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Connecting Cues: Overlapping Regularities Support Cue Discovery in Infancy

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Abstract

The present work examined the discovery of linguistic cues during a word segmentation task. Whereas previous studies have focused on sensitivity to individual cues, this study addresses how individual cues may be used to discover additional, correlated cues. Twenty-four 9-month-old infants were familiarized with a speech stream, in which syllable-level transitional probabilities and an overlapping novel cue served as cues to word boundaries. Infants' behavior at test indicated they were able to discover the novel cue. Additional experiments showed that infants did not have a preexisting preference for specific test items, and that transitional probability information was necessary to acquire the novel cue. Results suggest one way learners can discover relevant linguistic structure amidst the multiple overlapping properties of natural language.

Connecting Cues: Overlapping Regularities Support Cue Discovery in Infancy

Natural languages exhibit structure at multiple levels in parallel (e.g., phonological, lexical, morphological, syntactic, and discourse). For the adult listener, this complexity creates temporary ambiguities that must be resolved for speech to be understood. Individual bits of information are imprecise, such as the meaning of words like *bow*, *colon*, *saw*, and *wave*. Such ambiguities are resolved via a constraint satisfaction process that exploits correlations among different types of information (MacDonald, Pearlmutter, & Seidenberg, 1994). While individual cues are often unreliable, combinations of cues are not. The principal characteristic of the constraint satisfaction process is that it allows learners to utilize the correlations of cues. For example, the word *saw* has several meanings (related to seeing, cutting, a tool for cutting, etc.) and is thus highly ambiguous in isolation. Embedded within an utterance such as "I saw you", "I" restricts its interpretation to verbs. The object "you" further restricts the interpretation to the "seeing" meaning, since a person is more likely to be seen than sawed, though the result might differ if the context were a magic show. Similarly, hearing *saw* in a hardware store suggests the noun interpretation of *saw* as a tool. Rapid on-line comprehension is possible because of our ability to exploit constraints between different types of information (Seidenberg & MacDonald, 1999).

While studies of adult language have investigated how constraints are combined to resolve ambiguities, studies of language acquisition have examined how children use statistical cues to learn their native language. These are complementary issues, the "constraints" that are relevant to adult listeners are the "cues" by which the child acquires language (Seidenberg, 1997). Seminal work by Saffran, Aslin & Newport (1996) showed that 8-month-olds are sensitive to the transitional probability (TP) between two syllables (the frequency of the two

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syllables divided by the frequency of the first syllable) when listening to a fluent stream of speech. This study, and the large body of work that has followed it, suggest that infants are sensitive to statistical regularities that exist in natural languages, and can use them to learn aspects of their native language.

Experiments investigating language acquisition via statistical learning have typically focused on infants' abilities to use one statistical cue at a time (e.g., Curtin, Mintz, & Christiansen, 2005; Saffran et al., 1996). However, natural speech is complex, containing overlapping regularities at multiple levels. For the language learner, this presents a difficult problem: how are these cues discovered? There are many ways speech can be analyzed; how does the child determine which aspects of the input are relevant? Moreover, the fact that any given bit of information may contribute to multiple levels of analysis (e.g., */b/* is the first sound in the word *baby*; the beginning of the first syllable; receives primary stress making it louder and longer; the transition point between the words *the baby*, and so on) creates a difficult learning problem. The complexity of this learning problem is sometimes thought to severely limit the explanatory role played by statistical learning in language acquisition (Yang, 2004).

Alternatively, the constraint satisfaction approach suggests that the complexity of natural language provides a rich system for learning mechanisms to exploit. Linguistic regularities reinforce each other across levels, allowing statistical learning mechanisms to capitalize on multiple cues and redundancies. For example, lexical stress patterns are found in numerous languages of the world. These patterns consist of a specific ordering of strong and weak syllables that occur frequently and can help identify word boundaries or classify groups of words. In English, many words have a trochaic, or strong-weak, stress pattern, as in the words *BAby* and *MOmmy* (Cutler & Carter, 1987). In other languages it is more common for words to have an iambic (weak-strong) stress pattern, as in the word *guiTAR*. And in some languages stress cannot be used to group syllables or identify word boundaries at all. Because these cues vary from language to language, they must be learned. How then does the infant discover that stress patterns are informative? Strong regularities like lexical stress overlap with other regularities at multiple levels, highlighting and reinforcing their utility. The acoustic regularities (i.e., higher pitch, longer duration and increased volume) of stressed syllables can draw attention to the beginning of trochaic words. Distributional cues, such as the overrepresentation of trochaic items in speech to English-learning children, ensure that young language-learners have plenty of exposure to the pattern. Together these regularities can enhance the accessibility of the lexical stress pattern.

