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Evidence for Cross-situational Syntactic Bootstrapping: Three-year olds Generalize Verb Meaning across Different Syntactic Frames

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Abstract

Previous research suggests that a verb's meaning is learned partly through the aggregated profile of syntactic frames associated with it. For example, "turn" occurs with transitive and intransitive frames in causative alternation ("He turned the car"/"The car turned"), indicating it is a causal verb. Some evidence demonstrates that young children combine multiple frames to map verbs to appropriate events. However, previous work always presented these frames together, in a single dialogue. What remains unknown is how verb learning occurs when the frames are separated, uttered in different referential contexts, as is likely in children's everyday life. In a series of cross-situational word-learning experiments, we show that both adults and three-year-olds generalize verb meanings across different syntactic frames in a cross-situational learning task. These results shed light on the cross-situational mechanisms of syntactic bootstrapping.

Keywords: Verb learning, Syntactic bootstrapping, Cross-situational learning, Acquisition, Psycholinguistics

Introduction

All human languages feature systematic links between the meanings of words and the syntactic structure of the sentences they compose. For instance, verbs which refer to events with multiple participants are typically used in transitive frames (e.g., "She carried him") while verbs referring to events with a single participant are typically used in intransitive frames (e.g., "She smiled"). By using the sentence frames that a new word occurs in, learners can gain insight into the word's meaning—a process known as "syntactic bootstrapping" (Gleitman, 1990; Landau & Gleitman, 1985; Naigles, 1990, 1993).

Syntactic bootstrapping is likely particularly critical in helping children to infer the meanings of verbs, which tend to be more difficult to learn from observation of the referent world alone (Gleitman et al., 2005). Indeed, past work has shown that children can map verbs to the correct, co-present event by relying on a rich array of syntactic cues, including argument number, function words, transitivity, and argument order (Bernal et al., 2007; Fisher, 2002; Gertner et al., 2006; He & Lidz, 2017; Naigles, 1990; see Fisher, Gertner, Scott

& Yuan, 2010 for a review). Syntax can act as a "zoom lens," helping to identify a word's target meaning in dynamic and ambiguous learning contexts (Nappa et al., 2009, Gleitman et al., 2005).

According to the theory of syntactic bootstrapping, learners can also use the set of syntactic frames a verb occurs in to make inferences about a verb's semantic subclass (Gleitman, 1990; Fisher et al., 1991; Landau & Gleitman, 1985). For example, the unique distributional profile of the verb "see," which takes NP and CP complements, is sufficient to indicate to blind children that "see" is a perception verb (Landau & Gleitman, 1985). Similarly, verbs that participate in dative alternation often encode the meaning of transfer (Fisher et al., 1991). Therefore, it is a crucial question how children accumulate this information and successfully update verb meanings as they encounter the verb across different syntactic contexts.

Recent work has shown that children can retain syntactic constraints on meaning across exposures to a word. Two-year-olds who hear a verb used in a transitive frame during a dialogue on one exposure are then more likely to map the verb to a two-participant causative event on a later exposure, compared to toddlers who heard the verb used in an intransitive context during the dialogue (Arunachalam & Waxman, 2010; Yuan & Fisher, 2009).

Moreover, children can even combine information provided by multiple syntactic frames within a single dialogue to constrain subsequent verb mappings (Naigles, 1996; Scott & Fisher, 2009). Scott and Fisher showed children could distinguish between two types of verbs used in both transitive and intransitive frames: causal alternation verbs, which map to causal events and feature both inanimate and animate subjects (e.g., "He broke the car"/"The car broke"), and unspecified-object verbs, which map to contact events and reliably feature animate subjects (e.g., "He dusted the car"/"He dusted"). In that study, children heard a dialogue featuring a novel verb of either type. On a subsequent test, two-year-olds preferred the

contact meaning when the verb had always occurred with an animate subject whereas they preferred a causal meaning when the verb occurred with animate and inanimate subjects. This suggests children use information from multiple syntactic frames to learn verbs.

Current Work

However, these previous studies have always presented the syntactically informative frames together, in a single dialogue. What remains unknown is how verb learning occurs when these syntactic frames are encountered separately, in different referential contexts. After all, while children will sometimes encounter a new word in adjacent but differing syntactic frames (e.g., “He dusted? Well, he dusted the car.”), the majority of children’s experience is likely to be with more isolated instances of a verb (Newport et al., 1977; Waterfall, 2006).

