

On the Discovery of Novel Wordlike Units From Utterances: An Artificial-Language Study With Implications for Native-Language Acquisition

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In 4 experiments, adults were familiarized with utterances from an artificial language. Short utterances occurred both in isolation and as part of a longer utterance, either at the edge or in the middle of the longer utterance. After familiarization, participants' recognition memory for fragments of the long utterance was tested. Recognition was greatest for the remainder of the longer utterance after extraction of the short utterance, but only when the short utterance was located at the edge of the long utterance. These results support the incremental distributional regularity optimization (INCDROP) model of speech segmentation and word discovery, which asserts that people segment utterances into familiar and new wordlike units in such a way as to minimize the burden of processing new units. INCDROP suggests that segmentation and word discovery during native-language acquisition may be driven by recognition of familiar units from the start, with no need for transient bootstrapping mechanisms.

Children typically learn their first words at about 10 or 12 months of age. They learn words slowly for the next 6 or 8 months, averaging roughly one word per day. At about 18 to 20 months, they begin to use two-word combinations much more frequently, and their rate of vocabulary acquisition increases markedly. To acquire each new vocabulary item, a child must associate the sound pattern of a word with its meaning and, at some point, its syntactic function. Young children's ability to discover and memorize the meaning and syntactic function of each sound pattern would be remarkable enough to warrant serious scientific investigation even if the sound patterns themselves were obvious from the linguistic environment. However, speech does not appear to contain any reliable acoustic marking of word boundaries,

so the input children receive is better modeled as a sequence of unsegmented utterances than as a sequence of words; the sound patterns of individual words must be discovered.

This article focuses on processes by which children could identify wordlike units to use as candidate sound patterns for association with meaning. The investigation is motivated by the incremental distributional regularity optimization (INCDROP) model of speech segmentation and word discovery (Brent, 1997; see also Brent, 1996, 1999; Brent & Cartwright, 1996). INCDROP asserts that the process of segmenting utterances and inferring new wordlike units is driven by the recognition of familiar units within an utterance. By *utterance*, we mean a complete act of speaking surrounded by silent pauses and ending in the prosodic characteristics of clause boundaries. In particular, INCDROP predicts that familiar units will tend to be extracted from an utterance, and the remaining contiguous stretches will be inferred as novel units. For example, if *look* is recognized as a familiar unit in the utterance *Lookhere!* then *look* will tend to be segmented out and the remaining contiguous stretch, *here*, will be inferred as a new unit. As a special case of this general principle, INCDROP predicts that utterances containing no familiar units will be treated as a single novel unit and stored in memory. Thus, no special "bootstrapping" or initialization mechanism is necessary to start the process of discovering new units by extracting familiar units. Our working hypothesis is that the INCDROP segmentation and word-discovery mechanisms are available throughout life, from the first word learned to the last. In the present study, we set out to test some of INCDROP's predictions with a series of experiments in which adults listened to miniature artificial languages.

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Bootstrapping the Lexicon

A number of proposals have been put forth to explain how children discover their first wordlike units. These proposals

are motivated by the notion that children cannot begin to use a segmentation strategy based on the extraction of familiar words until they already know some words. Thus, it has been proposed that young children use certain transient strategies to discover their first words. Eventually, as children learn more words, the recognition of familiar words comes to play a greater role and the early strategies recede into the background, perhaps continuing to play a role as cues to speed the recognition of familiar words during on-line processing. Two classes of proposed strategies for discovering first words are those based on stress and those based on transitional probability.