Psycholinguistic studies support the hypothesis that infants are sensitive to the conjunction of multiple probabilistic cues (Gerken, Wilson, & Lewis, 2005; Shi, Werker, & Morgan, 1999). Additionally, studies of infant categorization and conceptual development demonstrate that the natural environment provides infants with a multitude of correlated cues that they are able to exploit (e.g., Bhatt, Wilk, Hill, & Rovee-Collier, 2004; Madole, Oakes, & Cohen, 1993; Rakison, 2004; Younger, 1992; Younger & Cohen, 1986). Finally, connectionist models have shown that simple learning mechanisms that capitalize on structure within a complex system can exploit multiple correlated cues that exist in the infants' world. Computational models have demonstrated how problems such as finding word boundaries (Christiansen, Allen, & Seidenberg, 1998), generating properly inflected forms (Joanisse & Seidenberg, 1999; Mirkovic, MacDonald, & Seidenberg, 2005), and grouping common objects into categories (Rogers & McClelland, 2004) can be solved using multiple cues.

Despite this progress, it remains to be determined how language learners isolate and combine cues given the complexity of human language. In considering this problem, it is helpful to distinguish between two classes of potentially useful cues: language-general cues and language-specific cues. Measures of co-occurrence or predictability between syllables are language-general cues, in that they operate in similar ways across natural languages. For example, transitional probabilities are not specific to any given language (though the units over which these computations are performed are).

Other cues may or may not be useful in any given language and are thus language-specific, and must be learned. For example, languages have different lexical stress patterns (iambic vs. trochaic), and in some languages stress patterns do not mark boundaries or help individual units cohere. By 9 months of age, infants typically show sensitivity to a range of language-specific cues (for a recent review, see Saffran & Sahni, in press).

In the domain of word segmentation, previous work suggests that younger infants tend to use language-general cues and later shift to language-specific cues (Thiessen & Saffran, 2003). In a segmentation study using a nonsense language, TPs, a language-general cue operating over novel syllable combinations, were placed in conflict with the language-specific stress pattern of English. Six and a half month-olds segmented the fluent speech using the language-general strategy of relying on TPs. In contrast, infants who were two months older used language-specific lexical stress patterns (also see Johnson & Jusczyk, 2001). This shift suggests that over time, infants become more sensitive to idiosyncratic cues, learning which regularities are relevant (and, presumably, which are not) for their native language. However, little is known about how this process unfolds.

How might infants discover these language-specific cues? One potential explanation is that language-general cues provide a basis for discovering overlapping or co-occurring language-specific cues. For example, in word segmentation, infants may use their sensitivity to TP cues, which is present early in life (Kirkham, Slemmer, & Johnson, 2002; Teinonen, Fellman, Naatanen, Aklu, & Huotilainen, 2009), to discover language specific cues that are correlated with TPs.

The present work tested the hypothesis that infants can discover novel cues by exploiting redundancies between language-general and language-specific cues. Nine-month-old infants were exposed to a fluent speech stream that contained two overlapping cues to word boundaries: a language-general cue (TPs) and a language-specific cue (*/t/*-onsets). TPs are known to be salient to 9-month-old infants. The second cue was specific to the artificial language and therefore novel: each word in the speech stream began with */t/*. Experiment 1 was thus designed to test the hypothesis that infants can use the language-general TP cue to discover the overlapping language-specific */t/*-onset cue. The */t/*-initial syllables are only informative as a cue to word boundaries due to their overlap with the TP cue; the TP cue positions the */t/*-initial syllable at the onset of each word. Consequently, the only way infants can extract this pattern is to use its overlap with the TP cue. We tested infants using items that were all novel relative to the exposure corpus, but which varied in their use of the */t/*-onset cue. The question of interest was whether infants would be sensitive to the presence of */t/*-onsets in the test items. If so, this would provide evidence that infants can isolate individual cues by using redundancies in the speech stream.

Experiment 1

To examine whether infants can use a language-general segmentation cue to discover an overlapping novel language-specific cue, infants heard a fluent speech stream that contained two overlapping cues to word boundaries: (1) dips in TPs at word boundaries, and (2) */t/*-initial syllables at word onsets. To determine whether infants acquired the novel */t/*-onset pattern, test items either adhered to the pattern (began with a */t/*-syllable) or violated it (contained a medial */t/*). Crucially, these items were previously unheard combinations of syllables from the speech stream (i.e., TP = 0). Therefore, TP information would not allow infants to distinguish between the two types of test items. Instead, successful discrimination hinged on discovery of the */t/*-initial pattern present in the speech stream played during familiarization.

Method

Participants—Twenty-four 9.5-month-old monolingual English-learning infants (mean age 9.5 months, range 9.0-10.0) participated in this experiment. All infants were born full-term and had fewer than 4 prior ear infections and no history of hearing or vision impairments. Data from an additional 8 infants were excluded due to fussiness (4) and parents stopping the experiment (4).

