Memory, sleep and generalization in language acquisition

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Language is acquired over multiple instances and unfolds over time, raising questions about the effects of memory on learning. Work investigating how prior experience affects later learning suggests that prior experience can act as a scaffold, supporting learning of a more complex structure that would not be learned otherwise. In other cases prior experience narrows the range of structures infants will consider. Additionally, research on the effects of sleep on infant learning shows that sleep can lead to a more abstract memory, an adaptive and crucially important transformation for language learners who must retain key aspects of learning yet generalize to novel information. Both sets of findings point to the importance of taking memory into account in our understanding of language acquisition.

Keywords: Language learning; language acquisition; statistical learning; memory; prior experience; sleep-dependent memory consolidation

1. Introduction

Learning is an important focus in recent infant language research (e.g. see Gómez & Gerken 1999, 2000; Marcus et al. 1999; Saffran, Aslin & Newport 1996, for the earliest studies). Many findings demonstrate the increasing attunement to one’s native language (e.g. Werker & Tees 1984; Jusczyk et al. 1993; Jusczyk, Luce & Charles-Luce 1994; Mattys & Jusczyk 2001; Mattys et al. 1999) but these findings shed little light on the learning mechanisms available to infants per se. With the many correlated cues occurring in natural language it is difficult to identify the locus of learning and virtually impossible to separate the effects of prior experience from learning.

Artificial languages offer a useful approach because the cues provided to learners can be manipulated and controlled, as can prior experience. The structure of natural language, thought to contribute to learning, can be built into artificial languages, and infants can be tested for their ability to acquire such structure. For
instance by stringing together four novel trisyllabic words in continuous speech, Saffran et al. (1996) created a language in which the conditional probability of predicting a syllable from its precursor within a word was higher than the conditional probability of predicting the first syllable in a word from the last syllable in a preceding word. Infants heard strings of the form:

$pabiku-golabudaropi-tibudo$.

where the transitions between syllables within the ‘words’ ($pabiku$, $golabu$, $daropi$, and $tibudo$) were more frequent (occurring with a transitional probability of 1.0), and transitions between words occurred with the lower transitional probability of .33 ($\text{TP}=\frac{\text{Frequency of XY}}{\text{Frequency of X}}$, such that the transitional probability for $latu$ in $golatu = 1$, $\text{TP}_{latu} = 1/1$, and for $tuda$ in the transition from $golatu$ to $daropi$ is .33, $\text{TP}_{tuda} = 1/3$). After only two minutes’ exposure, 8-month-old infants listened longer on a subsequent listening-time test to part-words of the language (e.g. $golatu$ and $daropi$) than to words (e.g. $pabiku$ and $tibudo$), demonstrating their ability to discriminate the two stimulus types. With the only information indicating word boundaries being the differential conditional probabilities within versus between words, the findings demonstrated an early ability to rapidly segment words by tracking conditional probabilities in sequential structure (see also Aslin, Saffran & Newport, 1998).

Work since Saffran et al. (1996) has used the same paradigm to examine infants’ learning in other domains: their ability to track the frequency of phonetic units for learning phoneme categories (Maye, Werker & Gerken 2002; Maye, Weiss & Aslin 2008), to learn phonotactic dependencies in novel words (Chambers, Onishi & Fisher 2003), to infer rules in a novel stress system (Gerken 2004; Gerken & Boltt 2008), to acquire sentence-like structure as defined by finite-state grammars (Gómez & Gerken 1999; Saffran & Wilson 2003; Saffran, et al. 2008), and to abstract higher-order relations necessary for acquiring functional-like and lexical-like categories and their predictive relations (Gerken, Wilson & Lewis 2005; Gómez & Lakusta 2004; Lany & Gómez 2008).

These studies demonstrate precocious learning abilities but they have been criticized for limitations in complexity, their relation to natural language, and in their ability to scale up to the challenges of real world language learning (Pelucchi, Hay & Saffran 2009; Gambell & Yang 2003; Yang 2004). For instance, Gambell and Yang (2003) tested the predictability of transitional probabilities in a corpus of child-directed speech. With a hit rate of 23.3%, transitional probabilities were only moderately successful at segmenting real speech, yielding a sobering assessment of their potential usefulness. However, such a low success rate may still be enough to help infants make headway on real-world word segmentation. When Thiessen and Saffran (2003) tested the relative informativeness of trochaic stress and conditional
probabilities for segmenting words, 6-month-olds relied more on conditional probabilities whereas 7.5-month-olds relied more on stress. If a predominant stress pattern can be used to segment words (Cutler 1996; Jusczyk, Houston & Newsome 1999), and if infants can use even a subset of words they initially segment based on conditional probabilities in order to learn the predominant stress pattern of their native language (Swingley 2005; Thiessen & Saffran 2003), they can then use this stress template in addition to conditional probabilities to extend their word segmentation.