It is a critical question, then, how syntactic bootstrapping plays out cross-situationally: across multiple exposures to a verb in different referential contexts. This process may be challenging in at least two respects. First, retaining a verb’s syntactic frames in memory across exposures may be difficult for young children. Prior work on cross-situational word learning suggests children retain only limited information about a word’s meaning across exposures—perhaps only their prior hypothesized meaning (e.g., Aravind et al., 2018; Medina et al., 2011; Trueswell et al., 2013; Woodard et al., 2016). Second, children have been shown to have difficulty generalizing verb meanings across different instances. Specifically, prior work suggests that preschoolers often struggle to extend verbs to events differing in features such as the actors involved, the instruments or objects used in the event, and the manner in which the action is performed (Forbes & Poulin-Dubois, 1997; Haryu et al., 2011; Maguire et al., 2008). Emphasizing this difficulty for causal alternating verbs, in particular, Kline & Demuth (2014) found that 3-year-olds who learned an alternating verb in one frame (e.g., “Joey’s daxing the sock”) had only mixed success producing it in the alternative frame (“The sock is daxing.”).

Here, we take a first step in addressing how syntactic bootstrapping plays out cross-situationally. To test whether learners spontaneously generalize verb meanings across syntactic frames at multiple exposures, we asked adult (Experiment 1) and three-year-old (Experiment 2) learners to learn novel causal verbs (like *turn* in English), which in principle are compatible with both transitive and intransitive frames. Learners were first exposed to these verbs in one frame (e.g., transitive) and were then tested in the other frame (e.g., intransitive). Previous research has established that when learners first encounter a verb, they can use the verb’s syntactic frame to map it to an event (e.g., mapping “She is turning the boy” to a two-participant causal turning event) (e.g., Naigles, 1990). But when learners then encounter that same verb again in a different situation, in a

new frame (e.g., “The boy is turning”), will they be able to update their original meaning to incorporate the new frame (e.g., identifying “turn” as a causative alternating verb - which can mean both revolving and causing to revolve)? Alternatively, would learners reject their previously hypothesized meaning as incompatible with the current frame and propose a new meaning, selecting among all co-present, frame-compatible events? Across two experiments, we directly assess which of these possible strategies adult and child learners take when they encounter a recently learned verb in a new frame.

Experiment 1

We first tested whether adult participants show generalization across frames in a novel verb learning paradigm. Participants learned each verb in one type of syntactic frame (either transitive or intransitive) and were then tested in the alternative frame. For example, participants might hear a verb used in a transitive frame first (e.g., “The boy is fepping the girl”), paired with a causal event (e.g., he crosses her arms) and a synchronous event (e.g., both actors lunging) (Figure 1 Exposure). In this case, based on prior work, we expect learners to select the causal event because it is the only event consistent with the transitive frame (cf., Naigles, 1990). Then at test, participants would hear the same verb used in the alternative, intransitive frame (e.g., “The boy and the girl are fepping together”) (Figure 1 Test). The referent events presented at test depended on condition. Participants in the Integrative condition could select either the target “Integrative” event, which both preserved a core semantic component of their previous hypothesis and complied with the new frame (e.g., two actors crossing their own arms), or a “Distractor” event, one that complied with the test frame but had been presented (though not selected) with a different verb during learning (Figure 1 Test). For participants in the Baseline condition, the Integrative event was replaced by the “Previously Unselected” event (e.g., both actors lunging) that was paired with the target verb at exposure but had not been selected. If learners are integrating the new frame with their previous hypothesis, and not simply with any previously co-occurring meanings, participants should prefer the Integrative event, but not the Previously Unselected event, at test.

Methods

Participants Eighty monolingual adult speakers of English (Mean age = 37.7 years) based in the United States recruited from Prolific (www.Prolific.co) participated in the experiment. They were compensated at the rate of \$12/hour.

Materials We created 48 short video clips, each of which depicted a novel action and lasted 1-3 seconds. One actor and one actress were both present in every video. Among the 48 video clips, 12 pairs represent causal/synchronous

alternations of the same action (i.e., cross arms, spin in chair, wave hands, sway, flap arms, stand up, lift arm, raise head, flex arm, squat, lift leg, and bend over).

