

meanings are altogether different. Traditional theories of sentence comprehension have assumed that the mind treats sentences in a rather algorithmic fashion, meaning that words are evaluated for the potential part of speech they might play in the sentence, and the best match is determined by a set of rules for syntactic assignment. In "Good-enough Representations in Language Comprehension," Ferreira, Bailey, and Ferraro review recent research that offers a different interpretation. Sentence syntax is one source of information to help derive meaning from a sentence, but there are others, such as context. People may only process syntax to the point that they are satisfied that they have derived a meaning that is sensible. Surprisingly, when it becomes clear that this meaning is incorrect, the old meaning seems to persist, along with the new, correct meaning.

Even if we fully understood how sentences are comprehended, we still would not have a complete account of language. Research shows that when we read a story, for example, we keep track of what is happening in the story. This representation is called a situation model. For example, if we are told that a character is in her apartment, we note that fact, and if we are later told that she goes down a stairway to the basement of the building, we update the situation model to reflect her new location. In "Situation Models: The Mental Leap into Imagined Worlds," Zwaan reviews the basic components of a story that are maintained in the situation model, and also presents evidence that the reader sees him or herself as being *in* the narrative; when our hero goes downstairs to the basement, we go with her.

The four articles in this section offer the latest perspectives on the cognitive processes that support language; however, they also offer a perspective on a large-scale issue of enduring interest: is language innate or learned? Most any researcher would argue that the answer must be "both"; we learn language, but are biologically prepared to do so, and the relative importance of learning and innateness varies with different aspects of language. Nevertheless, it's worth noting that two of the articles in this section—Saffran and Landauer—show the power of relatively simple learning processes that focus on key information in the environment, and accrue learning over the long term.

Statistical Language Learning: Mechanisms and Constraints

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Abstract

What types of mechanisms underlie the acquisition of human language? Recent evidence suggests that learners, including infants, can use statistical properties of linguistic input to discover structure, including sound patterns, words, and the beginnings of grammar. These abilities appear to be both powerful and constrained, such that some statistical patterns are more readily detected and used than others. Implications for the structure of human languages are discussed.

Keywords

language acquisition; statistical learning; infants

Imagine that you are faced with the following challenge: You must discover the underlying structure of an immense system that contains tens of thousands of pieces, all generated by combining a small set of elements in various ways. These pieces, in turn, can be combined in an infinite number of ways, although only a subset of those combinations is actually correct. However, the subset that is correct is itself infinite. Somehow you must rapidly figure out the structure of this system so that you can use it appropriately early in your childhood.

This system, of course, is human language. The elements are the sounds of language, and the larger pieces are the words, which in turn combine to form sentences. Given the richness and complexity of language, it seems improbable that children could ever discern its structure. The process of acquiring such a system is likely to be nearly as complex as the system itself, so it is not surprising that the mechanisms underlying language acquisition are a matter of long-standing debate. One of the central focuses of this debate concerns the innate and environmental contributions to the language-acquisition process, and the degree to which these components draw on information and abilities that are also relevant to other domains of learning.

In particular, there is a fundamental tension between theories of language acquisition in which learning plays a central role and theories in which learning is relegated to the sidelines. A strength of learning-oriented theories is that they exploit the growing wealth of evidence suggesting that young humans possess powerful learning mechanisms. For example, infants can rapidly capitalize on the statistical properties of their language environments, including the distributions of sounds in words and the orders of word types in sentences, to discover important components of language structure. Infants can track such statistics, for example, to discover speech categories (e.g., native-language consonants; see, e.g., Maye, Werker, & Gerken, 2002), word boundaries (e.g., Saffran, Aslin, & Newport, 1996), and rudimentary syntax (e.g., Gomez & Gerken, 1999; Saffran & Wilson, 2003).

However, theories of language acquisition in which learning plays a central role are vulnerable to a number of criticisms. One of the most important arguments against learning-oriented theories is that such accounts seem at odds with one of the central observations about human languages. The linguistic systems of the world, despite surface differences, share deep similarities, and vary in nonarbitrary ways. Theories of language acquisition that focus primarily on pre-existing knowledge of language do provide an elegant explanation for cross-linguistic similarities. Such theories, which are exemplified by the seminal work of Noam Chomsky, suggest that linguistic universals are prespecified in the child's linguistic endowment, and do not require learning. Such accounts generate predictions about the types of patterns that should be observed cross-linguistically, and lead to important claims regarding the evolution of a language capacity that includes innate knowledge of this kind (e.g., Pinker & Bloom, 1990).

