007, 2011). In turn, the template as an unanalyzed unit may also have become associated with a global meaning, thereby enabling generalization. If this is the case, infants' ability to generalize should be impaired when only one cue is present during testing.

A second possibility is that rather than forming an unanalyzed auditory template in the initial listening phase of Lany and Saffran (2010), infants in the Experimental condition learned correlations between the distributional and phonological cues. This sensitivity would

Table 1 Auditory Familiarization materials from Lany and Saffran (2010) and the current study

a_1X_{1-8}	a_2X_{1-8}	b_1Y_{1-8}	b_2Y_{1-8}
ong coomo	erd coomo	alt deech	ush deech
ong fengle	erd fengle	alt gope	ush gope
ong kicey	erd kicey	alt jic	ush jic
ong loga	erd loga	alt skige	ush skige
ong paylig	erd paylig	alt vabe	ush vabe
ong wazil	erd wazil	alt tam	ush tam
ong bevit	erd bevit	alt vot	ush vot
ong meepeer	erd meepeer	alt rud	ush rud

Note: Three each of the bolded *X*s and *Y*s were used as labels for pictures of animals and vehicles in Referent Training. The remaining *X*s and *Y*s were used during the generalization test. The specific *X*s and *Y*s used during Training and Test were counterbalanced across infants.

in turn provide a foundation for learning the correlated semantic properties of words during referent training. Furthermore, it is possible that the phonological–semantic associations they formed differed in strength from distributional–semantic associations. Thus, while infants appear to track correlations between distributional and phonological information to form rudimentary categories, these cues may nonetheless contribute independently to word learning, perhaps even developing on different timetables.

Phonological properties of novel words can serve as a cue to semantic information via their perceptual similarity to known words. For example, the word ‘spin’ may be more readily mapped to an action than to an object because words that begin with consonant clusters are more likely to be verbs than nouns (Monaghan *et al.*, 2005). Indeed, there is evidence that proficient language users, including both school-aged children and adults, use phonological cues in this way: they interpret novel words with phonological properties typical of nouns as referring to novel objects, while interpreting words with phonological properties typical of verbs as referring to novel actions (Fitneva, Christiansen & Monaghan, 2009; Kelly, 1992). Likewise, adults are quicker to process familiar words that are phonologically typical of their category when they are presented in sentence contexts that strongly predict a word from that category (Farmer, Christiansen & Monaghan, 2006).

To our knowledge, there have been no previous studies of infants’ ability to use phonological cues marking syntactic categories when learning the meanings of novel words. However, recent studies on the development of priming during infancy suggest that even fairly young infants could take advantage of these cues. For example, there is evidence of phonological priming in 18-month-olds: activating the word ‘cat’ speeds processing of the word ‘cup’, which shares an onset phoneme with ‘cat’ (Mani & Plunkett, 2010). By 21 months of age, infants show priming for semantically related words: presenting the word ‘cat’ facilitates finding the referent of a semantically related word, such as ‘dog’ (Arias-Trejo & Plunkett, 2009). This suggests that during the second year, infants are building associations between words based on their phonological and semantic properties, and that these connections are activated during real-time language processing. The current study will build on these findings by testing whether *category-level* phonological properties can cue semantic information.

Distributional cues could become associated with semantic information in two different ways. First, words providing distributional cues could become associated with semantic information through their reliable co-occurrence with the specific labels for those referents. For example, high-frequency function words often precede or follow words with particular semantic properties (e.g. nouns in English are often preceded by determiners, such as ‘a’ and ‘the’, while verbs are often preceded by auxiliaries such as ‘is’ and ‘was’ or pronouns such as ‘he’

and ‘they’), and thus they provide particularly good distributional cues to word meanings. Similarly, in languages with noun classifier systems, words with particular semantic properties (e.g. an elongated shape) reliably co-occur with a classifier morpheme that denotes that semantic property. A second way that distributional cues could also take on general semantic properties is by direct co-occurrence with individual referents: because determiners and classifiers reliably precede specific labels, they also often occur with the referents themselves.

The existing evidence on infants’ use of distributional cues in word learning is mixed. By 14 months, English-learning infants will selectively map a novel word used in a sentence context characteristic of nouns (e.g. ‘*This one is a blicket*’) to a novel object rather than to a property, such as color or texture (Waxman & Booth, 2001). One interpretation of these findings is that infants are starting to learn the distributional contexts in which nouns typically occur, and use this information to help them identify the referents of novel words that occur in those contexts, even in very early stages of word learning. However, rather than tracking distributional properties of nouns and using them to learn novel words, infants may simply recognize a few highly familiar frames that are often used in ostensive naming contexts (e.g. ‘*This is a _____*’ or ‘*It’s a _____*’; Cameron-Faulkner, Lieven & Tomasello, 2003). Moreover, other studies have suggested that using distributional cues to learn words is challenging. For example, children only show robust evidence of using distributional cues to learn words other than nouns, such as adjectives and verbs, between 24 and 36 months of age (Naigles, 1990; Waxman, Lidz, Braun & Lavin, 2009; Hall & Lavin, 2004; Markman & Jaswal, 2004; Bernal, Lidz, Millotte & Christophe, 2007; though see Yuan & Fisher, 2009; and Oshima-Takane, Ariyamam, Kobayashi, Katerelos & Poulin-Dubois, 2011, for demonstrations of verb learning a few months earlier). Testing the role of distributional information in word learning is complicated by the fact that the semantics of adjectives and verbs are less transparent than nouns (e.g. Genter & Boroditsky, 2001), and also because they are less reliably marked by distributional cues (e.g. Cameron-Faulkner *et al.*, 2003; Christiansen & Monaghan, 2006). Thus, an important goal of the current study is to provide a controlled test of infants’ ability to use distributional cues to learn novel words.