On the basis of Slobin's (1973) operating principle "Pay attention to salient parts of speech," Gleitman and her colleagues suggested that stressed syllables (in stress-accent languages like English) might help young children identify their first words (Gleitman, Gleitman, Landau, & Wanner, 1988; Gleitman & Wanner, 1982). Echols and Newport (1992) reported that the first words produced by English-learning children tend to omit unstressed syllables and syllables that are not word final. This suggests that perceptual and attentional biases for stressed syllables and word-final syllables may assist in the initial extraction of wordlike units. Jusczyk, Cutler, and colleagues have proposed that infants use stressed syllables to hypothesize the beginning of words in fluent speech (Cutler, 1994, 1996; Houston, Jusczyk, & Newsome, 1995; Newsome & Jusczyk, 1995). This proposal is related to the metrical segmentation strategy (Cutler, 1990; Cutler & Carter, 1987; Cutler & Norris, 1988), which was first put forth as a strategy used by English-speaking adults to optimize lexical access by hypothesizing word onsets at strong syllables.¹ Jusczyk and his colleagues (Houston et al., 1995; Jusczyk, 1997; Jusczyk & Aslin, 1995; Newsome & Jusczyk, 1995) found evidence that 7½-month-old infants can segment words beginning with a strong syllable, such as *DOctor*, out of fluent speech but not words beginning with an unstressed syllable, such as *guiTAR* (see also Echols, Crowhurst, & Childers, 1997; Morgan, 1996). Furthermore, they found that if the stressed syllable was consistently followed by the same syllable, infants would treat the two-syllable sequence as a single wordlike unit; if the context after the stressed syllable varied, however, infants seemed to restrict the extracted unit to the stressed syllable. This suggests that 7½-month-old infants are sensitive to distributional regularities as well as preferring stressed-syllable onsets when constructing wordlike units. Unlike 7½-month-olds, 10½-month-olds were able to extract units that started with an unstressed syllable, suggesting that word segmentation is less constrained by prosodic factors at this age. Morgan and his colleagues (Morgan, 1994; Morgan & Saffran, 1995) also found that rhythm (the alternation of stressed and unstressed syllables) and regularities of syllabic sequence led infants to cluster syllables as a unit; moreover, they found that 9-month-old infants were sensitive to the consistency between rhythmical and distributional factors, whereas 6-month-olds grouped syllables by rhythmic regularity, regardless of whether syllable-sequence regularity was also present.

Transitional probabilities form the basis for another class

of proposals about how children segment utterances into wordlike units before they know any such units (Goodsitt, Morgan, & Kuhl, 1993; Hayes & Clark, 1970; Saffran, Aslin, & Newport, 1996; Saffran, Newport, & Aslin, 1996). The transitional probability between two phonemes or syllables x and y is defined to be the proportion of occurrences of x that are followed by y . Transitional probabilities have been argued to be higher within words than between words, because the pairs of adjacent phonemes or syllables within words are constrained by the lexicon and by phonotactics, whereas pairs of adjacent phonemes or syllables spanning a word boundary are less constrained. Thus, it has been proposed that children posit word boundaries at points of low transitional probability. Saffran, Aslin, and Newport (1996) showed that, after exposure to a continuous stream of syllables, 8-month-old infants showed differential durations of listening for sequences of syllables that had always occurred successively and sequences that had occurred successively less often, suggesting a sensitivity to statistical relationships between neighboring speech sounds. According to this segmentation strategy, word-boundary locations at any given time are based on the transitional-probability computations of the utterances heard before. However, transitional-probability computations do not take into account the segmentation points in previous utterances; in other words, having isolated some words does not help in isolating other words or even the same words later on.

The proposal that young children discover new words based on transitional probabilities is motivated as a temporary strategy that infants might use to extract their first wordlike units. Saffran, Newport, and Aslin (1996) suggested that its role would be limited to serving "as an initial bootstrapping device for generating candidate lexical hypotheses" (p. 611).

According to the INCDROP model, however, there is no need to assume a special strategy for segmenting the very first words. The same word-segmentation principles are applied at all stages of language acquisition (and possibly in lexical access for adults; see Brent, 1997). Children segment each utterance by recognizing and extracting units they have already discovered. If an utterance does not contain any familiar units, or if no units at all have been discovered yet (the "empty lexicon" case), the utterance is treated as a single unit and stored in memory. This default behavior provides some familiar units that can then be used to segment later utterances. For example, if a child heard *Getit!* she or he would treat the entire utterance as a single novel unit, erroneously in this case. If he or she later heard *Yougetit!* then the *getit* part would be recognized as familiar and segmented out, isolating the novel unit *you*. Because child-directed speech contains many such short utterances

¹ A *strong syllable* in Cutler's sense is one with an unreduced vowel, even if it is not stressed (e.g., Fear, Cutler, & Butterfield, 1995). Although there is a strong correlation between unreduced vowels and stress in English, it is by no means a perfect correlation. Research on infants, however, has compared syllables that have both stress and an unreduced vowel with those that have neither.