Further work in this area demonstrates how the output of initial learning feeds into other linguistic tasks, from demonstrations that the sequences of sounds that infants segment can be used to facilitate the acquisition of word meanings (Graf Estes et al. 2007) to demonstrations that the morphosyntactic categories that infants can acquire in an artificial language can be mapped onto semantic categories (Lany & Saffran 2010). Furthermore, the types of mechanisms infants might use for acquiring key syntactic structures such as functional elements and their long-distance relations (Gómez 2002) or functional and lexical categories (Braine 1987) have important parallels in natural language (Gerken et al. 2005; Santelmann & Jusczyk 1998). Although the mechanisms investigated so far may not be able to account for all the challenges and complexity faced by language learners, they do provide infants with an opening wedge for meeting some of their initial learning challenges.

One consideration that has been neglected until recently is the role of memory in language acquisition. Memory can play several different roles in the language acquisition, first with prior learning and its role in shaping later learning experiences, second with the accumulation of experience and its effects on what infants learn at different points in developmental time, and third with changes in what is learned during memory consolidation.

2. Prior learning

Learning does not take place in a vacuum. Learners continually encounter new examples with the potential to add to, detract from, or, in some other way, update the generalizations they are making. Previous studies have rarely taken the history of the learner into account, but on any view what children learn at an earlier point in time should influence their learning at a later point. Lany and Gómez (2008) investigated this issue by exposing 12-month-old infants to $aX$ and $bY$ structures where their task was to learn that $a$-elements predict $X$s and $b$-elements predict $Y$s, but that $a$-elements do not predict $Y$s, much as children have to learn that determiners predict nouns but not verbs (see also Braine 1987; Gerken, Wilson, & Lewis 2005; Gómez & Lakusta 2004). There were two $a$-elements ($ong$, $erd$) and two $b$-elements...
(alt, ush), intended to mimic functor-like elements distributionally, and 8 each Xs and Ys intended to mimic lexical-like elements (e.g. Xs – kicey, fengle, etc., and Ys – ghope, jic, etc). The X and Y elements had different features much like nouns and verbs in natural language, both in terms of their distributional patterns (Cartwright & Brent 1997; Mintz 2002; Mintz, Bever & Newport 2002; Monaghan, Chater & Christiansen 2005; Redington, Chater & Finch 1998) and their phonological cues (Christiansen & Monaghan 2006; Farmer, Christiansen & Monaghan 2006; Kelly 1992; Monaghan et al. 2005). In Lany & Gómez, the Xs and Ys were differentiated by number of syllables such that the words in one category were monosyllabic and the words in the other were disyllabic. Previous work has shown that having a differentiating feature is critical to acquiring different categories like X and Y (e.g. Braine 1987; Frigo & MacDonald 1998; Gerken et al. 2005; Gómez & Lakusta 2004).

Learning occurred over phases such that in the first phase infants were exposed to a simpler version of the grammar (e.g. aX bY) than they would ultimately have to learn in the second phase (acX bcY). During Phase 1 infants listened to strings of the form aX bY (or bY aX in a counterbalanced version of the language) for approximately 9 minutes while playing quietly on the floor of our playroom with the experimenter and a parent present. The experimental group heard strings consisting of aX and bY combinations of a1-2X1-8 and b1-2Y1-8 with four combinations held out. The control group listened to a grammar that was unlearnable because a- and b-elements were associated with both categories (e.g. a1-2 were paired with X1-4 and Y1-4, and b1-2 were paired with Y4-8 and X4-8). In Phase 2, the infants were taken to a different room in the lab where they were habituated to the held-out strings from Phase 1 presented in a more difficult form that does not normally lead to learning (acX and bcY where the c-element in these structures was instantiated by a single monosyllabic word, hes). We have shown in previous studies that nonadjacent dependencies are particularly difficult for infants this age to acquire (Gómez & Maye 2005) providing a test of whether the infants would bootstrap from more simple to more complex structure.