In sum, the current experiment was designed to test the contributions of distributional and phonological cues to infant word learning. Given the different ways in which these cues are related to semantic regularities, we were also interested in whether there are differences in infants’ use of these cues. The semantics and phonology of a word are likely to be tightly linked in representational space because they are both properties of the word itself, and generalization can emerge from learning individual mappings between words and their referents. However, tracking and using distributional–semantic relationships may be more computationally demanding. In particular,

it requires forming a generalization based on function words' reliable co-occurrence with words referring to instances from a common category, co-occurrence with the referents themselves, or both. As a result, tracking distributional cues to category membership may place heavier demands on encoding and memory than tracking phonological cues to category membership. On this view, infants with more advanced verbal processing abilities may be better able to track and use distributional cues than infants with less advanced verbal skills. Indeed, there is some evidence that infants' sensitivity to distributional information is associated with gains in language proficiency, such as increases in vocabulary size and sensitivity to grammatical structure. Young children's use of distributional cues in identifying the referents of familiar words is related to language proficiency (Lew-Williams & Fernald, 2007). Likewise, only 2-year-olds with larger vocabularies use sentence context cues to learn a new preposition (Fisher, Klinger & Song, 2006), and children who are delayed in their vocabulary development, or 'late talkers', show less evidence of using grammatical knowledge to build their vocabularies than typically developing children (Moyle, Ellis Weismer, Evans & Lindstrom, 2007).

In sum, while infants appear to use correlated distributional and phonological cues to form lexical categories (Lany & Saffran, 2010), the underlying mechanisms by which these cues support learning the semantic properties of words and word categories are poorly understood. While correlated distributional and phonological information may serve as a unitary, unanalyzed cue, these cues may also make independent contributions as cues to category membership. Moreover, infants may differ in their use of distributional and phonological cues as a function of language proficiency: less proficient infants may find word-internal phonological cues more accessible, while infants who have achieved higher native language proficiency may be more likely to exploit distributional cues.

To investigate infants' differential use of these cues in word learning, we presented them with an artificial language in which distributional and phonological cues were both reliably associated with lexical categories. Infants were next trained on pairings between words and referents, and finally, they were tested on their ability to find a novel referent given either a distributional cue or a phonological cue to category membership. We hypothesized that both cues would facilitate learning the meaning of a novel word, but that infants' weighting of the two cues during generalization would be related to their native language proficiency.

Method

In this study we used a three-phase method previously developed by Lany and Saffran (2010). In the first phase, *Auditory Familiarization*, infants listened to an artificial language that contained two lexical categories reliably

marked by correlated distributional and phonological cues. Next, during *Referent Training*, infants were exposed to pairings between phrases from the language and pictures; words from one category referred to pictures of unfamiliar animals and words from the other category referred to pictures of unfamiliar vehicles. The *Test* phase assessed whether infants could use distributional and phonological cues to generalize to novel pictures. Infants saw a pair of pictures on each trial, depicting a novel animal and a novel vehicle. On *Distributional Cue test trials*, infants heard an *a*-word or *b*-word alone. On *Phonological Cue test trials*, infants heard a novel word with phonological cues characteristic of one of the categories. Because just one cue was available during each type of test trial, infants' performance provides a measure of their ability to use each cue independently when selecting a novel referent.

Participants

Forty 22-month-old monolingual English-speaking infants (mean age = 669 days, range = 653–685 days, 24 female) participated in this experiment. All infants were born full term, were free of problems with hearing, vision, or language development, according to parental report. Expressive vocabulary on the MCDI Short Form: Level II (Fenson, Pethick, Renda, Cox, Dale & Reznick, 2000) ranged from 6 to 90 words (mean = 42.8), with percentile scores ranging from 5 to 95 (mean = 38%). Data from additional infants were excluded because of excessive fussiness (crying for longer than approximately 30 seconds, or refusal to return to the parent's lap after getting down) (16), inattention (9), or parental or sibling interference (2).

Materials

In the *Auditory Familiarization* phase, the materials consisted of an artificial language composed of nonsense words belonging to the categories *a*, *b*, *X*, and *Y* (see Table 1), taken from Lany and Saffran (2010). There were two *a*-words (*ong*, *erd*) and two *b*-words (*alt*, *ush*), and eight each of the *X*- and *Y*-words. The *X*-words were disyllabic (e.g. *coomo*, *loga*), while the *Y*-words were monosyllabic (e.g. *deech*, *skige*). Words from these categories were combined into phrases of the form *aX* and *bY*. Thus, the *X* and *Y* categories were distinguished by correlated phonological and distributional cues: *X*-words were disyllabic and followed *a*-words in phrases (e.g. *ong coomo*, *erd coomo*), whereas *Y*-words were monosyllabic and followed *b*-words in phrases (e.g. *alt deech*, *ush deech*).

The materials were spoken by an adult female in an animated voice and digitized for editing. One token of each word was selected; phrases were created by splicing these tokens separated by 0.1-sec pauses. The language contained 32 unique phrases (16 *aX* and 16 *bY*). Strings were created by combining an *aX* phrase and a *bY*

phrase, separated by 0.3-sec pauses. Strings were separated by 0.7-sec pauses.