(e.g., Aslin, Woodward, LaMendola, & Bever, 1996; Bernstein Ratner, 1996; Brown & Bellugi, 1964; Newport, Gleitman, & Gleitman, 1977; Snow, 1972), it is not difficult to find such examples to prime the segmentation and word-discovery pump. Thus, INCDROP differs from other proposals in asserting that the child's experience with the wordlike units of the language, rather than the statistical relationships between phonological units, is the primary determinant of early segmentations. Because the segmentation of an utterance is directly related to the lexical units stored in memory, INCDROP can be described as a model in which segmentation is lexically driven.

It is important to stress that INCDROP does not exclude the possibility that other segmentation strategies play a role in the discovery of wordlike units (see Christiansen, Allen, & Seidenberg, 1998, for a multicue approach). However, our proposal does remove one theoretical motivation for such strategies: the apparent need for special priming mechanisms before new words can be isolated by recognizing familiar words.

The INCDROP Model and Its Predictions

INCDROP is based on a mathematical model devised by Brent and Cartwright (1996; see also Brent, 1999). In addition to their formulas, Brent and Cartwright presented a more abstract, qualitative characterization of the model, one subsequently refined by Brent (1996, 1997). INCDROP is aimed at predicting how people segment a given utterance or sequence of utterances, that is, predicting which segmentation they will choose. The model assumes that each part of an utterance is either attributed to a familiar unit or attributed to a novel unit to be stored in memory. It attempts to predict which familiar and novel units each part of the utterance will be attributed to. Brent (1997) presented three segmentation criteria stating that people segment an utterance in such a way as to (a) minimize the total length of all novel words, that is, the fraction of the utterance attributed to novel words (and hence maximize the portion of the utterance attributed to familiar words); (b) minimize the total number of novel words; and (c) maximize the product of relative frequencies of all words. The relative frequency of a word is the number of times it has been encountered as a proportion of the total number of word tokens that have been encountered. The product of relative frequencies of a segmentation is the result of multiplying together the relative frequencies of the individual words in the segmentation, including novel as well as familiar words. The second and third criteria are closely related because novel words have the lowest possible relative frequency.² If one competing segmentation is favored over the alternatives because it implies fewer novel words, that same segmentation is typically favored because it has a greater product of relative frequencies. Because the number of novel words in a segmentation is a more intuitive quantity than the product of relative frequencies, we focus on the number of novel words when both criteria support the same segmentation.

From a cognitive perspective, INCDROP can be interpreted as a "least effort" model in which segmentation is

driven by an attempt to minimize the processing burdens of memorizing new words and accessing the memories of familiar words. The burden of memorizing new words increases with both the number and length of new words to be memorized. The burden of accessing the memories of familiar words decreases as the relative frequencies of the words to be accessed increase.

The INCDROP criteria can sometimes conflict, one criterion supporting one segmentation while another criterion supports a different segmentation. In that case, the predicted segmentation depends on how the total length of novel words, number of novel words, and product of relative frequencies are combined into a single number. In the mathematical model of Brent and Cartwright (1996), the logarithm of the product of relative frequencies is added to the other terms. In general, this suggests that the product of relative frequencies will tend to be outweighed by the other terms when they conflict. However, the precise resolution of conflicts depends on how raw length and frequency translate into cognitive burden, something about which there is little evidence at present.

Specific Predictions

Although some of the general predictions of INCDROP have already been mentioned, it is worthwhile to see how the segmentation criteria lead to these predictions. Predictions for four cases are considered: an utterance that contains no familiar wordlike units, an utterance that contains one familiar unit at the beginning or end, an utterance that contains one familiar unit in the middle, and an utterance that contains two familiar units that overlap and hence compete with one another.

If an utterance does not contain any familiar wordlike units, INCDROP's segmentation criteria predict that it will be treated as a single novel unit and will be stored in memory; thereafter, it is considered a familiar unit. Treating the whole utterance as one novel unit satisfies the segmentation criteria better than dividing it into multiple novel units. The single-unit analysis minimizes the number of novel units (and maximizes the product of relative frequencies); the total length of novel units is the same regardless of how the utterance is divided up, because the utterance contains no familiar units.