In a synchronous event, both actors performed the same target action autonomously (e.g., both actors autonomously crossed their own arms over their chest). In a causal event, one actor caused the other to take the target action (e.g., the boy crossed the girl's arms). The identity of the causer was counterbalanced. The rest of the clips contained (unpaired) 12 causal and 12 synchronous events, with no synchronous/causal counterpart.

Procedure After consenting, participants were directed to the online experiment via a URL link. The experiment consisted of three blocks identical in structure. In each block, participants learned four novel verbs and were tested on two of them. During each exposure trial, learners heard the verb presented in either a transitive (e.g., “The boy is fepping the girl!”) or an intransitive (“The boy and the girl are fepping together!”) frame, with one causal and one synchronous event presented as possible referents. Learners were then prompted to select the event described by the verb (“Find fepping!”). Half of the verbs in each block occurred in a transitive frame, and half in an intransitive frame. The events were counterbalanced for position on the screen. Both videos were on loop and participants had unlimited time to select one as the verb's referent. We expected learners to reliably select the event compatible with the

verb's syntax (causal events for transitive syntax; synchronous events for intransitive) on each exposure trial.

After each set of 4 exposure trials, learners were tested on 2 of those 4 verbs (one transitive, one intransitive). These verbs were now presented in the alternative frame (e.g., verbs learned in transitive frames were tested in intransitive frames) (Figure 1). Learners selected a referent event from two options, which varied by condition. In the Integrative condition, participants chose between the target “Integrative” event, which shared a semantic component of the event they selected at exposure but also complied with the new frame, and an Unassociated event, which had been the non-compliant event for another verb during exposure. Positions were counterbalanced on the screen. For learners in the Baseline condition, the Integrative event was replaced by Previous Unselected event, which had co-occurred with the verb at exposure but had not been selected (as it did not match the original syntactic frame) (Figure 1).

Analysis We first examined whether participants complied with the frame at exposure. To analyze test trials, we then only included trials for verbs that received frame-compliant selections at exposure, ensuring all participants began with the same hypothesis.

For the test phase, we tested whether learners in each condition showed a preference for the condition's target event (the Integrative event in the Integrative condition and the Previous Unselected event in Baseline), building separate logistic mixed-effect models for each. Finally, we