Can learning-oriented theories also account for the existence of language universals? The answer to this question is the object of current research. The *constrained statistical learning framework* suggests that learning is central to language acquisition, and that the specific nature of language learning explains similarities across languages. The crucial point is that learning is constrained; learners are not open-minded, and calculate some statistics more readily than others. Of particular interest are those constraints on learning that correspond to cross-linguistic similarities (e.g., Newport & Aslin, 2000). According to this framework, the similarities across languages are indeed nonaccidental, as suggested by the Chomskian framework—but they are not the result of innate linguistic knowledge. Instead, human languages have been shaped by human learning mechanisms (along with constraints on human perception, processing, and speech production), and aspects of language that enhance learnability are more likely to persist in linguistic structure than those that do not. Thus, according to this view, the similarities across languages are not due to innate knowledge, as is traditionally claimed, but rather are the result of constraints on learning. Further, if human languages were (and continue to be) shaped by constraints on human learning mechanisms, it seems likely that these mechanisms and their constraints were not tailored solely for language acquisition. Instead, learning in nonlinguistic domains should be similarly constrained, as seems to be the case.

A better understanding of these constraints may lead to new connections between theories focused on nature and theories focused on nurture. Constrained learning mechanisms require both particular experiences to drive learning and preexisting structures to capture and manipulate those experiences.

LEARNING THE SOUNDS OF WORDS

In order to investigate the nature of infants' learning mechanisms, my colleagues and I began by studying an aspect of language that we knew must certainly be learned: word segmentation, or the boundaries between words in fluent speech. This is a challenging problem for infants acquiring their first language, for speakers do not mark word boundaries with pauses, as shown in Figure 1. Instead, infants must determine where one word ends and the next begins without access

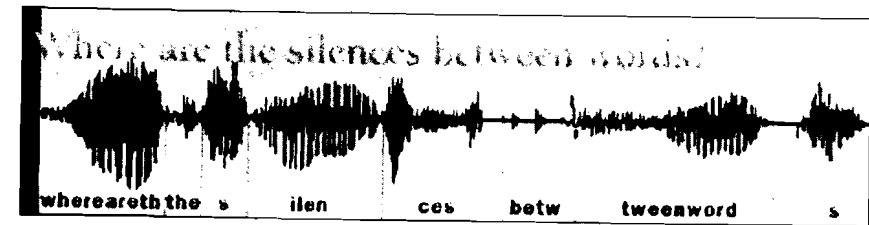


Fig. 1. A speech waveform of the sentence "Where are the silences between words?" The height of the bars indicates loudness, and the x-axis is time. This example illustrates the lack of consistent silences between word boundaries in fluent speech. The vertical gray lines represent quiet points in the speech stream, some of which do not correspond to word boundaries. Some sounds are represented twice in the transcription below the waveform because of their continued persistence over time.

to obvious acoustic cues. This process requires learning because children cannot innately know that, for example, *pretty* and *baby* are words, whereas *tyba* (spanning the boundary between *pretty* and *baby*) is not.

One source of information that may contribute to the discovery of word boundaries is the statistical structure of the language in the infant's environment. In English, the syllable *pre* precedes a small set of syllables, including *ty*, *tend*, and *cedes*; in the stream of speech, the probability that *pre* is followed by *ty* is thus quite high (roughly 80% in speech to young infants). However, because the syllable *ty* occurs word finally, it can be followed by any syllable that can begin an English word. Thus, the probability that *ty* is followed by *ba*, as in *pretty baby*, is extremely low (roughly 0.03% in speech to young infants). This difference in sequential probabilities is a clue that *pretty* is a word, and *tyba* is not. More generally, given the statistical properties of the input language, the ability to track sequential probabilities would be an extremely useful tool for infant learners.