If part of an utterance matches a familiar unit, the segmentation criteria predict that, in most cases, this familiar unit will be extracted and the remaining contiguous stretches treated as novel units. This is because extracting the familiar units reduces the total length of the novel units. However, if extracting a familiar unit implies the existence of novel units in the utterance, then there is a conflict among the segmentation criteria. To get a better understanding of this conflict,

² Within the model, the "relative frequency" of a word is actually computed as $(f + 1)/(m + 1)$, where f is the number of times the word has occurred so far and m is the total number of occurrences so far of all words. Thus, the relative frequency of a novel word (one that has not occurred before) is $1/(m + 1)$, not zero. See Brent (1999) for details.

consider the special case in which the familiar unit is at the edge of an utterance that contains no other familiar units; for example, *look* is the only familiar unit in the utterance *Lookhere!* The competing segmentations include (a) extracting the familiar unit (*look*) and storing the remainder (*here*) as a novel unit and (b) treating the entire utterance as one long novel unit. Both options imply one novel unit, but the portion of the utterance attributed to novel words after extracting the familiar unit is smaller. Thus, the number of novel units is neutral, and the length of novel units favors extraction of the familiar unit. However, extracting reduces the product of relative frequencies by a factor of the relative frequency of the familiar unit.³ The balance in this conflict depends on the length and frequency of the familiar unit: The longer it is, the better extraction satisfies the length criterion, and the more frequent it is, the less extraction violates the product of relative frequencies criterion; units that are both short and rare may not be segmented out. Note that this is consistent with the observation that, across many languages, short words tend to have high frequency (Zipf, 1949). As mentioned earlier, however, the product of relative frequencies is weakened by a logarithmic transformation in the formulas of Brent and Cartwright (1996), suggesting that one should predict extraction of the familiar unit as the default, except in extremes of length and relative frequency.

If a familiar unit is in the middle of an utterance that contains no other familiar units—for example, if *look* is the only familiar unit in the utterance *Don'tlookhere!*—the situation is quite different. Extracting the familiar unit now implies two novel units, one on each side, whereas treating the entire utterance as a single long novel unit implies only one. Thus, the number of novel units criterion changes from being neutral to opposing extraction. The opposition of the product of relative frequencies criterion is likewise strengthened, because novel units have the lowest possible relative frequency. If the familiar unit is sufficiently long and sufficiently frequent, it should still be segmented out, but the model predicts that the extraction of familiar units from the middle of long utterances will impose a greater cognitive burden and hence will be rarer.

Finally, consider the case in which more than one familiar unit competes for extraction, because the same portion of the input could be attributed to one unit or the other but not both. For example, in the utterance *anicedog*, either *an* or *nice* can be extracted but not both, because the *n* cannot be attributed to both words. In such cases, the prediction depends on which segmentation of the entire utterance satisfies the segmentation criteria better. However, there is a special case in which it is obvious that extracting one familiar unit satisfies the criteria better than extracting the other. When two familiar units of roughly equal length and frequency are the only familiar units in a longer utterance, and when one of the two is at the edge while the other is in the middle, then the one at the edge will be extracted in preference to the one in the middle. As discussed above, this is because extracting from the middle of the utterance implies two novel words, whereas extracting from the edge implies only one.

Role of the Utterance in Segmentation and Word Discovery

An important aspect of INCDROP is the central role accorded to the utterance, which serves three distinct functions. First, the utterance is a default unit, in the case where it contains no familiar units. Second, it provides the domain within which alternative segmentations are evaluated according to the model's criteria. That is, the model allows the locations of word boundaries at the beginning of an utterance to be influenced by sounds that occur at the end of the utterance, but such influences cannot extend across utterance boundaries. Third, utterance boundaries provide unambiguous word boundaries that are evident on the surface. Peters (1983) suggested that children might begin by storing the whole utterance as a single unit in the lexicon. Aside from Peters's approach, other approaches to segmentation and word discovery accord the utterance only the last of the three functions—supplying unambiguous word boundaries—and even this function is often left implicit. Thus, the central role accorded to the utterance within INCDROP is one of the most important differences between INCDROP and most other approaches.

Empirical evidence from a number of sources is consistent with the central role that INCDROP assigns to the utterance. First, infants as young as 2 months of age appear to treat the utterance as a single coherent unit (Mandel, Jusczyk, & Kemler Nelson, 1994; Mandel, Kemler Nelson, & Jusczyk, 1996). Turning to the role of the utterance as default unit, this strategy would be most effective if children were addressed with at least a few short utterances, ideally, although not necessarily, single-word utterances. Aslin et al. (1996) reported that 17 of the 19 mothers whom they asked to teach novel words to their 12-month-olds produced at least some instances of the novel words in isolation and that the proportion of utterances in which the novel word was presented in isolation reached 70% for some mothers. Although INCDROP predicts that isolated words are useful for getting the segmentation process started, it does not predict that they are necessary; short multiword utterances that can occur inside other utterances suffice, as illustrated by the *Getit? . . . Yougetit!* example, in which the word *you* is discovered from two multiword utterances. The vast literature on child-directed speech uniformly reports the predominance of such short utterances in speech to children. The effectiveness of the INCDROP strategy receives further support from computer simulations reported by Brent and Cartwright (1996) and Brent (1999), in which INCDROP's segmentation criteria produced relatively good segmenta-