Stimuli—A fluent stream of speech was created from recordings of a female native English speaker who was blind to the structure of the artificial language. The language contained 6 bisyllabic words: *tohsigh*, *teemay*, *tiepu*, *tukee*, *tayla*, *tafo*. A pseudosynthesis technique was used to create the speech stream, which allowed for use of naturally produced syllables while permitting control over co-articulation, duration, pitch and volume of all syllables in the language. All three-syllable sequences that occurred in the language, both within and between word boundaries (e.g., *tohsightee*, *sighteemay*), were recorded in a monotone, isochronous register. Medial syllables were spliced out of the three syllable sequences and concatenated together with no silence between syllables. By using these medial syllables, co-articulation within each syllable and between every pair of syllables in the language was maintained. Syllables were edited prior to concatenation to have the same duration, pitch and volume. The stream contained 40 repetitions (2 min 17 sec) of each word in a pseudo-random order with no word appearing twice in succession (see the Appendix for a transcript of the complete familiarization language). Each within-word syllable pair had a TP of 1.0; between-word syllable pairs had a TP between .1 and .25 (mean = .20). The speech stream thus contained two overlapping, and completely redundant cues to word boundaries: dips in TPs and */t/*-onsets.

Four novel test items were constructed from syllables in the artificial language. Two of these items began with */t/* (*tiemay*, *tohla*), and two contained a medial */t/* (*fota*, *keetu*). Test items were created from recordings of each bisyllabic item spoken in isolation. Duration, pitch and volume were edited so that all test items were essentially equivalent.

Procedure—During familiarization, infants listened to the speech stream at a comfortable volume, played over speakers mounted on each sidewall while viewing an unrelated Baby Einstein video. An experimenter then entered the booth, covered the monitor that displayed the video, and placed headphones playing masking music on the caregiver. The test phase began with 2 practice trials (a recording of piano tones), designed to help the infants learn the contingency between their head-turns and the lights/sounds. The practice trials were followed by 12 test trials, 3 blocks of each of the 4 test items (*tiemay*, *tohla*, *fota*, *keetu*). Infants' ability to discriminate the test items was assessed using the Headturn Preference Procedure (Kemler Nelson et al., 1995). The experimenter was seated outside the booth, observing the infants' head turns on a closed circuit TV, and controlling the experiment via custom software. Lights were mounted on the center wall (directly facing the infant) and sidewalls. Each trial began with the center light blinking. Once the infant fixated on the light, it was extinguished and one of the sidelights began to blink. When the infant fixated on the blinking sidelight a sound was played from the speaker below the light. On each test trial, an item was repeated until the infant looked away for at least 2 sec, or until the item had repeated15 times. If the infant failed to fixate on the side light for at least 1 sec during a test trial, the trial was excluded and an additional trial of that test item was automatically added after the third test block.

Results

We tested infants' ability to discriminate /t/-initial from /t/-medial test items over the three blocks of testing with a 2 (test item type: /t/-initial vs. /t/-medial) × 3 (test block: 1, 2, 3) repeated-measures ANOVA (means shown in Table 1). The main effect of test item type (/t/-initial vs. /t/-medial) was not significant [$F(1, 23) = .975$, $p = .33$]. The assumption of sphericity was violated for the type by block interaction term (Mauchly's W =.687) and so multivariate analyses were used to evaluate the significance of the interaction. With a large violation of sphericity (i.e., when Mauchly's W < .7) the statistical power of multivariate techniques tends to be greater than univariate techniques (Keppel, 1991;Mendoza, Toothaker, & Nicewander, 1974). There was a significant interaction between test item type and block [$F(2, 22) = 8.15$, $p = 0.002$]. As shown in Figure 1, the significant interaction reflects a reversal in the direction of preference over the course of testing. The familiarity preference present in the first two test blocks shifts to a novelty preference in the third block. Block interactions and shifts in direction of preference have been previously observed elsewhere in the literature (Gerken et al., 2005), but are not often discussed.

Subsequent analyses focused on the first two blocks (8 test trials), as these looking times are more proximal to the familiarization phase, and thus most likely to reflect learning from the fluent speech. A one-way (test item type: /t/-initial vs. /t/-medial) repeated-measures ANOVA revealed a significant difference in looking times to the two types of items [$F(1, 23) = 6.30$, $p = .02$] (see Figure 2). Infants looked longer to the /t/-initial test items, which adhered to the pattern presented during familiarization. Recall that the TPs between syllables in the test items were all zero. Thus, infants could not have discriminated /t/-initial from /t/-medial test items based on TP cues. These results suggest that infants learned the /t/-initial pattern, and generalized it to include the novel test items.