To explore whether humans can use statistical learning to segment words, we exposed adults, first graders, and 8-month-olds to spoken nonsense languages in which the only cues to word boundaries were the statistical properties of the syllable sequences (e.g., Saffran et al., 1996). Listeners briefly heard a continuous sequence of syllables containing multisyllabic words from one of the languages (e.g., *golabupabikututibubabupugolabubabupu . . .*). We then tested our participants to determine whether they could discriminate the words from the language from sequences spanning word boundaries. For example, we compared performance on words like *golabu* and *pabiku* with performance on sequences like *bupabi*, which spanned the boundary between words. To succeed at this task, listeners would have had to track the statistical properties of the input. Our results confirmed that human learners, including infants, can indeed use statistics to find word boundaries. Moreover, this ability is not confined to humans: Cotton-top tamarins, a New World monkey species, can also track statistics to discover word boundaries (Hauser, Newport, & Aslin, 2001).

One question immediately raised by these results is the degree to which statistical learning is limited to language-like stimuli. A growing body of results suggests that sequential statistical learning is quite general. For example, infants

can track sequences of tones, discovering "tone-word boundaries" via statistical cues (e.g., Saffran, Johnson, Aslin, & Newport, 1999), and can learn statistically defined visual patterns (e.g., Fiser & Aslin, 2002; Kirkham, Slemmer, & Johnson, 2002); work in progress is extending these results to the domain of events in human action sequences.

Given that the ability to discover units via their statistical coherence is not confined to language (or to humans), one might wonder whether the statistical learning results actually pertain to language at all. That is, do infants actually use statistical learning mechanisms in real-world language acquisition? One way to address this question is to ask what infants are actually learning in our segmentation task. Are they learning statistics? Or are they using statistics to learn language? Our results suggest that when infants being raised in English-speaking environments have segmented the sound strings, they treat these nonsensical patterns as English words (Saffran, 2001b). Statistical language learning in the laboratory thus appears to be integrated with other aspects of language acquisition. Related results suggest that 12-month-olds can first segment novel words and then discover syntactic regularities relating the new words—all within the same set of input. This would not be possible if the infants formed mental representations only of the sequential probabilities relating individual syllables, and no word-level representations (Saffran & Wilson, 2003). These findings point to a constraint on statistical language learning: The mental representations produced by this process are not just sets of syllables linked by statistics, but new units that are available to serve as the input to subsequent learning processes.

Similarly, it is possible to examine constraints on learning that might affect the acquisition of the sound structure of human languages. The types of sound patterns that infants learn most readily may be more prevalent in languages than are sound patterns that are not learnable by infants. We tested this hypothesis by asking whether infants find some phonotactic regularities (restrictions on where particular sounds can occur; e.g., /fs/ can occur at the end, but not the beginning, of syllables in English) easier to acquire than others (Saffran & Thiessen, 2003). The results suggest that infants readily acquire novel regularities that are consistent with the types of patterns found in the world's languages, but fail to learn regularities that are inconsistent with natural language structure. For example, infants rapidly learn new phonotactic regularities involving generalizations across sounds that share a phonetic feature, while failing to learn regularities that disregard such features. Thus, it is easier for infants to learn a set of patterns that group together /p/, /t/, and /k/, which are all voiceless, and that group together /b/, /d/, and /g/, which are all voiced, than to learn a pattern that groups together /d/, /p/, and /k/, but does not apply to /t/.² Studies of this sort may provide explanations for why languages show the types of sound patterning that they do; sound structures that are hard for infants to learn may be unlikely to recur across the languages of the world.

STATISTICAL LEARNING AND SYNTAX

Issues about learning versus innate knowledge are most prominent in the area of syntax. How could learning-oriented theories account for the acquisition of

abstract structure (e.g., phrase boundaries) not obviously mirrored in the surface statistics of the input? Unlike accounts centered on innate linguistic knowledge, most learning-oriented theories do not provide a transparent explanation for the ubiquity of particular structures cross-linguistically. One approach to these issues is to ask whether some nearly universal structural aspects of human languages may result from constraints on human learning (e.g., Morgan, Meier, & Newport, 1987). To test this hypothesis, we asked whether one such aspect of syntax, phrase structure (groupings of types of words together into subunits, such as noun phrases and verb phrases), results from a constraint on learning: Do humans learn sequential structures better when they are organized into subunits such as phrases than when they are not? We identified a statistical cue to phrasal units, predictive dependencies (e.g., the presence of a word like *the* or *a* predicts a noun somewhere downstream; the presence of a preposition predicts a noun phrase somewhere downstream), and determined that learners can use this kind of cue to locate phrase boundaries (Saffran, 2001a).