During *Referent Training*, the materials consisted of *aX* and *bY* phrases heard during Auditory Familiarization, paired with pictures of animals and vehicles. We selected three *X*-words and three *Y*-words to be uniquely paired with a picture of an animal or vehicle taken from a set of five animals and five vehicles unlikely to be familiar to infants of this age according to MCDI norms (Dale & Fenson, 1996; see Table 2). Importantly, the *aX* phrases referred to pictures from one category (e.g. animals), while the *bY* phrases referred to pictures from the other category (e.g. vehicles). Thus, the semantic properties of words were correlated with the distributionally and phonologically cued category structure presented during the Auditory Familiarization phase. While this structure is unfamiliar to the English-learning infants in this experiment, there are other natural languages in which subclasses of nouns are used with different determiners (e.g. Algonquin; Corbett, 1991) or classifiers (e.g. Chinese, Korean, Japanese, and ASL; Aikhenvald, 2000) based on their semantic properties.

The particular picture–phrase pairings were counterbalanced such that for half of the infants *aX* phrases referred to animals and *bY* phrases referred to vehicles, and vice versa for the remaining infants. The pictures that were trained versus withheld to examine generalization in the test phase were also counterbalanced. Each *X*- and *Y*-word was used as a label in two unique phrases (e.g. *ong coomo*, *erd coomo*). Thus, there were unique pairings between *X*s and *Y*s and the trained pictures, while the *a*- and *b*-words were present in the labeling phrases of all the pictures from a given category. The *a*- and *b*-words thus provided *distributional* cues to category membership, while the *X*- and *Y*-words provided *phonological* cues to category membership.

The *Test* materials consisted of two familiar pictures from referent training (one animal and one vehicle) and four unfamiliar pictures (two novel animals and two novel vehicles) (see Table 3). On *Familiar* trials, infants saw a pair of pictures (one animal and one vehicle) that they had previously encountered during referent training, and heard an *aX* or *bY* phrase that had been associated with one of them (Figure 1 depicts an example of a test

Table 2 *Referent Training materials*

Animal referents	Vehicle referents
guinea pig	Vespa truck
koala bear	velomobile
ram	golf cart
meerkat	Segway 4-wheeler
porcupine	Saab blackbird

During *Referent Training*, *aX* and *bY* phrases familiar to infants from *Auditory Familiarization* (see Table 1) were used as labels for pictures of animals and vehicles. The pairings between word categories and picture categories were counterbalanced across conditions, such that for half of the infants *X*s referred to animals and *Y*s to vehicles (and vice versa). Infants were exposed to three animal picture-label pairings, and three vehicle picture-label pairings. The remaining pictures were used to test generalization.

Table 3 *Mean proportion looking to the target picture on trials, with standard errors in parentheses*

	Proportion looking to target		Increase in proportion looking to target
	Baseline	Target	
Low-Vocabulary			
Familiar	.50(.016)	.58(.036)	.08(.039)
Phonological Cue	.47(.018)	.56(.031)	.08(.036)
Distributional Cue	.49(.021)	.49(.031)	.001(.04)
High-Vocabulary			
Familiar	.48(.024)	.53(.025)	.05(.036)
Phonological Cue	.50(.018)	.49(.032)	-.01(.039)
Distributional Cue	.49(.017)	.59(.025)	.10(.025)

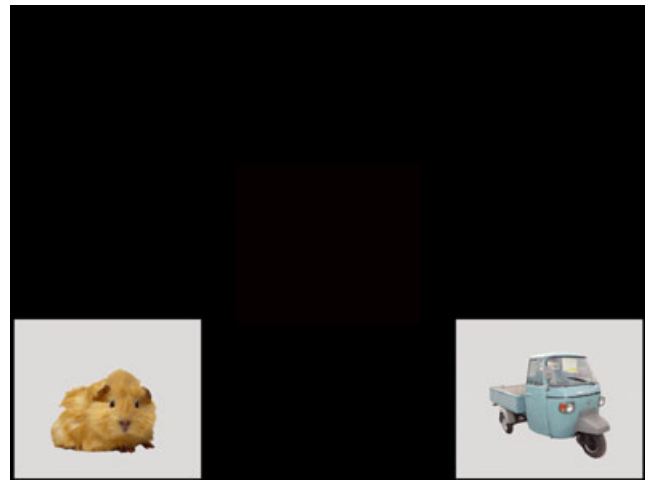


Figure 1 *An example of a test trial containing a guinea pig and a Vespa truck. Two seconds after the appearance of the pictures, the auditory stimulus began to play.*

trial). These trials provided an opportunity to replicate Lany and Saffran's (2010) finding that infants can learn the trained associations between phrases and pictures. We also included the familiar trials to help rapidly acquaint infants with the structure of the task. In most studies of word learning, there are overt sentential cues, such as 'Look at the...' and 'Find the...' that guide infants' looking behavior. Given the use of artificial materials, we could not use English frames to orient infants to the nature of the task. The familiar trials, depicting trained associations and distractors, were included to play this role.

In addition to Familiar trials, there were two kinds of *Generalization* trials, during which infants saw two novel pictures (one animal and one vehicle) not presented during Referent Training. Recall that the *a*- and *b*-words provide distributional contexts as cues to category membership, while the *X*- and *Y*-words provide phonological cues to category membership. Thus, during *Distributional Cue* generalization trials, infants heard an *a*- or *b*-word alone (with no *X*- or *Y*-word) while viewing two unfamiliar pictures, with each specific marker used as a label twice during the test phase. Similarly, during *Phonological Cue* gener-

alization trials, they heard an *X*- or *Y*-word alone (with no *a*- or *b*-word) that was familiar from Auditory Familiarization, but that had not been used during referent training, while viewing two different unfamiliar pictures. The *X*s and *Y*s were each used as a label four times over the course of testing. The Generalization trials were designed to probe whether infants can use either distributional or phonological cues alone to generalize to novel pictures from the animal and vehicle categories.