After habituation, the infants were tested on two legal trials (consisting of acX bcY strings heard during habituation) and two illegal trials (consisting of acY bcX strings that violated the structure of the habituation grammar). The experimental group listened significantly longer to illegal strings, thus demonstrating that prior exposure to a simpler form of the grammar played some role in learning the more complex nonadjacent forms (the control group showed no such difference). If 12-month-old infants are able to learn the more difficult nonadjacent structure in the Phase 2 grammar, the control group should have shown learning too – the control group was exposed to the vocabulary and to the fact that a- and b-elements predicted unique sets. They also were habituated to the
same stimuli in Phase 2 as the experimental group. The only difference was the coherence of the learning materials in Phase 1 such that learning the $aX$ and $bY$ dependencies enabled the experimental group to track novel dependencies during habituation in Phase 2.

This finding demonstrates how infants might scaffold learning of more difficult nonadjacent structure from learning of adjacent dependencies, which are easier to learn. They demonstrate in one way at least that prior experience can affect later learning. Other work in our lab explores how prior experience can alter the course of learning such that experience with highly reliable forms results in excellent learning combined with an inability to transfer to less reliably cued structure, whereas learning with more weakly cued structure results in successful transfer to related, imperfectly cued forms (Lany & Gómez submitted). Given that linguistic forms are rarely perfectly cued, this work is an important next step in exploring the circumstances that support the more challenging scenarios found in natural language learning.

3. How pressures from the input can alter learning over developmental time

Classic work on infant speech perception shows that infants can discriminate speech sounds occurring in other languages early on in development but become limited in the non-native forms they can discriminate as they become more attuned to their native language (Best, McRoberts & Sithole 1988; Polka & Werker 1994; Werker & Tees 1984). Presumably this change is the result of increased experience with their native language. Gerken and her colleagues have addressed the issue of how children’s input shapes learning over longer periods developmentally, with artificial languages (Dawson & Gerken 2009; Gerken & Bollt 2008). This research suggests that infants learn different kinds of information at different points in time because what is learnable also changes as a function of experience with the ambient language.

As in the work on perceptual reorganization of speech structure, younger infants appear able to learn structure that older infants cannot. For instance, Gerken and Bollt (2008) find that 7.5-month-olds are able to learn a stress principle atypical of human languages (namely, that syllables starting with the consonant /t/ are stressed) whereas 9-month-olds fail to learn this arbitrary principle. However, 9-month-olds can learn a principle found in human languages – that syllables ending in a consonant are stressed. This pattern of learning is consistent with the fact that, in the words acquired most frequently by children up to 5 years of age, syllables are far more likely to carry stress when they end in a consonant

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than when they begin with /t/. By 9 months of age infants appear to be sensitive to this frequency difference (Gerken & Bollt 2008).

Similarly, Dawson and Gerken (2009) have shown that 4-month-olds can learn repetition patterns in AAB/ABA strings instantiated in chords whereas 7-month-olds cannot. This finding is consistent with the fact that repetitions of chords among adjacent and nearby notes do not exceed levels expected by chance in the music they hear. While infants display this ability early on, they lose it because it is not supported by their experience with music. These findings are also consistent with the fact that, over time, infants accumulate substantial experience with syllables, and this familiarity is likely to help them track repetition patterns over syllables at 7.5 months.

Presumably these losses in ability reflect increased tuning to the statistics of English (in the case of Gerken & Bollt) and increased tuning to canonical music structure (in the case of Dawson & Gerken), leading older infants to ignore less frequent patterns in favor of more frequent ones. In this way experience constrains the types of generalizations infants make over developmental time.

4. Sleep and memory consolidation

The findings for learning so far are all based on testing performance immediately after a learning experience. However, research on memory consolidation shows that new memories undergo an organic time-dependent process of neural change (McGaugh 2000). Initial consolidation in sequential learning occurs during periods of wake (e.g. Brashers-Krug; Shadmehr & Bizzi 1996; Muellbacher et al. 2002; Walker et al. 2003), with additional improvement associated with sleep in adult subjects (Fischer et al. 2002; Gais et al. 2000; Karni et al. 1994; Korman et al. 2003; Stickgold, James, & Hobson 2000; Stickgold et al. 2000; Walker et al. 2002; Walker et al. 2003; Walker & Stickgold 2006). This raises questions about the extent to which learning observed immediately is representative of changes that could occur over time.