Discussion

The results of Experiment 1 suggest that infants were able to exploit the /t/-initial pattern, successfully discriminating novel test items that followed the pattern from those that did not. This pattern was not immediately obvious in the input; the speech stream consisted of syllables beginning with /t/ alternating with syllables that began with other sounds. In order to discover that the /t/ segment signaled word onsets, infants presumably capitalized on the TP cues in the speech stream, which also provided cues to word boundaries. On this view, infants discovered the language-specific /t/-onset cue by capitalizing on the language-general TP cue.

One interesting feature of these data is that infants' looking behavior changed over the course of testing. Familiarity to novelty preference switches are not uncommon in infant behavioral studies, though the factors responsible for the shift may vary (Fantz, 1964; Hunter, Ames, & Koopman, 1983). The test items used in this study consisted of novel combinations of syllables from the familiarization language. This introduction of novel items at test forces infants to generalize beyond the training corpus, making it more likely that participants will show a familiarity preference at the outset of testing (e.g. Thiessen & Saffran, 2003). However, during the course of testing, infants received differential amounts of exposure to the test items. Figure 3 depicts the difference in looking times to /t/-initial and /t/-medial test items across the three test blocks. Initially, infants looked longer to /t/-initial items, thus receiving more exposure to them than to the /t/-medial items. This pattern of listening during testing may have led the infants to become bored with these items, moving them toward a novelty preference. To test this hypothesis, we examined individual participants' looking preferences across the testing session. Fifteen of 24 participants showed an initial familiarity preference that transitioned into a novelty preference, 5 showed an initial familiarity preference that remained a familiarity preference, and 4 showed an initial novelty preference that remained a novelty preference. A majority of participants showed the predominant pattern of increased exposure to the */t/*-initial items in the first two blocks with a novelty preference in the third block. A chi-square test confirmed that this pattern of behavior would not be expected by chance (x^2=20.3, df=3, p=.0001). This pattern of results suggests that while infants' initial test responses were linked to learning during the familiarization phase, the novelty preference in Block 3 may have reflected infants' experiences during testing.

The findings from Experiment 1 support the hypothesis that infants used low TPs at word boundaries to acquire the overlapping but novel */t/*-onset pattern. However, there is an alternate explanation for these results: it is possible that infants' behavior reflected pre-existing preferences for individual items. A counter-balanced language composed of items that all contain a medial */t/* would clarify this issue. However, previous work (Endress, Scholl, & Mehler, 2005) has shown that it may be easier to generalize from patterns that occur at the edges of sequences, as opposed to those occurring medially. Consequently, the two counterbalanced languages might not be equally learnable. A second experiment tested this possibility with a new group of infants, who participated only in the test phase of the experiment. If infants in Experiment 1 had an a priori preference for the */t/*-initial test items, infants in Experiment 2 should show a similar pattern of behavior. If infants in Experiment 2 do not show a similar pattern, this would suggest that exposure to familiarization materials that contained the two overlapping cues was necessary to elicit the preference for */t/*-initial test items.

Experiment 2

This experiment was designed to test the hypothesis that infants in Experiment 1 listened longer to the */t/*-initial test items due to an a priori preference for these particular items. Infants in Experiment 2 were not exposed to the familiarization speech stream, participating only in the testing procedure used in Experiment 1.

Method

Participants—Twenty-four 9.5-month-old monolingual English-learning infants (mean age 9.5 months, range 9.0-9.9) participated. Data from an additional 5 infants were excluded from the analyses because of experimenter error (1), fussiness (2), failure to contribute at least 2 trials for each item (1), and mean looking time to one or both sides less than 3 sec (1).

Stimuli—The test items were the same as those used in Experiment 1.

Procedure—There was no exposure phase. The testing procedure was identical to Experiment 1, with 2 practice trials followed by 12 test trials.

Results & Discussion

As in Experiment 1, a 2 (test item type: */t/*-initial vs. */t/*-medial) × 3 (test block: 1, 2, 3) repeated-measures ANOVA was conducted. There was no significant effect of test item type (*/t/*-initial vs. */t/*-medial) [$F(1, 23) = .081$, $p = .78$], nor was the interaction between block and test item type significant [$F(2, 46) = .35$, $p = .70$] (see Table 1 and Figure 3). These results indicate that infants in Experiment 2 did not discriminate between */t/*-initial and */t/*-medial test items.

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We next conducted a 2 (test item type: /t/-initial vs. /t/-medial) × 2 (group: Experiment 1, Experiment 2) repeated-measures ANOVA over the data from the first two test blocks from Experiments 1 and 2. This analysis was intended to determine whether the behavior of infants differed reliably across the two experiments. The interaction between test item type and group was significant [$F(1, 46) = 6.19$, $p = .017$], suggesting that infants who heard the familiarization materials showed a different pattern of behavior at test than those who did not (see Figure 2).