Procedure

Infants were tested individually in a sound-attenuated booth. During the Auditory Familiarization phase, a 3.5-min sequence of *aX* and *bY* phrases was played from a speaker mounted in the booth. Each of the 32 unique phrases occurred four times during the randomized sequence. Infants were allowed to move around in the booth and play quietly during this phase.

During the Referent Training phase, each trial consisted of a single picture presented on the lower left or right corner of the screen via an LCD projector for 6.5 sec. The picture moved up and down once over the course of the trial to maintain infants' attention. Two labeling phrases (e.g. '*ong coomo*, *erd coomo*,² separated by 0.3 sec of silence) were played from the speaker below the screen beginning 2 sec after the picture appeared. Trials ended with .5 sec of blank screen and silence. Each of the six pictures was presented four times, with position on the screen (right or left) and order of the labeling phrases counterbalanced across trials, for a total of 24 training trials. A 7-sec cartoon was presented after every fourth trial to keep infants engaged in the task. Infants viewed the stimuli while seated on the parent's lap approximately 1 m from the screen. Parents wore blacked-out sunglasses to prevent them from seeing the pictures displayed on the screen. The duration of this phase was 3.5 min, and the presentation of stimuli was controlled by Habit X software (Cohen, Atkinson & Chaput, 2004).

In the Test phase, all trials consisted of two pictures (one animal and one vehicle) presented simultaneously for 6.25 sec, on the lower left and right sides of the screen. Two seconds into each trial, a label for one of the pictures (the Target) was played from the speaker. Test trial order was randomized, with a 7-sec cartoon again presented after every fourth trial.

On *Familiar* test trials, the pictures were taken from the Referent Training phase, and the label was an *aX* or *bY* phrase that had been associated with one of the pictures. For example, they might see a pair of previously encountered pictures, depicting a guinea pig and a Vespa truck, and hear '*ong coomo*'. On *Distributional Cue* generalization trials, the pictures were an unfamiliar animal and vehicle, and the auditory materials consisted of either an *a*- or *b*-word alone (*ong*, *erd*, *alt*, or *ush*). Infants had previously heard these words during Auditory Familiarization, and also during Referent Training,

where they occurred in the phrases associated with animal or vehicle pictures. On *Phonological Cue* generalization trials, the pictures were a different unfamiliar animal and vehicle. These pictures were accompanied by an *X*- or *Y*-word alone (e.g. *coomo* or *deech*) that had not been presented during Referent Training, but that had been presented during Auditory Familiarization. There were 24 test trials, eight of each of the three types, in random order. During Test trials, all pictures appeared with equal frequency and served as the Target equally often on the right and left sides of the screen. Infants' looking behavior during the test was recorded onto a DVD at 30 frames/sec.

After infants completed the experiment, we administered the MacArthur Short Form: Level II to their caregiver. The MCDI includes a measure of expressive vocabulary size (the number of items from a 100-word inventory spoken by the infant), and also an index of grammatical development (a measure of the frequency with which infants produce multi-word utterances; possible responses are 'not yet', 'sometimes', or 'often').

Results

Trained coders viewed the recordings of the test phase frame-by-frame, and indicated whether the infant was looking to the picture on the left, on the right, transitioning between pictures, or off-task for each frame (see Fernald, Zangl, Portillo & Marchman, 2008). We calculated the proportion of trials on which infants were looking to the target picture at each 33-ms interval, and then divided trials into two time windows. The Baseline window corresponded to the initial 2000 ms of the trial during which the labeling phrase had not yet begun to play. The Target window began at 2367 ms, or 367 ms after the onset of the labeling phrase, and ended at 4500 ms, or about 1500 ms after the offset of the *aX* or *bY* labeling phrase on Familiar trials, and about 2000 ms after the offset of the *a*-, *b*-, *X*-, or *Y*-word on Generalization trials. These windows were chosen based on previous studies using this paradigm (e.g. Fernald *et al.*, 2008; Lany & Saffran, 2010; Swingley, Pinto & Fernald, 1999). We then averaged each infant's proportion of looks across the frames within each window to get a measure of their mean proportion of looks to the target both before and after the onset of the labeling information. Trials during which infants were not attending to either picture for at least half of both the Baseline and Target Windows were not included in the analyses. Infants who did not contribute at least half (four of eight) of the usable trials for each type of test trial were not included in the final data set (see Participants section). Agreement between coders within a single frame was greater than 99%.

To assess accuracy, or whether infants showed increased looking to the Target picture in response to hearing label information, we subtracted each infant's mean proportion of looks to the target during the

baseline window from her mean proportion of correct looks to the target during the target window (Table 3). Preliminary analyses revealed no effects of infant sex on accuracy, and thus this factor was not included in subsequent analyses.

The principal question of interest concerned differences in accuracy as a function of word-learning proficiency. To this end, we used a median split of the distribution of infants' MCDI scores to form High- and Low-Vocabulary groups. Infants (13 female, 7 male) with a raw score of 40 or below ($M = 25.05$, $SE = 2.55$) were classified as Low-Vocabulary. Infants (11 female, 9 male) with a score of 41 or higher ($M = 60.55$, $SE = 3.87$) formed the High-Vocabulary group. The raw counts of the number of words an infant says can be converted into a normed percentile score that reflects vocabulary size relative to other infants of that age and sex. However, because the normed scores do not reflect vocabulary size *per se*, raw scores may be a better measure of infants' word learning abilities, particularly when the age range is small. Indeed, many studies investigating the relationship between vocabulary size and word learning have used raw, rather than normed, scores (e.g. Smith, Jones, Landau, Gershkoff-Stowe & Samuelson, 2002; Fernald, Perfors & Marchman, 2006; Fernald, Swingley & Pinto, 2001; Fisher *et al.*, 2006).