With memory consolidation, a newly formed memory trace is transformed into a more stable, less disruptable state over a period of hours, days, and years (McGaugh 2000; Müller & Pilzecker 1900). Consolidation results in greater accuracy, faster execution of a task or skill, increased generalization, and integration of new knowledge into existing knowledge. Importantly, many of these improvements arise from molecular, cellular, and systems-level processes associated with sleep. Evidence for this stems from the fact that patterns of activation observed during training re-appear during REM sleep (e.g. Maquet et al. 2000; Wilson & McNaughton 1994; Euston, Tatsuno & McNaughton 2007). Additionally, performance on a
learning task correlates with the magnitude of brain activity during the first REM episode that occurs after learning (Peigneux et al. 2003). Brain activity during sleep also correlates with later increases in performance (Peigneux et al. 2004). The findings linking brain activity in sleep to initial learning and later performance are important for ruling out explanations based on the idea that sleep-related benefits come from a decrease in interference during sleep, as opposed to consolidation processes associated with sleep. Additionally, Frank et al. (2001) have shown that changes in visual cortex, associated with depriving kittens of visual input in one eye, that occur after sleep, do not occur when kittens undergo a similar period of time awake in the dark.

Studies with adult learners reveal many of the ways sleep alters new memories. Walker and his colleagues have shown that learners were faster and more accurate at performing a sequence of key presses in a sequential learning task after sleep than they were before they slept (Walker et al. 2003). Sleep also appears to be associated with changes in memory involving insight into a problem solution. Wagner and his colleagues gave learners a problem with two possible routes to solutions (Wagner et al. 2004). One route involved applying simple rules in an iterative fashion. The other route involved a rule that if discovered would result in an immediate solution. Problem-solving performance was observed immediately after instructions were administered for the iterative process and 8 hours later for a group that slept and for a group that did not sleep. Twice as many participants in the sleep group discovered the hidden rule compared to those participants who spent an equivalent time awake. This again suggests that sleep is implicated in this process.

Among results that may be more relevant to language acquisition, sleep has also been implicated in memory transformations involving higher-order generalizations in sequential information. In one study investigating transitive inference of relations, Ellenbogen et al. (2007) trained participants on visual stimuli following the rules A > B (A precedes B), B > C, C > D, D > E, E > F. Learners were then tested after intervals of 20 min, 12 hours wake, 12 hours sleep, or 24 hours, on their ability to infer relations they had not encountered in training (e.g. B > D, C > E, and B > E). Retention of the pairs acquired during training was similar for all groups at approximately 85%, whereas generalization occurred only for the groups tested 12 hours or 24 hours later. As an example, generalization to the most distant and most difficult inference pair (B > E) was 93% accuracy in the 12-hr sleep group as compared to 69% accuracy in the 12-hour wake group.

In another study involving word identification, listeners heard a nonce word produced in synthetic speech and had to type a match on a computer keyboard. Learners were faster and more accurate at typing new words 12 hours after training if they slept during this interval compared to the same time awake (Fenn, Nusbaum, & Margoliash 2003). Participants in the sleep group showed the same
level of generalization to new words as learners tested immediately after training, whereas participants in the wake group showed decreased generalization. Importantly, the time of day learning took place was controlled with one group who learned in the morning and in the other who learned in the evening. Both showed identical generalization when tested 24 hours later because both groups slept during the interval.

Finally, Gaskell and his colleagues have conducted a series of experiments investigating the role of sleep in the incorporation of new words into the lexicon (Dumay & Gaskell 2007; Davis et al. 2009). A hallmark of this incorporation is when the new word comes to compete with the processing of an existing similar-sounding word. This is reflected in the reaction time to detect a pause in the existing word (e.g. “cathedr_al”), which is longer after learning a novel word (e.g. “cathedruke”) than it is otherwise. Although novel words are readily learned, as indicated by an immediate recognition test, they are not immediately incorporated into memory. Rather this appears to depend on sleep, as reflected in the fact that there is no reduction in reaction time to the original word if participants are trained and tested in a 12-hour interval during the day (morning training, evening test), but it is reflected in reaction time if learning takes place in the evening and learners are then tested the next morning after sleep. Participants who learn the novel words in the morning do show competition 24 hours later, but only after they have slept.