³ The relative frequency of a novel unit is $1/(m + 1)$, where m is the total number of word tokens encountered so far. Thus, if an utterance is treated as a single novel unit, the product of relative frequencies is simply $1/(m + 1)$. If an utterance is divided into a familiar unit (e.g., *look*) and a novel unit (e.g., *here*), then the product of relative frequencies is the relative frequency of the familiar unit, $(freq(look) + 1)/(m + 1)$, multiplied by the relative frequency of the novel unit, $1/(m + 1)$. Because relative frequencies are always less than one, $(freq(look) + 1)/(m + 1) \times 1/(m + 1) < 1/(m + 1)$.

tions when applied to broad phonetic transcripts of child-directed speech. Finally, one of the most straightforward consequences of INCDROP is that an utterance that does not contain any familiar units is stored as a single unit, even though it may in fact contain more than one lexical unit. Several studies have reported the presence in children's early productions of formulas or formulaic expressions, apparent units that consist of more than one adult word (Hickey, 1993; Peters, 1983; Plunkett, 1993). The same phenomenon has been found for second-language learners (Hakuta, 1976; Vihman, 1982; Weinert, 1995; Wong Fillmore, 1976).

Limits of the INCDROP Model

Despite this evidence supporting its plausibility, the INCDROP model remains an idealization that does not attempt to account for all of the factors that might bear on segmentation and word discovery. In particular, recognition of a familiar unit requires a certain degree of similarity between the representation of the familiar unit in memory and its acoustic realization in the context of a larger utterance. Because of coarticulation and other phonetic phenomena in continuous speech, this similarity may be low and recognition may fail, independently of the cognitive burden accounted for by INCDROP's criteria.

Moreover, INCDROP models the *relative* cognitive load involved in memorizing new units and accessing the memories of familiar units, but it does not attempt to model the limits of cognitive load at which this process fails. For utterances containing no familiar units, the model predicts that committing them to memory as a single novel unit will impose a smaller processing burden than other analyses of the same utterance. But that burden may still be very large, in absolute terms, if the utterance is long. In such cases, children may simply let the utterance go by without committing any new units to memory. Or they may use some other segmentation strategy, such as a strategy based on stress or transitional probabilities, to break the long stretches up and commit only some of the smaller units to memory, abandoning others. Rather than add some arbitrary threshold of cognitive load into the model, we simply acknowledge that it will break down when even the best analysis is too difficult.

In addition to those cases in which the cognitive burden of exhaustive analysis is too great, there are cases in which multiple competing segmentations impose fairly similar burdens. In those cases, one would expect the choice among competing segmentations to be influenced by language-specific knowledge of other sorts, to the extent that the child has acquired such knowledge. For example, English-learning children appear to demonstrate a preference for words that begin with strong syllables from a very early age (Jusczyk, Cutler, & Redanz, 1993), perhaps reflecting the fact that the majority of English content words begin with a strong syllable (Cutler & Carter, 1987). If there are two competing segmentations of an utterance that are fairly equal in terms of the cognitive burden modeled by INCDROP, but one of them posits a novel word beginning with a weak syllable and the other posits a novel word beginning

with a strong syllable, an English-learning child might well select the latter segmentation. Indeed, as the child forms more phonological generalizations about the way words typically sound in her or his language, these generalizations may come to play an increasing role in segmentation. For example, Brent and Cartwright (1996) discussed how children could learn phonotactic constraints on the consonant clusters that can occur at the beginnings and ends of words and showed, via computer simulation, that such constraints can greatly aid in segmentation and word discovery. Various kinds of probabilistic phonotactics, including transitional probabilities, could also play a role in characterizing what words typically sound like in the language being learned (Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997).