We first evaluated infants' performance on Familiar trials, which tested picture–phrase associations presented during Referent Training. Using the difference score as the dependent measure, we found no difference in accuracy for High- and Low-Vocabulary infants [$M = .05$, $SE = .036$, and $M = .08$, $SE = .039$, respectively; $t(30) = .49$, $p = .6$; all t -tests were two-tailed with an alpha of .05] (see Table 3). Replicating Lany and Saffran (2010),¹ when the High and Low groups were combined, infants showed a significant increase in looking to the target picture ($M = .06$, $SE = .027$): $t(39) = 2.35$, $p = .024$, $d = .36$). Thus, infants exposed to $aX bY$ phrases containing correlated cues can learn trained associations between those phrases and pictures.

Using an ANOVA with test-trial type as a within-participant factor, and vocabulary score (High and Low) as a between-participants factor, we next assessed performance on the two kinds of Generalization trials. We found an interaction between test-trial type and vocabulary [$F(1, 38) = 6.7$, $p = .014$, $\eta_p^2 = .15$], suggesting that infants' ability to find the target picture on the two types of generalization trials differed as a function of their vocabulary size. No other effects reached significance.

We examined each test-trial type separately to unpack the effect of vocabulary size on test performance. On Distributional Cue generalization trials, there was a significant difference between High- and Low-Vocabulary infants' increase in looking to the target picture

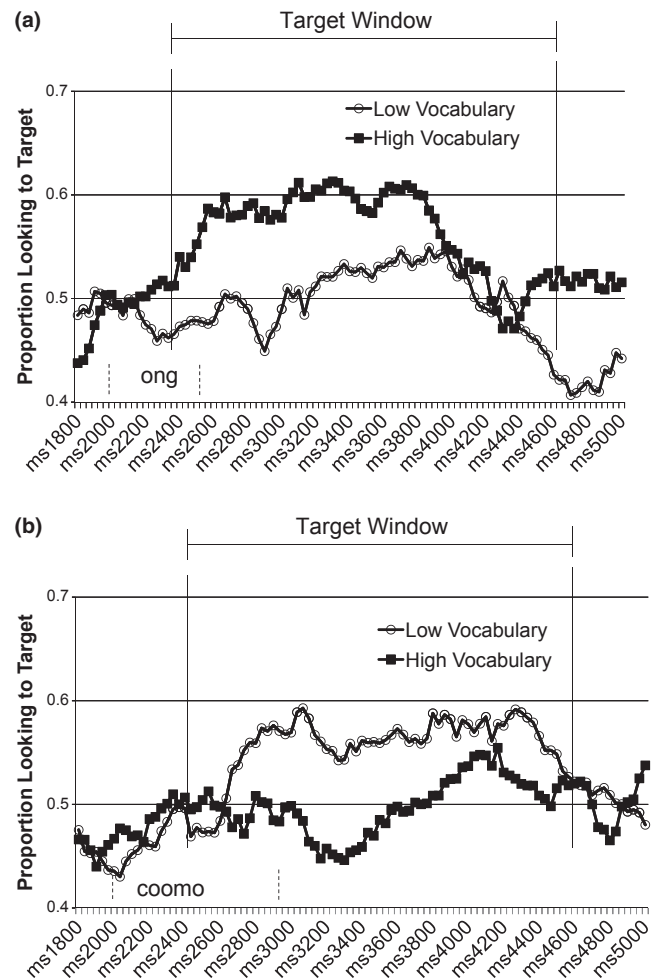


Figure 2 Performance on Distributional Cue trials (a) and on Phonological Cue trials (b).

[$t(38) = 2.05$, $p = .048$, $d = .63$], with High-Vocabulary infants showing greater increases than Low-Vocabulary infants (Figure 2a). Moreover, the High-Vocabulary infants showed significant increases in looking to the target picture from the baseline window to the target window [$t(19) = 4.05$, $p = .001$, $d = .88$], while the Low-Vocabulary infants did not [$t(19) = .15$, $p = .89$; see Table 3], suggesting that only the High-Vocabulary infants were able to use distributional cues alone to generalize to novel pictures.

On Phonological Cue generalization trials, the High- and Low-Vocabulary infants also differed, but the effect was in the opposite direction: the Low-Vocabulary infants showed marginally greater increases in looking to the target picture than the High-Vocabulary infants [$t(38) = 1.76$, $p = .08$, $d = .53$] (Figure 2b). Moreover, the Low-Vocabulary infants reliably increased looking to the target picture over baseline [$t(19) = 2.24$, $p = .037$, $d = .49$], but the High-Vocabulary infants did not [$t(19) = .36$, $p = .72$; see Table 3]. Thus, only the Low-Vocabulary infants appear to have used the phonological properties of X- and Y-words to generalize to novel referents.

¹ Lany and Saffran (2010) also collected MCDI scores and found no effects of vocabulary on learning trained referents.

Because learning the distributional properties of words is also critical for learning grammatical patterns, we hypothesized that there may be a relationship between infants' performance on Distributional Cue trials and their level of grammatical development. Thus, we created two groups based on infants' grammatical development scores on the MCDI. Infants combining words often formed the High-Grammatical Proficiency group ($N = 20$, 11 female and 9 male), and those combining only sometimes or not at all formed the Low-Grammatical Proficiency group ($N = 20$, 13 female and 7 male). We found a marginal difference between the groups [$t(38) = 1.99$, $p = .06$, $d = .61$]: infants who combined words often showed significant increases in looking to the target picture on the Distributional Cue trials [$M = .10$, $SE = .028$; $t(19) = 3.57$, $p = .002$, $d = .79$], but those who combined words only sometimes or not at all did not [$M = .01$, $SE = .038$; $t(19) = .21$, $p = .83$].