Given the adult findings on the importance of sleep in memory consolidation, there is every reason to think that sleep is also implicated in infant memory, but little is known about this. Established findings on infant sleep-wake states does find that sleep-wake state organization is a predictor of cognitive development in infancy: Poor organization reflects less advanced cognitive development, and better organization more advanced cognitive development (e.g. Ednick et al. 2009; Gertner et al. 2002; Gómez, Newman-Smith, Breslin & Bootzin 2011 for a review). The finding that sleep plays a role in brain development in animals also speaks to the role of sleep in human infants (Frank et al. 2001). Furthermore, Fagan and Rovee-Collier (1983) found that retention of a memory that had been reactivated eight hours earlier was correlated with amount of sleep in that interval in 3-month-old infants. Recent work from my lab also supports this view (Gómez, Bootzin & Nadel 2006; Hupbach et al. 2009).

My colleagues and I familiarized 15-month-olds with an artificial language four hours prior to a lab visit. Infants were placed in one of three groups: in an experimental sleep group, an experimental no-sleep group, and a control sleep group. The artificial language required infants to track sequential dependencies between the first and third words in sentences such as pel-wadim-jic or vot-kicey-rud. Infants were familiarized with strings of the form aXb and cXd (in a counterbalanced version of the language, infants heard aXd and cXb) and

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had to discriminate these from strings of the form $aXd$ and $cXb$ at test (for the counterbalanced version, illegal items were $aXb$ and $cXd$). Infants only detect the differences in the languages if they have learned that the first word in a string predicts the last word (vocabulary by position and bigrams is identical in the two languages, so the only way to tell the two languages apart is by tracking nonadjacent dependencies). Such learning is difficult for infants and adults alike (Gómez 2002; Newport & Aslin 2004) but is successful when the middle element is drawn from a sufficiently large set so as to make the first and last words and their dependencies stand out perceptually (Gómez 2002; Gómez & Maye 2005).

For the purposes of our sleep study, experimental groups were familiarized with strings for which the middle elements were drawn from a large set that should promote learning (set size = 24), while infants in the control group heard just as many strings, and were exposed to the nonadjacent dependencies to the same extent as the experimental groups, but were familiarized with a small set size that should not promote learning (set size = 3). The purpose of the control group was to rule out the possibility that sleep itself would result in learning in a condition that would otherwise not produce this result. Infants in the experimental and control sleep groups were scheduled at a time of day when they were likely to nap in the four-hour interval after familiarization. Infants in the experimental no-sleep group were scheduled at a time when they were not likely to nap in this interval. We visited infants in their homes, familiarizing them with the artificial language by playing it from a tape-recorder while interacting quietly with them for 15 minutes.

Infants were then tested in the lab four hours after familiarization, using the head-turn preference procedure (Kemler Nelson et al. 1995). In an earlier study, infants this age listened longer to familiar strings than to unfamiliar ones when tested immediately after familiarization (Gómez & Maye 2005), reflecting recognition of specific nonadjacent word-pairs. Thus, one possibility was that infants in the sleep group would show the same effect. On the other hand, sleep could result in a more abstract memory involving not specific first and third words per se, but rather an expectation of a more general predictive relationship holding between any first and third word. If so, infants could show a preference for the nonadjacent word-pairs encountered on the first trial of the test even when they were not the exact nonadjacent words encountered earlier, such that they would track those particular dependencies for the remainder of the test. With respect to differences between the three groups, we predicted that if time alone is instrumental in learning, both the sleep and no-sleep groups should show the same pattern of effects. However, if sleep alters learning, then performance should differ between the two conditions. On the other hand, if sleep alone is enough to alter learning apart from the set size manipulation, then the nap-control (familiarized with a set size that
typically does not result in learning) should show the same pattern of effects as the experimental sleep group.