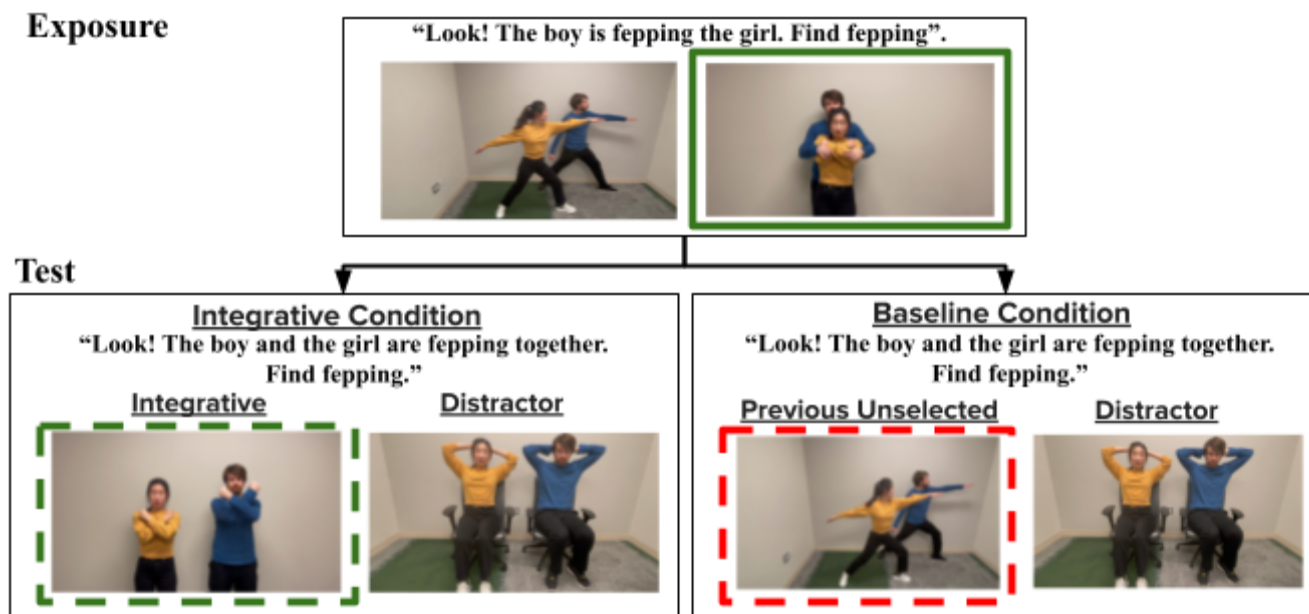


Figure 1. Sample Exposure and Test trials (using a transitive-first critical verb). Adults learned the word “fep” in a transitive frame during the exposure. They are expected to select the causal event (marked with green frame). They were then tested on the word with an intransitive frame. The events shown at test depended on whether they are in Integrative or Baseline condition. If learners are integrating the new frame with their previous hypothesis, and not simply with any previously co-occurring meanings, participants should prefer the Integrative event (marked with green dashed frame), but not the Previously Unselected event (marked with red dashed frame), at test.

compared the two conditions in another logistic mixed-effect model, testing whether learners preferred the Integrative event to a greater degree than the Previous Unselected event.¹

Results

Frame Compliance at Exposure As expected, participants almost always chose the frame-compliant event at Exposure. When participants heard a transitive sentence (e.g., “The boy is fepping the girl”), they chose the causative event 99.8% of the time. Similarly, when they heard an intransitive sentence (e.g., “The boy and the girl are fepping together.”), they chose the synchronous event 91% of the time. Learners were significantly more likely to comply with transitive frames than intransitive frames ($\beta = 4.234$, $SE = 1.760$, $p = 0.016$), a pattern also reported in previous literature (e.g., Arunachalam & Waxman 2010).

Selection at Test We next analyzed the test trials. Participants in the Integrative condition showed a significant preference for the Integrative Event at test ($\beta = 0.733$, $SE = 0.179$, $p < 0.001$) (Figure 2 Left). In contrast, those in the Baseline condition did not show any preference between the Unassociated Event and the Previous Unselected event ($p > 0.05$, Figure 2 Right). Thus, learners did not privilege the previously associated (though unselected) referent.

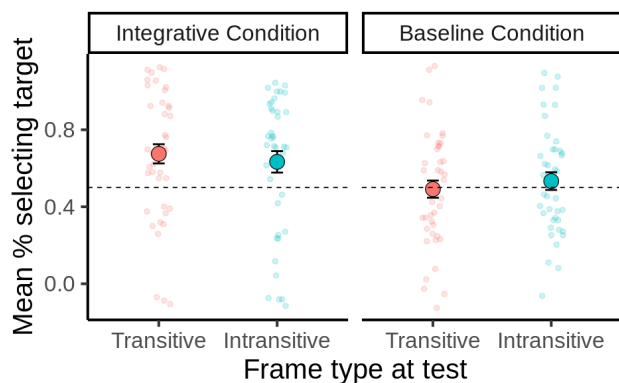


Figure 2. Participants’ mean proportion of selecting the target (i.e., the Integrative event in Integrative Condition) or target control (i.e., the Previously Unselected event in Baseline Condition) at test in Exp. 1. Dashed line indicates chance probability (50%). Error bars represent standard errors of the mean.

Furthermore, a between-condition multilevel logistic regression revealed a reliable effect of Condition: learners were more likely to select the Integrative event in the

¹ For the random-effect structure of all models, we started out with a maximal model (including random intercepts for subject and item and a condition-by-item slope, in this case) and simplified the structure as needed. The final random-effect structure consists of by-participant and by-item intercepts.

Integrative condition than the Previous Unselected event in the Baseline Condition ($\beta = -0.298$, $SE = 0.098$, $p = 0.003$). Notably, there was also no effect of Frame Type ($p > 0.05$), indicating learners were similarly successful in learning alternating verbs regardless of which frame they encountered the verb in first.

Thus, when presented with verbs in alternating frames, learners consistently chose a referent event that incorporated a key component of the previous hypothesized meaning, consistent with an interpretation of the verb as a causal verb. In contrast, they showed no preference for a referent event which had previously co-occurred with the verb at exposure but been non-compliant with the syntactic frame, indicating mere co-occurrence was insufficient to facilitate integration across exposures.