Relationship Between Segmentation and Chunking

Segmentation can be thought of as the result of recoding long stimuli into smaller units or chunks. Chunking is a natural, perhaps automatic, tendency to process stimuli by parts (Bower & Springston, 1970; Johnson, 1970; Miller, 1956; Tulving, 1962). It has been observed with verbal materials but in other cognitive domains as well, such as music perception (e.g., Deutsch, 1980; Dowling, 1973) and artificial-grammar learning using strings of letters (e.g., Servan-Schreiber & Anderson, 1990), which suggests that the mechanism for chunking rests on a general cognitive ability. The presence of chunks has been shown to directly influence the storage of stimuli in memory (Dowling, 1973), as well as the processing of subsequent stimuli: The more a subsequently presented novel string of letters can be divided into familiar chunks, the more familiar it seems (Buchner, 1994; Servan-Schreiber & Anderson, 1990; see Perruchet & Pacteau, 1990, who defined chunks as bigrams of letters). Chunks can delimit low-level units, such as words, but can also be combined and hence mark higher level units, such as phrases and sentences (Servan-Schreiber & Anderson, 1990). Morgan, Meier, and Newport (1987) and Valian and Levitt (1996) found evidence that prosodic phrasing, in highlighting structural relationships between words, can help in learning of the syntax of an artificial language. Chunks can be induced by the presence of blanks between groups of letters (Servan-Schreiber & Anderson, 1990) or by rhythmic cues, such as the lengthening of the last tone of a group and a pause between groups of tones (Dowling, 1973). In the present research, we aimed to show that chunking can be induced by previously stored chunks or familiar units, in the absence of any explicit boundary between units.

The Present Artificial-Language Study

We have cited evidence that infants recognize the coherence of utterances, evidence that the INCDROP strategy for segmentation and word discovery might be effective, and evidence that children sometimes treat a string of words as a single unit. However, there is no direct evidence that people segment and infer new wordlike units by making use of the familiar units they have previously stored. The series of experiments presented here investigated the inference of

new units by adults exposed to utterances from an auditory artificial language. Of course, evidence from adults learning an artificial language would not imply similar behavior by young children acquiring their native language. On the other hand, if we do find evidence that adults behave according to the predictions of INCDROP, there is no particular reason to believe that children would be different. Previous language-learning studies have shown similar findings for adults exposed to an artificial language and children or even infants exposed to the same type of language (Braine et al., 1990; Saffran, Aslin, & Newport, 1996; Saffran, Newport, & Aslin, 1996). This suggests that certain mechanisms involved in language learning are available to humans regardless of age (at least after very early infancy).

This study consisted of presenting adult listeners with utterances from a miniature artificial language, that is, sequences of nonsense syllables such as /dobuneripo/. Use of the artificial-language methodology enables one to experimentally manipulate the language-acquisition process with perfect control of the input (e.g., Brooks, Braine, Catalano, Brody, & Sudhalter, 1993; MacWhinney, 1983; Meier & Bower, 1986; Moeser & Bregman, 1972; Valian & Coulson, 1988; Valian & Levitt, 1996). Our stimuli were designed to render the participants' knowledge of their native language irrelevant to the task by including no English words, no syntactic or semantic information, and no consonant clusters. Furthermore, the experimental design controlled for effects of the predominant stress patterns of English. The use of artificial language also allowed us to manipulate the factors that INCDROP predicts will influence segmentation and word discovery, such as the familiarity or novelty of possible units and their relative frequencies.

The nonsense utterances we presented to participants were of two kinds: short utterances of two or three syllables and long utterances of five syllables that contained the short utterance. We hypothesized that participants would treat the short utterance in isolation as one unit and would recognize the short utterance in the long utterance, segment it out, and store the remaining contiguous stretches of the long utterance as new units. After participants had been exposed to the artificial-language utterances, we examined whether they had inferred new units, using two different paradigms. The first paradigm (used in Experiment 1) consisted of presenting participants with test items and asking them to decide, for each one, whether it consisted of a word of the language they had just heard. Half of the test items corresponded to the predicted inferred unit after extraction of the familiar unit, whereas the other half consisted of smaller or larger fragments of the long utterance. We hypothesized that the test item corresponding to the inferred unit would seem more familiar. We expected the greater familiarity of the inferred units, as compared with longer or shorter fragments of the utterances, to be reflected in the explicit judgments made by participants. Comparing performance on the predicted inferred units with performance on items that did not respect the predicted inferred-unit boundaries directly addressed the segmentation and discovery of novel wordlike units.