Infants in the no-sleep group showed veridical memory for the nonadjacent dependencies, listening longer to familiar over unfamiliar trials, consistent with results found with immediate testing (Gómez & Maye 2005). Infants in the sleep group showed the rather unusual effect of listening longer to sentences consistent with the specific nonadjacent dependency they encountered on the first test trial. That is, infants hearing a legal string on the first test trial listened longer to legal strings for the remaining trials, whereas infants hearing an illegal string first listened longer to illegal strings on the remaining trials. We interpreted this pattern as infants having abstracted enough away from specific nonadjacent words that they registered the particular nonadjacent dependencies encountered on the first test trial (whether or not these were identical to the non-adjacencies from training) and then tracked these for the remainder of the test. Although unusual, this pattern was replicated with a group of infants who were originally intended for the no-sleep group but who ended up sleeping anyway (this result was also replicated in the experiment below). The control group showed no learning, ruling out the possibility that sleep alone can alter memory apart from the learning manipulation.

We next asked whether infants this age must sleep soon after learning or whether, like adults, nighttime sleep is sufficient for consolidation (Hupbach et al. 2009). We familiarized two groups with the artificial language from Gómez et al. (2006), comparing a sleep group who napped in the 4-hour interval between familiarization and test and a group who did not nap. Both groups were tested 24 hours later. Although the nap group showed generalization 24 hours later, the no-nap group showed no retention whatsoever despite the fact that both groups received equal amounts of nighttime sleep. Thus, even at 15 month of age, when many infants have graduated to taking only one nap a day, sleep fairly soon after a learning experience appears to be necessary for the retention and abstraction of novel information. The requirement for sleep may be relaxed for information that is not entirely novel, but for new information sleep appears critical.

These findings raise a number of interesting questions about the nature of abstraction relevant for language acquisition. Infants could track and learn both specific and abstract information but respond to these differentially before and after sleep. Or infants could forget specific details of the stimulus with sleep. The latter seems more likely given that infants who did not sleep immediately after test showed no memory for the artificial language 24 hours later. We are presently investigating these hypotheses using an AAB/ABA language that should result in a more straightforward test result (the effect we have reported before, where infants’ listening times are conditional on the first trial encountered at test, may

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stem from the fact that legal and illegal strings are so similar in form with only the specific non-adjacencies, but not the underlying structure, differing). Infants in our studies are familiarized with AAB or ABA strings with A and B elements instantiated in different timbres. They are then tested with visually-presented AAB and ABA shape sequences or with tones (in both cases infants must transfer knowledge of the pattern to new stimuli). If infants discriminate in the visual modality, this would suggest they have formed an amodal abstraction, but there is also evidence for modality-specific abstraction if they can transfer from timbre to musical tones.

In short, findings like these suggest that the organic process of memory consolidation is instrumental in constraining learning. In our studies so far, memory consolidation associated with sleep introduces flexibility into learning, such that infants recognize a pattern at test regardless of whether it is instantiated exactly as it was before. Sleep then sustains the learning of previously encountered information in a form that enables children to generalize to similar but not identical cases, and it also introduces flexibility into learning. The ability to abstract in this way may be particularly important for infants who need to retain key aspects of prior experience for generalizing to novel scenarios.

5. Summary

I have reviewed some key work from the research on learning as related to language acquisition. Although important inroads have been made with respect to scaling up learning in the lab to the challenges of learning a natural language, one important consideration is the role of memory in language acquisition. Prior memory plays a role in the acquisition process by shaping later learning experiences (e.g. Lany & Gómez 2008, submitted). So does the accumulation of experience with its effects on what infants can learn at different points during development (Dawson & Gerken 2009; Gerken & Bollt 2008). Changes in learning also arise from the process of memory consolidation (Gómez et al. 2006; Hupbach et al. 2009). These findings necessarily temper our understanding of learning measured by immediate tests. Not only does prior experience contribute to what infants can and cannot learn, but it is also an important factor in understanding the learning they show at different ages. When we do not take these considerations into account, we have a more superficial view of learning. And the effects we measure at test may not be the same effects that will result after memory consolidation.

One further caveat: The artificial languages used to study infant learning mechanisms are necessarily quite simple. They are not meant not to scale up to the complexity of a natural language, but rather to identify specific problems faced by language learners in a way that can provide insight into the learning mechanisms
at work. Armed with these insights, the learning mechanisms identified can be used to make predictions about learning in the context of natural languages with all the complexities they entail, much as models are used to test and clarify theories in other domains. In this way, artificial language learning can increase our understanding of the generalization required in language learning.

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