Experiment 2

In Experiment 1, we showed that when adult learners encounter a verb in multiple syntactic frames across exposures, they integrate their previous hypothesis for a verb’s meaning with its current frame. Learners preferred this integrative strategy regardless of frame order. In Experiment 2, we tested whether children are also able to perform this inference. We adapted the selection paradigm that we used in Experiment 1 to a preferential looking paradigm and tested 15 three-year-olds in this cross-situational verb learning task.

Methods

Participants Fifteen English-acquiring children (mean age = 42.2 months, $SD = 3.7$; 6 female, 9 males) recruited from interested families in the University of Pennsylvania database and local preschools participated. Data collection is ongoing with a target sample size of 24 children. Participating families received a \$10 Amazon gift card in compensation. We excluded 1 child due to audio-recording failure and 3 children who did not robustly show the expected looking preference to the target on our known-word trials, where they were asked to find “carrying”, “clapping”, “the girl” and “the boy.”

Procedure Expt. 2 adopted a similar design to the Integrative condition from Expt. 1. However, to adapt the task to children, we made three key changes. First, we used a preferential looking paradigm instead of selection: looking patterns of children were recorded using a web-cam. Looking preference on each trial was calculated as the time spent looking to the target event divided by the total time looking to both events, starting from the onset of the first prompt sentence (e.g., “Where’s fepping? Find fepping!”). Second, to accustom children to the task, the study began with a series of four familiarization trials with known words: two trials introducing the actors (as “the boy” and “the girl”) and two trials featuring familiar verbs and events (“clapping” and “carrying”). Third, because of children’s

attention and working memory constraints, we reduced the number of trials so that children only learned eight verbs in the task (and were tested on four), evenly distributed across four blocks.

On each exposure trial, after seeing an attention grabbing animation in the center of the screen, children viewed two videos depicting novel actions presented on the screen in silence for 2 s, then heard a novel verb used in a carrier sentence (Figure 3). Just as in Expt. 1's exposure phase, only one of these videos matched the sentence's syntax (a causal action for transitive frames; a synchronous, non-causal action for intransitive frames). Children heard two utterances of the key frame on all trials (e.g., "The boy is fepping the girl! Really, the boy is fepping the girl!"). We expected that children would prefer to look at the frame-compliant event. At Test, which immediately followed Exposure in this abridged design, the verb was presented in the alternative frame and children saw two frame-compliant events: an Integrative event (the counterpart of the Exposure target event) and a Distractor event (which had occurred previously as the frame-incompliant event for a different verb in that block). If children are able to generalize verb meanings across syntactic frames, they should prefer the Integrative event.

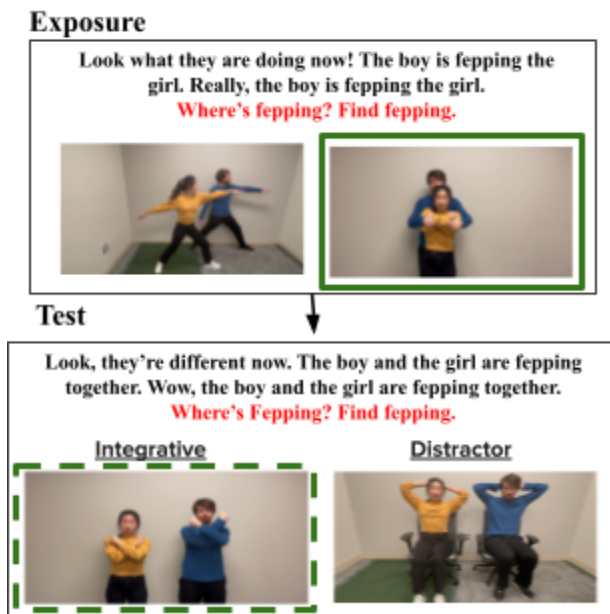


Figure 3. Sample trials (using a transitive-first critical verb). At Exposure, children heard a novel verb used in a transitive frame paired with a causal and non-causal (synchronous) event. Children are expected to look at the causal event longer (marked above with a green circle). At Test, the verb was used in an intransitive frame, and participants chose between two synchronous events. The prompt during whose utterance looking pattern was analyzed was marked in red.