The second paradigm (used in Experiments 2, 3, and 4)

consisted of a recognition-memory task. Participants were presented with sequences of syllables and asked to decide, for each sequence, whether they had heard it during the familiarization phase. Among those test items that consisted of sequences of syllables that had occurred during familiarization, some exactly corresponded to the predicted inferred unit, whereas the others were shorter or longer. We hypothesized that the inferred units have their own representation in memory, whereas utterance fragments that are not inferred units can be accessed only by retrieving and analyzing the representation of the whole utterance. This suggested to us that participants might be most accurate and fastest at remembering that they had heard a test item before if this test item corresponded to an inferred unit. Several findings in the literature support such a prediction. First, Johnston, Dark, and Jacoby (1985) showed that words are identified more quickly and accurately when presented for the second time than when they appear for the first time. Second, Dowling (1973) showed that people are better at remembering having heard a string of tones in the preceding longer string when the test string consisted of a chunk or unit induced by rhythm in the long string than when the test string straddled two rhythmic units in the long string. The same phenomenon was predicted in the present study.

Experiment 1

The aim of Experiment 1 was to see whether participants would extract a familiar wordlike unit located at the edge of an utterance containing no other familiar units, infer that the remainder of the utterance is a novel unit, and store the novel unit in memory. We also wanted to see if it matters whether the familiar unit is located at the beginning or end of the utterance. Although INCDROP does not predict a difference, one can imagine that it might be easier to extract the familiar unit first, before hearing the entire utterance, than to hold the entire utterance in memory until the familiar unit is recognized at the end and then go backward to construct a novel unit from the beginning of the utterance.

Before going into methodological details, it is useful to outline the design principles and introduce some terminology. The experiment consisted of a familiarization phase and a test phase. The materials can be grouped into item sets, each consisting of several utterances presented during familiarization together with the corresponding test items. The familiarization utterances in each item set consisted of a two-syllable or three-syllable short utterance (e.g., *abc* or *ij*, each letter representing a syllable) and a five-syllable long utterance, which contained the short utterance either at the beginning or at the end. For example, the long utterance *abcde* begins with the short utterance *abc*, whereas the long utterance *fghij* ends with the short utterance *ij*. Each item set also contained a two-syllable test item and a single three-syllable test item, each consisting of a fragment of the long utterance taken from the edge that did not contain the short utterance (e.g., *de* and *cde* from *abcde*, when *abc* is the short utterance). For the familiarization phase, all participant groups received the same long utterances, but they received short utterances of different lengths (e.g., *abc* or *ab*). The

Table 1
Experiment 1: Materials Organized Into Four Item Sets (Presented With Their Letter Codes and Phonemic Notations) and Two Practice Sets

| Set | Long utterance | | Short utterance or test item | | | |
|----------|----------------|--------------|------------------------------|----------|------------|----------|
| Item | <i>abcde</i> | /koʃedifenu/ | <i>ab</i> | /koʃe/ | <i>cde</i> | /difenu/ |
| | | | <i>abc</i> | /koʃedi/ | <i>de</i> | /fenu/ |
| | <i>fghij</i> | /dobuneripo/ | <i>fg</i> | /dobu/ | <i>hij</i> | /neripo/ |
| | | | <i>fgh</i> | /dobune/ | <i>ij</i> | /ripo/ |
| | <i>klmno</i> | /tegivemofu/ | <i>kl</i> | /tegi/ | <i>mno</i> | /vemofu/ |
| | | | <i>klm</i> | /tegive/ | <i>no</i> | /mofu/ |
| | <i>pqrst</i> | /belizekufo/ | <i>pq</i> | /beli/ | <i>rst</i> | /zekufo/ |
| Practice | | /muzibo/ | <i>pqr</i> | /belize/ | <i>st</i> | /kufo/ |
| | | /kezoru/ | | /bo/ | | /muzi/ |
| | | | | /ke/ | | /ru/ |