In a direct test of the theory that predictive dependencies enhance learnability, we compared the acquisition of two nonsense languages, one with predictive dependencies as a cue to phrase structure, and one lacking predictive dependencies (e.g., words like *the* could occur either with or without a noun, and a noun could occur either with or without words like *the*; neither type of word predicted the presence of the other). We found better language learning in listeners exposed to languages containing predictive dependencies than in listeners exposed to languages lacking predictive dependencies (Saffran, 2002). Interestingly, the same constraint on learning emerged in tasks using nonlinguistic materials (e.g., computer alert sounds and simultaneously presented shape arrays). These results support the claim that learning mechanisms not specifically designed for language learning may have shaped the structure of human languages.

DIRECTIONS FOR FUTURE RESEARCH

Results to date demonstrate that human language learners possess powerful statistical learning capacities. These mechanisms are constrained at multiple levels; there are limits on what information serves as input, which computations are performed over that input, and the structure of the representations that emerge as output. To more fully understand the contribution of statistical learning to language acquisition, it is necessary to assess the degree to which statistical learning provides explanatory power given the complexities of the acquisition process.

For example, how does statistical learning interact with other aspects of language acquisition? One way we are addressing this question is by investigating how infants weight statistical cues relative to other cues to word segmentation early in life. The results of such studies provide an important window into the ways in which statistical learning may help infant learners to determine the relevance of the many cues inherent in language input. Similarly, we are studying how statistics meet up with meaning in the world (e.g., are statistically defined "words" easier to learn as labels for novel objects than sound sequences spanning word boundaries?), and how infants in bilingual environments cope with multiple sets of statistics. Studying the intersection between statistical

learning and the rest of language learning may provide new insights into how various nonstatistical aspects of language are acquired. Moreover, a clearer picture of the learning mechanisms used successfully by typical language learners may increase researchers' understanding of the types of processes that go awry when children do not acquire language as readily as their peers.

It is also critical to determine which statistics are available to young learners and whether those statistics are actually relevant to natural language structure. Researchers do not agree on the role that statistical learning should play in acquisition theories. For example, they disagree about when learning is best described as statistically based as opposed to rule based (i.e., utilizing mechanisms that operate over algebraic variables to discover abstract knowledge), and about whether learning can still be considered statistical when the input to learning is abstract. Debates regarding the proper place for statistical learning in theories of language acquisition cannot be resolved in advance of the data. For example, although one can distinguish between statistical versus rule-based learning mechanisms, and statistical versus rule-based knowledge, the data are not yet available to determine whether statistical learning itself renders rule-based knowledge structures, and whether abstract knowledge can be probabilistic. Significant empirical advances will be required to disentangle these and other competing theoretical distinctions.

Finally, cross-species investigations may be particularly informative with respect to the relationship between statistical learning and human language. Current research is identifying species differences in the deployment of statistical learning mechanisms (e.g., Newport & Aslin, 2000). To the extent that nonhumans and humans track different statistics, or track statistics over different perceptual units, learning mechanisms that do not initially appear to be human-specific may actually render human-specific outcomes. Alternatively, the overlap between the learning mechanisms available across species may suggest that differences in statistical learning cannot account for cross-species differences in language-learning capacities.

CONCLUSION

It is clear that human language is a system of mind-boggling complexity. At the same time, the use of statistical cues may help learners to discover some of the patterns lurking in language input. To what extent might the kinds of statistical patterns accessible to human learners help in disentangling the complexities of this system? Although the answer to this question remains unknown, it is possible that a combination of inherent constraints on the types of patterns acquired by learners, and the use of output from one level of learning as input to the next, may help to explain why something so complex is mastered readily by the human mind. Human learning mechanisms may themselves have played a prominent role in shaping the structure of human languages.

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Notes

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2. Voicing refers to the timing of vibration of the vocal cords. Compared with voiceless consonants, voiced consonants have a shorter lag time between the initial noise burst of the consonant and the subsequent vocal cord vibrations.

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