This between-group analysis, coupled with the within subject analysis showing no effect of test item type, indicates that infants in Experiment 2 did not have an a priori preference for the /t/-initial items relative to the /t/-medial items. We can therefore attribute infants' behavior in Experiment 1 to familiarization with the fluent speech stream. Nevertheless, it is still unclear which aspects of the familiarization stimuli elicited infants' successful discrimination between /t/-initial and /t/-medial test items. It is possible that, as originally hypothesized, low TPs at word boundaries anchor the alternating /t/ syllables, allowing infants to extract the /t/-onset cue and generalize it to the novel test items. Another possibility is that infants are extracting the extremely regular alternating /t/ syllable pattern (created because each of the bisyllabic words begins with a /t/) and uniformly mapping the /t/ syllable to word onsets. According to this alternative hypothesis, infants could capitalize on a systematic pattern (/t/-onsets) without the aid of another cue. On this account, they detect the regular alternation and map it onto onsets, potentially because onsets are privileged perceptually and/or lexically (e.g., Brent & Cartwright, 1996; Jusczyk, Jusczyk, Kennedy, Schomberg, & Koenig, 1995; Magnuson, Dixon, Tanenhaus, & Aslin, 2007; Marslen-Wilson & Zwitserlood, 1989).

To explore this hypothesis, we designed a new speech stream to determine whether infants could extract the novel /t/-onset pattern without the aid of another cue for bootstrapping. The resulting speech stream did not have low TPs at word boundaries, but still contained the /t/-onset pattern. If infants can extract the /t/-onset pattern without an overlapping cue, infants in Experiment 3 should show a significant difference in looking time to /t/-initial items compared to /t/-medial items. However, if TPs played a critical role in the discovery of the novel pattern via bootstrapping, infants should not show a significant difference in looking time to /t/-initial items compared to /t/-medial items in the absence of TP cues.

Experiment 3

This experiment was designed to determine whether the overlapping cue from Experiment 1, low TPs at word boundaries, was necessary for infants to acquire the novel /t/-onset pattern. Infants were exposed to a new fluent speech stream that did not have low TPs at word boundaries, but still contained the novel /t/-onset pattern. The procedure and test items were identical to Experiment 1.

Method

Participants—Twenty-four 9.5 month-old monolingual English learning infants (mean age 9.5 months, range 9.1-10.0) participated in this experiment. Data from an additional 17 infants were excluded from the analyses because of parental interference (5), sleepiness (1), external noise (1), fussiness (7), and failure to contribute at least 1 trial for each item type in every block (3).

Stimuli—A fluent speech stream was created using the procedure and words (*tohsigh, teemay, tiepu, tukee, tayla, tafo)* from Experiment 1. Again, all syllables in the language were measured and edited such that duration, pitch and volume were equivalent for all syllables. Unlike Experiment 1, in which words were repeated in a random order, the words in this fluent speech stream were repeated in exactly the same order 40 times (teemaytieputukeetafotaylatohsigh**teemaytieputukeetafotaylatohsigh**...)(see Curtin et al., 2005 for another example of this method). This method generated a 2 min 7 sec stream in which every pair of syllables had a transitional probability of 1.0 and every other syllable in the language began with a */t/*. The test items were identical to those in Experiment 1 and 2 (*tiemay, tohla, fota, keetu*).

Procedure—The experimental procedure was the same as Experiment 1.

Results & Discussion

As in the previous experiments, we first ran a 2 (test item type: */t/*-initial vs. */t/*-medial) × 3 (test block: 1, 2, 3) repeated-measures ANOVA. There was no significant effect of test item type [$F(1, 23) = .07$, $p = .80$], and the interaction with block was not significant [$F(1, 23) = .27$, $p = .61$] (see Table 1 and Figure 3). This pattern of results indicates that infants did not differentiate between */t/*-initial and */t/*-medial test items in the absence of the TP cue. We next ran a 2 (test item type: */t/*-initial vs. */t/*-medial) × 2 (group: Experiment 1, Experiment 3) repeated-measures ANOVA contrasting the data from the first two test blocks of Experiments 1 and 3. This test item type by group interaction did not reach significance [$F(1, 46) = 2.87$, $p = .20$] (see Figure 2).

Though the between-group analysis is inconclusive, infants' failure to discriminate the test items in Experiment 3 is consistent with the hypothesis that infants were influenced by the presence of TP cues in Experiment 1. Without the low TPs at word boundaries to anchor the alternating */t/* syllables to segment onsets, infants seem unable to extract the novel pattern.