Results

Frame Compliance at Exposure As expected, children preferred to look at the frame-compliant event at Exposure ($M = 65.6\%$, $\beta = 0.121$, $SE = 0.034$, $p = 0.007$). Although children showed a numerically stronger preference for the frame-compliant event when they heard a transitive frame than an intransitive frame ($M_{\text{Transitive}} = 70.0\%$, $M_{\text{Intransitive}} = 60.9\%$), Frame Type was not a significant predictor of children's looking to the target ($p > 0.05$).

Looking Preference at Test In line with our prediction, children showed a reliable looking preference for the Integrative event at test ($M = 62.9\%$, $\beta = 0.124$, $SE = 0.040$, $p = 0.004$) (Figure 4), regardless of the order in which they had encountered the alternating frames ($p > 0.05$). Thus, children successfully integrated their previously hypothesized verb meaning with the verb's new syntactic frame, extending verbs to causal or non-causal events as indicated by the syntactic cues.

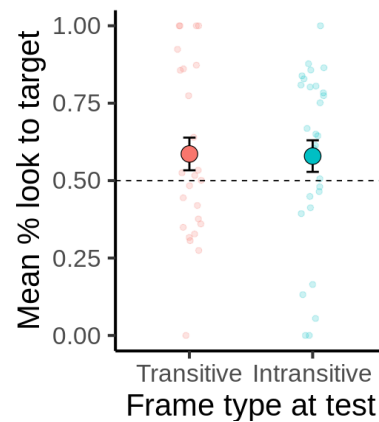


Figure 4. Proportion of looks to the target at test. Children significantly prefer the Integrative event when critical verbs were presented in both types of frames, indicating they generalized their previous hypotheses of verb meaning to a different frame. Each point represents one trial. Error bars represent SEM.

General Discussion

In two experiments, we showed that when child and adult learners encounter a verb in different syntactic frames across exposures, they integrate their previous hypothesis for a verb's meaning with its current frame. Indeed, learners used this integrative strategy regardless of the order in which they encountered the transitive and intransitive frames. This flexibility in children's verb learning is a requirement for cross-situational syntactic bootstrapping to succeed. Even when children are exposed to a verb's different frames across multiple, distinct events, they nonetheless arrive at a

cohesive verb meaning, generalizing across different syntactic frames and events with different causal structures.

Adult learners' stronger preference for the Integrative event in the Integrative condition than for the Previous Unselected event in the Baseline condition also suggests that even sophisticated adult learners only performed this sort of integration for their *hypothesized* meaning. Although the Previous Unselected event co-occurred with the verb at both Exposure and Test, learners showed no preference for it. This is consistent with hypothesis testing models of cross-situational word learning, which suggest learners retain only hypothesized meanings across exposures (e.g., Trueswell et al., 2013; Stevens et al., 2017). This finding is not as readily explained under global models of word learning which rely on tracking word-referent co-occurrences (e.g., Fazly et al., 2010), though modified models that incorporated learners' attention to different referents during exposure might account for it (cf. Kachergis et al., 2012; Macdonald et al., 2017).

These results present multiple avenues for future research. First, ongoing research asks how children will perform in the Baseline condition. We expect children to perform at chance, in line both with our adult results from Experiment 1 and with prior work suggesting children rely on hypothesis-testing in cross-situational word-learning. However, if children are less certain of the syntactic mappings at exposure, perhaps they would show a bias for the Previous Unselected event at test. In addition, future work should examine how learners integrate meanings across frames when the frames are separated by more substantial delays or are applied to events with different actors and contexts, as is likely common in daily life. Future work might also ask how other kinds of verbs are learned across frames, beyond the causative alternation verbs preserving the event's manner of motion used here. While the current work tests whether children construct a cohesive meaning even across categorically different (i.e., transitive vs. intransitive) frames, future work might also examine whether this cohesion is similarly facilitated by more neutral frames (e.g., "Look, daxing!"). Lastly, future work might test even younger children, between 18 and 30 months, to assess how the ability to integrate verb meanings across frames develops.

In sum, these findings suggest that learners can integrate syntactic and referential information across word-learning exposures, updating their previously hypothesized meaning to incorporate a new syntactic frame. This provides new insight into the nature of cross-situational syntactic bootstrapping, revealing a powerful learning strategy for using a verb's syntax to identify its meaning.

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