Infants' grammatical development scores were positively correlated with their vocabulary size, $r(40) = .58$, $p < .001$, consistent with many other studies investigating the relationship between these two measures (see Bates & Goodman, 1997, for a review). Indeed, 15 of the 20 infants in the High-Grammatical Proficiency group were also in the High-Vocabulary group, and 15 of the infants in the Low-Grammatical proficiency group were also in the Low-Vocabulary group. The fact that vocabulary size is correlated with grammatical development, and that both predict the use of distributional cues in word learning, supports the hypothesis that vocabulary size, grammatical development, and use of distributional cues in word learning are interrelated.

However, despite the fact that both vocabulary size and grammatical development are related to infants' use of distributional cues, and the fact that vocabulary development is also related to phonological cue use, we did not find a relationship between *grammatical development* and infants' use of phonological cues. On Phonological cue trials, infants combining words sometimes or not at all showed numerically better discrimination ($M = .05$, $SE = .045$) than infants combining words often ($M = .02$, $SE = .036$), but this difference did not approach significance [$t(38) = .40$, $p = .69$]. Thus, infants' grammatical development scores were selectively related to their use of distributional cues, while their vocabulary development scores were related to use of both distributional and phonological cues in this task.

General discussion

The current experiment investigated how experience with statistical cues marking lexical categories supports word learning. After listening to an artificial language containing two word categories that were reliably marked by correlated distributional and phonological cues, infants were trained on pairings between words from the two

categories and pictures of animals and vehicles. Infants were tested both on their memory for the trained associations, and on their ability to use distributional and phonological cues independently to generalize to an untrained referent. Interestingly, we found that infants' use of phonological and distributional cues to generalize was related to their language proficiency. Those with smaller vocabularies successfully generalized when given phonological cues to the new words' potential referents, but did not succeed when given only distributional cues. Infants with larger vocabularies and more advanced grammatical skills, on the other hand, successfully used distributional information marking a category to generalize, but showed no evidence of using the phonological cues.

To our knowledge, this is the first investigation of infants' ability to generalize semantic properties of word categories based solely on phonological cues. Previous studies suggest that phonological cues guide school-aged children's interpretation of novel words (Fitneva *et al.*, 2009), facilitate adults' processing of familiar words (Farmer *et al.*, 2006), and influence adults' interpretation of novel words (Kelly, 1992). Consistent with these findings, we found that 22-month-old infants use phonological cues to help identify the referent of a novel word. Thus, even for infants who are not yet expert word learners, phonological similarity can serve as a cue to novel words' referents.

These results also shed light on infants' use of distributional cues to learn the meanings of novel words. Specifically, we found that for infants with larger vocabularies and more advanced grammatical development, high-frequency words that reliably co-occur with pictures from one category and their labels can become associated with semantic regularities. There are two different computations that might contribute to sensitivity to links between distributional cues and semantics. First, High-Vocabulary infants could be tracking the co-occurrence relationships between *a*-words with specific *X*-words referring to animals, and between *b*-words and specific *Y*-words referring to vehicles. Second, infants could be tracking the co-occurrence relationships between the *a*- and *b*-words and the picture referents themselves. The ability to generalize to novel referents using *a*- and *b*-words could emerge from either (or both) of these lower-level associations.

Why would only High-Vocabulary infants learn these regularities? Tracking distributional–semantic associations in addition to the specific mappings between *Xs* and *Ys* and their referents is computationally taxing relative to the phonological–semantic associations that Low-Vocabulary infants learned, which could arise simply through learning specific word–referent pairings. Because vocabulary size and grammatical development are related to infants' facility in processing verbal information (Fernald *et al.*, 2001, 2006), infants with more developed native language skills in our study were likely those with superior verbal processing abilities. This

processing advantage would facilitate tracking either the word–word or word–picture associations described above, thus allowing them to form a robust link between *a*- and *b*-words and semantic regularities.

This explanation is also consistent with studies of children with Specific Language Impairment (SLI), who exhibit persistent deficits in both lexical knowledge (i.e. they have small vocabularies, and difficulty learning new words) and grammatical development. An area of particular weakness for these children is in the acquisition of morphosyntactic structure, including closed-class morphemes like determiners and auxiliaries that provide important distributional information about words' syntactic categories (e.g. Stekol & Leonard, 1979). Children with SLI also exhibit challenges in statistical learning tasks involving the discovery of distributional patterns in both speech (Evans, Saffran & Robe-Torres, 2009) and non-speech (Plante, Gomez & Gerken, 2002; Tomblin, Mainela-Arnold & Zhang, 2007). Critically, children with SLI also have impairments in phonological short-term memory and verbal processing speed (Leonard, Ellis Weismer, Miller, Francis, Tomblin & Kail, 2007; Montgomery & Windsor, 2007), as well as reduced processing capacity for visual-spatial stimuli (Hoffman & Gillam, 2004). Thus, protracted processing deficits may lead to broad problems in learning words, using distributional cues, and acquiring grammatical structure in these children.