General Discussion

The results of these experiments indicate that infants are able to use a language-general regularity (dips in TPs at word boundaries) to discover a second, language-specific regularity (*/t/*-onsets). Moreover, infants generalized this newly learned cue to novel items, as demonstrated by their test performance. These findings suggest one possible class of solutions to the learning problem described earlier: How do infants discover relevant linguistic cues when there are many way to analyze speech and a single bit of information can be informative at multiple levels? Just as adults use correlations among cues to resolve ambiguities when using language, infants are able to use such correlations to acquire language, as suggested by the constraint satisfaction approach. Thus infants' learning capacities, such as the ability to encode correlations across different types of information (Rose & Ruff, 1987), seem well-matched to properties of natural language. What seems initially to be an insurmountable barrier to learning—the fact that elements of language contribute to multiple levels of structure simultaneously – actually helps solve the language acquisition problem (see Hirsh-Pasek, Golinkoff, Hennon, & Maguire, 2004 for a similar example in word learning).

Research over the past decade has shown that infants are sensitive to many different patterns that can be informative for language learning. It remains unclear, however, how infants find individual cues and combine different types of information to understand the complex structure of their language. Behavioral research on multiple cue usage in this domain has typically taken the form of cue-conflict studies, examining relative reliance on different types of information over time (e.g., Johnson & Jusczyk, 2001; Mattys, Jusczyk, Luce, & Morgan, 1999; Thiessen & Saffran, 2003). Although studies using this approach have been quite revealing, they cannot address how infants may capitalize on the redundancies in natural speech or how cues are discovered. More recent research has focused on the use of multiple probabilistic patterns to categorize lexical items (Gerken et al., 2005; Gómez &

Lakusta, 2004; Shi et al., 1999). Results from the present work demonstrate that the complexity of natural speech does not necessarily hinder language acquisition, but in fact may facilitate learning. Paradoxically, complexity may help learning – as long as the complexity is consistent with the structure to be acquired (Morgan, Meier, & Newport, 1987, 1989).

The process observed in the present work is reminiscent of bootstrapping: partial information about one element of language provides evidence about another element, which in turn provides further evidence for the first element (Gleitman & Wanner, 1982). On this view, the infant begins to pick up on TPs, facilitating discovery of the */t/*-onset cue, which in turn may further the consolidation of the TP cue. Both the TPs and the */t/*-onset cue provided evidence about the boundaries between words in the fluent speech stream. The */t/* cue is different, insofar as its discovery depended on some prior learning about TPs. We are not claiming that TPs or any specific regularity is necessary for this process to operate. Rather, any cues that infants can use to extract linguistic structure, and that overlap with other discoverable patterns, should be available for use in this fashion. This is an area where computational models of bootstrapping mechanisms would be informative. Existing models have typically built in different types of regularities, focusing on how combinations of given regularities can yield better learning outcomes than individual regularities (Christiansen et al., 1998; Shi, Morgan, & Allopenna, 1998). Models of how the cues themselves are identified, and the dependencies between them in learning, would be very timely.

This work shows that infants can use the overlapping nature of speech to isolate cues. Language-general regularities, such as TPs, may support the discovery of language-specific cues. Critically, the present research also expands the scope of statistical learning mechanisms. Not only can infants use such mechanisms to exploit the structure of their language, but they can also use statistical learning to **discover** the structure of their native language.

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Appendix Transcript of speech stream from Experiment 1

teemaytohsighteemaytukeetafotieputaylatohsightaylatukeeteemaytieputaylateemaytuk
eeteemaytohsightukeetafoteemaytukeetohsighteemaytohsighteemaytohsightafoteemayt
afotohsightukeetieputukeetieputafoteemaytieputohsightieputafoteemaytafotaylatohsig
htaylatafotohsightieputafotieputohsighteemaytafotieputaylateemaytieputaylatohsighte
emaytaylatafotukeetafoteemaytieputaylatieputafotukeetohsightaylatafotukeetohsightee
maytafotaylatieputafoteemaytukeetafotohsightieputafotaylatieputeemaytieputukeetayl
atieputukeetaylatieputohsightieputohsightafotaylatukeetaylatafotukeetafotukeetafotee
maytaylateemaytukeeteemaytohsighteemaytieputukeetohsighteemaytafotaylatafotaylat
eemaytaylatukeetieputukeetieputafotieputaylateemaytukeeteemaytieputaylatohsightay
latukeetohsightafotieputafotukeetohsightukeetieputaylatieputukeeteemaytaylatohsight
ukeetohsightaylatukeetohsightaylatieputeemaytafotaylatafoteemaytukeetafotieputaylat
ohsightafotaylatukeetohsightukeetafotaylateemaytukeetieputohsightukeetaylatohsighti
eputafotukeetieputohsightafotieputohsightafoteemaytukeetieputaylateemaytieputafota
ylatohsightaylateemaytohsighteemaytohsightukeeteemaytohsightukeetaylatohsightuke

etohsightukeeteemaytafotohsightaylateemaytafotieputukeetaylatukeetaylateemaytieput
eemaytieputohsightafotieputeemaytaylatohsightafotiepu

References

Bhatt RS, Wilk A, Hill D, Rovee-Collier C. Correlated attributes and categorization in the first half-year of life. Developmental Psychobiology. 2004; 44:103–115. [PubMed: 14994261]

Brent MR, Cartwright TA. Distributional regularity and phonotactic constraints are useful for segmentation. Cognition. 1996; 6:93–125. [PubMed: 8990969]

Christiansen MH, Allen J, Seidenberg MS. Learning to segment speech using multiple cues: A connectionist model. Language and Cognitive Processes. 1998; 13:221–268.

Curtin S, Mintz TH, Christiansen MH. Stress changes the representational landscape: Evidence from word segmentation. Cognition. 2005; 96:233–262. [PubMed: 15996560]

Cutler A, Carter DM. The predominance of strong initial syllables in the English vocabulary. Computer Speech and Language. 1987; 2:133–142.

Endress AD, Scholl BJ, Mehler J. The role of salience in the extraction of algebraic rules. Journal of Experimental Psychology: General. 2005; 134:406–419. [PubMed: 16131271]

Fantz RL. Visual experience in infants: Decreased attention to familiar patterns relative to novel ones. Science. 1964; 146:668–670. [PubMed: 14191712]

Gerken L, Wilson R, Lewis W. Infants can use distributional cues to form syntactic categories. Journal of Child Language. 2005; 32:249–268. [PubMed: 16045250]

Gleitman, LR.; Wanner, E., editors. Language acquisition: the state of the art. Cambridge University Press; New York: 1982.

Gómez RL, Lakusta L. A first step in form-based category abstraction by 12-month-old infants. Developmental Science. 2004; 7:567–580. [PubMed: 15603290]

Hirsh-Pasek, K.; Golinkoff, RM.; Hennon, E.; Maguire, MJ. Hybrid theories at the frontier of developmental psychology: The emergentist coalition model of learning as a case in point.. In: Hall, DG.; Waxman, SR., editors. Weaving a lexicon. MIT Press; Cambridge, MA: 2004. p. 173-204.

Hunter MA, Ames EW, Koopman R. Effects of stimulus complexity and familiarization time on infant preferences for novel and familiar stimuli. Developmental Psychology. 1983; 19:338–352.

Joanisse MF, Seidenberg MS. Impairments in verb morphology following brain injury: A connectionist model. Proceedings of the National Academy of Sciences of the United States of America. 1999:7592–7597. [PubMed: 10377460]

Johnson EK, Jusczyk PW. Word segmentation by 8-month-olds: When speech cues count more than statistics. Journal of Memory and Language. 2001; 44:548–567.

Jusczyk PW, Jusczyk AM, Kennedy LJ, Schomberg T, Koenig N. Young infants’ retention of information about bisyllabic utterances. Journal of Experimental Psychology: Human Perception and Performance. 1995; 21:822–836. [PubMed: 7643050]

Kemler Nelson DG, Jusczyk PW, Mandel DR, Myers J, Turk A, Gerken L. The head-turn preference procedure for testing auditory perception. Infant Behavior & Development. 1995; 18:111–116.

Keppel, G. Design and analysis: A researcher's handbook. 3rd ed.. Prentice-Hall, Inc.; Englewood Cliffs, NJ: 1991.

Kirkham NZ, Slemmer JA, Johnson SP. Visual statistical learning in infancy: Evidence for a domain general learning mechanism. Cognition. 2002; 83:B35–B42. [PubMed: 11869728]

MacDonald MC, Pearlmutter NJ, Seidenberg MS. The lexical nature of syntactic ambiguity resolution. Psychological Review. 1994; 101:676–703. [PubMed: 7984711]

Madole KL, Oakes LM, Cohen LB. Developmental changes in infants’ attention to function and form-function correlations. Cognitive Development. 1993; 8:189–209.

Magnuson JS, Dixon JA, Tanenhaus MK, Aslin RN. The dynamics of lexical competition during spoken word recognition. Cognitive Science. 2007; 31:133–156. [PubMed: 21635290]

Marslen-Wilson W, Zwitserlood P. Accessing spoken words: The importance of word onsets. Journal of Experimental Psychology: Human Perception and Performance. 1989; 15:576–585.

Mattys SL, Jusczyk PW, Luce PA, Morgan JL. Phonotactic and prosodic effects on word segmentation in infants. Cognitive Psychology. 1999; 38:465–494. [PubMed: 10334878]

Mendoza JL, Toothaker LE, Nicewander WA. A Monte Carlo comparison of the univariate and multivariate methods for the two-way repeated measure design. Multivariate Behavioral Research. 1974; 9:165–178.

Mirkovic J, MacDonald MC, Seidenberg MS. Where does gender come from? Evidence from a complex inflectional system. Language and Cognitive Processes. 2005; 20:139–167.