While High-Vocabulary infants in the current study preferentially used distributional cues to generalize to novel referents, and Low-Vocabulary infants preferentially used phonological cues, it is important to note that they would have been unlikely to do so if categories had been marked by distributional or phonological cues alone during Auditory Familiarization. Lany and Saffran (2010) found that when these cues were not correlated during Auditory Familiarization, but infants could still use either cue independently, infants both failed to learn familiar words and to generalize. These findings held for both High- and Low-Vocabulary infants, suggesting that the facilitatory effects of distributional and phonological cues on learning semantics are particularly powerful when embedded in a richly correlated cue structure.²

An important question, however, is whether High-Vocabulary infants learned distributional relationships, or whether they instead formed two different kinds of word–referent mappings without recourse to distributional statistics.³ The data from Familiar trials and from

Lany and Saffran (2010) suggest that infants learn specific mappings between *X*- and *Y*-words and their referents. Moreover, infants presented with a two-word phrase as a label preferentially associate the lower-frequency of the two words with the referent (Hochmann, Endress & Mehler, 2010), suggesting that infants in the current study were unlikely to treat the frequent *a*- and *b*-words as labels for the specific animal and vehicle pictures. However, infants nonetheless might have learned mappings between *a*- and *b*-words and the superordinate animal and vehicle categories, and it is possible that they did so without computing the specific co-occurrence relationships between *a*- and *b*-words and the specific animals and vehicles with which they co-occurred. Superior language processing abilities may have allowed High-Vocabulary infants to generalize by successfully tracking both mappings on a given trial, especially considering that learning labels for superordinate categories (e.g. *animal* and *vehicle*) is thought to be more challenging than labels for basic-level categories (e.g. *dog*, *cat*). On this account, neither High- nor Low-Vocabulary infants should have learned the specific co-occurrence relationships between *a*- and *b*-words and specific pic-

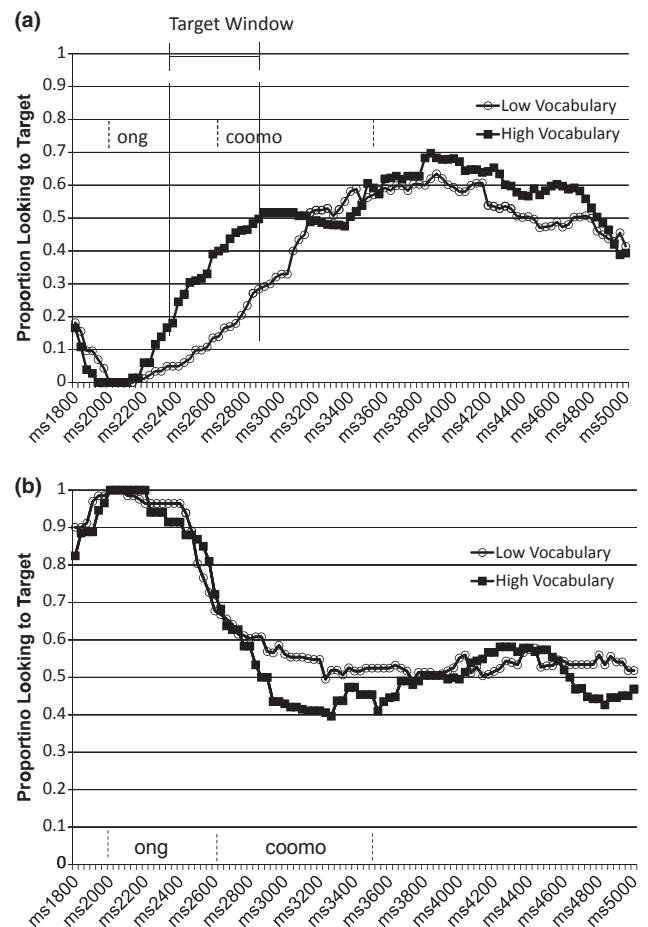


Figure 3 Proportion of looking to the familiar (Target) picture during trials on which infants were looking to the Target (3a) and Distractor (3b) at the onset of the label for the familiar picture.

² Using a language lacking variability in the phonological properties of *X*s and *Y*s (i.e. in which all *X*s and *Y*s are disyllabic) might result in a similar pattern of findings, as Gerken *et al.* (2005) found that 18-month-old infants fail to learn form-based categories under these conditions. Alternatively, minimizing phonological variability could make the task easier than the original Lany and Saffran task, thus enabling infants, particularly High-Vocabulary infants, to use distributional cues alone. This is an interesting issue to pursue in future studies, and we thank Anne Christophe for bringing it to our attention.

³ We thank an anonymous reviewer for suggesting this possibility.

tures (or the specific labels for those pictures) encountered during training. However, if High-Vocabulary infants' performance on Distributional Cue trials arises from tracking the distributional properties of *a*- and *b*-words, then they should be more sensitive to their specific co-occurrences than Low-Vocabulary infants.

Additional data from our laboratory support the latter explanation. A new group of 22-month-old infants ($N = 40:18$ in the High-Vocabulary group and 20 females), underwent the same Auditory Familiarization and Referent Training procedure as in the current study. At test, they viewed a familiar and novel picture from the same category (e.g. a familiar and a novel animal) while hearing the trained labeling phrase for the familiar picture. Because we were interested in the role of the *a*- or *b*-word in helping infants to locate the target picture, rather than their overall accuracy, we first looked at trials on which infants were looking at the unfamiliar picture at the onset of the labeling phrase. High-Vocabulary infants showed a greater increase in looking to the familiar picture in response to the *a*- or *b*-word than Low-Vocabulary infants [$M = .39$, $SE = .07$ and $M = .17$, $SE = .04$, respectively; $t(38) = 3.04$, $p = .004$, $d = .99$] (see Figure 3a). In contrast, on trials when infants were already looking to the familiar picture at the onset of the label (by chance), there were no differences in High- and Low-Vocabulary infants' looking behavior over the course of the trial (see Figure 3b). Together these findings suggest that High-Vocabulary infants' sensitivity to the distributional properties of *a*- and *b*-words facilitated their ability to rapidly locate a named object when they were not already attending to it, and suggest that High-Vocabulary infants do indeed form stronger associations between *a*- and *b*-words and their associated pictures during Referent Training than Low-Vocabulary infants.