Morgan JL, Meier RP, Newport EL. Structural packaging in the input to language learning: Contributions of prosodic and morphological marking of phrases to the acquisition of language. Cognitive Psychology. 1987; 19:498–550. [PubMed: 3677585]

Morgan JL, Meier RP, Newport EL. Facilitating the acquisition of syntax with cross-sentential cues to phrase structure. Journal of Memory and Language. 1989; 28:360–374.

Rakison DH. Infants' sensitivity to correlations between static and dynamic features in a category context. Journal of Experimental Child Psychology. 2004; 89:1–30. [PubMed: 15336916]

Rogers, TT.; McClelland, JL. Semantic cognition: A parallel distributed processing approach. MIT Press; Cambridge, MA: 2004.

Rose, SA.; Ruff, HA. Cross-modal abilities in human infants.. In: Osofsky, JD., editor. Handbook of Infant Development. 2nd ed.. John Wiley & Sons; Oxford, England: 1987. p. 318-362.

Saffran JR, Aslin RN, Newport EL. Statistical learning by 8-month-old infants. Science. 1996; 274:1926–1928. [PubMed: 8943209]

Saffran, JR.; Sahni, SD. Learning the sounds of language.. In: Joanisse, M.; Spivey, M.; McCrae, K., editors. Cambridge Handbook of Psycholinguistics. Cambridge University Press; Cambridge, MA: in press

Seidenberg MS. Language acquisition and use: Learning and applying probabilistic constraints. Science. 1997; 275:1599–1603. [PubMed: 9054348]

Seidenberg MS, MacDonald MC. A probabilistic constraints approach to language acquisition and processing. Cognitive Science. 1999; 23:569–588.

Shi R, Morgan JL, Allopenna P. Phonological and acoustic bases for earliest grammatical category assignment: A cross-linguistic perspective. Journal of Child Language. 1998; 25:169–201. [PubMed: 9604573]

Shi R, Werker JF, Morgan JL. Newborn infants' sensitivity to perceptual cues to lexical and grammatical words. Cognition. 1999; 72:B11–21. [PubMed: 10553673]

Teinonen T, Fellman V, Naatanen R, Aklu P, Huotilainen M. Statistical language learning in neonates revealed by event-related brain potentials. BMC Neuroscience. 2009; 10:21. [PubMed: 19284661]

Thiessen ED, Saffran JR. When cues collide: Use of stress and statistical cues to word boundaries by 7- to 9-month-old infants. Developmental Psychology. 2003; 39:706–716. [PubMed: 12859124]

Yang CD. Universal Grammar, statistics or both? Trends in Cognitive Sciences. 2004; 8:451–456. [PubMed: 15450509]

Younger BA. Developmental change in infant categorization: The perception of correlations among facial features. Child Development. 1992; 63:1526–1535. [PubMed: 1446567]

Younger BA, Cohen LB. Developmental change in infants' perception of correlations among attributes. Child Development. 1986; 57:803–815. [PubMed: 3720405]

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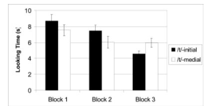

Figure 1.
Experiment 1: Mean looking times to */t/*-initial and */t/*-medial test items for each test block.

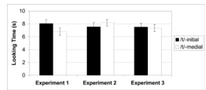

Figure 2.
The average looking time for */t/*-initial and */t/*-medial items across test blocks 1 and 2 for all three experiments.

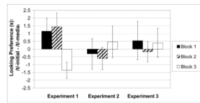

Figure 3.

The difference between looking times to */t/*-initial and */t/*-medial test items, for each block for all three experiments. Positive values indicate a familiarity preference; negative values indicate a novelty preference.

Table 1

Mean and Standard Errors for Looking Times

	Experiment 1		**Experiment 2**		**Experiment 3**	
	***/t/*-initial**	***/t/*-medial**	***/t/*-initial**	***/t/*-medial**	***/t/*-initial**	***/t/*-medial**
Block 1	8.69 (.80)	7.54 (.70)	8.44 (.88)	8.75 (.70)	8.30 (.96)	7.75 (.66)
Block 2	7.45 (.71)	6.02 (.75)	7.00 (.57)	7.56 (.70)	6.77 (.56)	6.95 (.68)
Block 3	4.58 (.39)	5.94 (.56)	6.79 (.68)	6.32 (.79)	7.18 (.85)	6.77 (.73)
Blocks 1 & 2 (averaged)	8.07 (.58)	6.78 (.59)	7.57 (.60)	8.18 (.53)	7.53 (.58)	7.35 (.55)
All Trials (averaged)	6.92 (.46)	6.53 (.46)	7.40 (.51)	7.52 (.48)	7.31 (.39)	7.09 (.50)