These data are consistent with findings that 18-month-olds locate the referent of a familiar word (e.g. *doggie*) more quickly and accurately when it is preceded by a frequent determiner (e.g. '*Look at the doggie*') than when it is presented without one (e.g. '*Look, doggie!*'); Fernald & Hurtado, 2006), or when it is preceded by a nonsense determiner (Zangl & Fernald, 2007). Gerken and MacIntosh (1993) showed similar disruption of lexical access in a picture-pointing task. Moreover, the presence of a nonsense determiner causes particular difficulties in locating the referent of a newly learned word, suggesting that infants rely strongly on links between words providing distributional cues and specific content words in online processing in the initial stages of learning a word (Zangl & Fernald, 2007). Consistent with such findings, the current research also suggests that infants track co-occurrences between high-frequency function-like words and specific content-like words and their referents, and that sensitivity to these relationships facilitates finding the referents of newly learned words. Beyond the finding that tracking distributional properties of words facilitates online lexical access of familiar and newly learned words, our findings suggest that the ability to

learn such co-occurrence relationships differs as a function of vocabulary size, and forms a basis for rapidly and accurately learning the referents of novel words. This latter finding may explain why determiners are particularly critical in identifying newly learned words.

Just as High-Vocabulary infants formed stronger associations between distributional and semantic information for trained referents than Low-Vocabulary infants, Low-Vocabulary infants might have more strongly associated phonological regularities with the trained referents. The Familiar trials in the current experiment contained both distributional and phonological cues, and thus cannot address this issue. Lany and Saffran (2010, Experiment 2) included trials in which infants could only use the *X*- or *Y*-word (which contains the phonological cue) to find the referent, but it is impossible to tease apart infants' use of phonological cues vs. use of the specific label on such trials. It is also possible that High- and Low-Vocabulary infants differed in the initial formation of categories during the initial Auditory Familiarization phase. While previous studies suggested that correlated cues are important, they have not included measures of vocabulary. These are both important topics for future research.

Given their nuanced sensitivity to distributional-semantic links and use of these associations to generalize, it is puzzling that High-Vocabulary infants did not use phonological cues to generalize when Low-Vocabulary infants did. One explanation may be that the distributional cues were highly frequent and identical across training and test trials (that is, the exact same *a*- and *b*-words recurred on both types of trials), whereas the individual *X*- and *Y*-words providing phonological cues occurred less frequently during training trials, and also required generalization to novel forms at test. Thus, while distributional cues may be harder to associate with semantics initially, once such associations are formed, they provide unambiguous cues to category membership of a picture referent. The cue structure in this experiment may have led High-Vocabulary infants (the only ones tracking distributional cues) to focus on distributional cues at the expense of phonological cues. Indeed, the fact that older children and adults use phonological cues in their native language suggests that they do not stop using them early in development.

The findings of Zangl and Fernald (2007) suggest another potential explanation for High-Vocabulary infants' failure to use phonological cues to generalize: hearing a nonce determiner with a newly learned word disrupts infants' processing of newly learned words. In the current study, the absence of the *a*- or *b*-words in an expected context may have likewise disrupted their processing of the novel *X*- and *Y*-words. The Low-Vocabulary infants, because they failed to form strong associations between determiners and *X*- and *Y*-words to begin with, would not have been similarly affected.⁴

⁴ We thank an anonymous reviewer for this suggestion.

However, another possible explanation for the differences in High- and Low-Vocabulary infants' use of distributional cues is that infants were simply confused by encountering a function-like word in isolation given that this seldom occurs in English, but that High-Vocabulary infants more quickly adjusted to this departure from training than Low-Vocabulary infants. At odds with this interpretation is the finding that at 18 to 21 months of age, there are no differences in infants' ability to use partial information from a familiar word to locate its referent as a function of vocabulary size (Fernald *et al.*, 2001). While Low-Vocabulary infants used phrase-final information and High-Vocabulary infants used phrase-initial information, it is also unlikely that differences in the position of distributional and phonological cues within phrases is responsible for their performance differences: Children are typically better able to use word-initial than word-final information to rapidly locate a referent in online processing tasks, while adults can use both word-initial and word-final information (Walley, 1988), suggesting that early-encountered phonological information should actually be easier for infants to use to locate referents. Nonetheless, future studies could more directly address this issue by using a language in which the order of cues was reversed to see if the same vocabulary patterns are obtained.

In sum, previous studies suggest that experience with correlated distributional and phonological cues is critical for beginning to group words into categories (Gerken *et al.*, 2005; Gomez & Lakusta, 2004), as well as for learning the meanings of those words and word categories (Lany & Saffran, 2010). Going beyond these studies, our results suggest two possible mechanisms by which overlap in the structure of statistical and semantic information can help infants coordinate the two domains during word learning. First, the phonological properties of novel words might play a role in this coordination by activating the semantics of words with similar phonological characteristics, thereby influencing how the novel word is mapped to a referent. Second, words providing distributional cues may support word learning by activating the semantic properties common to the words and their referents with which they co-occur. Use of distributional cues appears to be more computationally challenging, as they were only used by linguistically proficient infants in the current study. Beyond facilitating learning the meanings of novel words, these cues may facilitate infants' online processing of familiar words in similar ways.

The current study adds to a rapidly growing body of evidence that artificial language learning paradigms can be fruitfully applied to questions about natural language acquisition. Most importantly, these findings shed new light on the role of experience with statistical cues in language development: Infants' experience with statistical cues facilitates word learning by promoting the formation of associations between words' statistical and semantic properties. This process is supported by gains in

language proficiency, which, in turn, is likely promoted by continued learning from and about the rich network of connections and intercorrelations that characterize natural languages.

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