length of the short utterance was predicted to determine how the long utterance would be segmented and, thus, what new unit would be inferred. For example, the presentation of the short utterance *ab* in association with the long utterance *abcde* would trigger the inference of the new unit *cde*; conversely, the presentation of the short utterance *abc* in association with the long utterance *abcde* would trigger the inference of the new unit *de*. For the test phase, each test item was said to be in the word condition when it consisted of exactly the fragment that remained after the short utterance presented during familiarization was extracted from the long utterance (for example, if *ab* was the short utterance and *abcde* the long utterance, *cde* was said to be in the word condition). Otherwise, it was said to be in the nonword condition. The design consisted of testing participants who heard different familiarization phases on the same test items (see Redington & Chater, 1996, for methodological discussion). Each test item was tested an equal number of times in the word and nonword conditions. After the familiarization phase, participants were presented with test items and asked to decide whether each item was a word of the made-up language they had just heard. We predicted that participants would judge a test item to be a word more often in the word condition (i.e., when it corresponded to a predicted stored unit) than in the nonword condition. Note that a yes response does not mean that a new unit has been isolated and inferred, nor does a no response mean that the inference has failed. Rather, a higher percentage of yes responses in the word condition would indicate greater subjective familiarity with these items than with the nonword items.

Method

Participants

Forty-eight student volunteers from Johns Hopkins University were paid \$5 each for their participation. All were native speakers of English. They were tested separately in a sound-attenuated booth.

Materials

The materials consisted of four different item sets constructed out of consonant–vowel syllables that obeyed the minimal-word

constraints on English consonant–vowel words but were not actual words. The sets are presented in Table 1.

For each item set, the location of the short utterance in the long utterance was varied across participants: For half of the participants the short utterance was located at the beginning of the long utterance, with the test items thus at the end of the long utterance; for the other half, the short utterance was located at the end of the long utterance, with the test items thus at the beginning. Consequently, the short utterance for some participants was the test item for others, and vice-versa. In addition to the four item sets, two practice sets were included in which the short utterances were monosyllabic and the long utterances were trisyllabic. The purpose of the practice sets was to generate practice test items, allowing participants a few trials to become accustomed to the task before presentation of the experimental test items.

All utterances and test items were recorded by a female native speaker of English during a single session. She was instructed to pronounce each utterance slowly, at a regular pace and without pausing between syllables, placing the main stress on the first syllable of each utterance. This stress pattern was intended to minimize the possible influence of stress on segmentation. Furthermore, the design prevented an overall effect due to stress, because we predicted that different participant groups would segment identical utterance tokens in different ways.⁴ Four different tokens of each long and short utterance were selected for presentation in the familiarization phase, adding some acoustic variety. The use of natural speech with several tokens of the same sequences of syllables was intended to make the recognition of a familiar unit more realistic: Recognizing, say, *abc* in the utterance *abcde* would imply an abstract mapping, because *abc* in isolation and *abc* in a longer utterance are acoustically different. In addition, stimulus variability appears to enhance spoken-word recognition (Nygaard, Sommers, & Pisoni, 1995).

Design

For each item set, four different familiarization conditions were created, crossing location (whether the short utterance was at the beginning or at the end of the long utterance) with length (whether this short utterance was two or three syllables long). These four conditions were presented to four different groups of participants.

⁴ Differences between test items located at the right and left edges of the utterance might be attributable to the fact that only those on the left receive initial stress in the long utterance, but an overall effect of word versus nonword condition could not be attributed to stress.

Table 2
Experiment 1: Design of the Item Set abcde

| Group | Short utterance | Long utterance with predicted segmentation | Test item | Prediction |
|-------|-----------------|--------------------------------------------|------------|------------|
| 1a | <i>abc</i> | <i>abc_de</i> | <i>de</i> | Word |
| 1b | <i>abc</i> | <i>abc_de</i> | <i>cde</i> | Nonword |
| 2a | <i>ab</i> | <i>ab_cde</i> | <i>de</i> | Nonword |
| 2b | <i>ab</i> | <i>ab_cde</i> | <i>cde</i> | Word |
| 3a | <i>cde</i> | <i>ab_cde</i> | <i>abc</i> | Nonword |
| 3b | <i>cde</i> | <i>ab_cde</i> | <i>ab</i> | Word |
| 4a | <i>de</i> | <i>abc_de</i> | <i>abc</i> | Word |
| 4b | <i>de</i> | <i>abc_de</i> | <i>ab</i> | Nonword |

Each participant received four item sets, one in each location-by-length condition, yielding a Latin square design. For the test phase, each of the four groups was divided in half, and each subgroup was tested on only one of the two possible test items for each item set (e.g., either *cde* or *de*). The order in which the test items from each set were presented was maintained constant across groups. This design (illustrated in Table 2) allowed us to present the same test item to two groups for which the predictions were different. If differences in performance between the word and nonword conditions were found, they would result from the only difference between the conditions, namely, which short utterance was presented during familiarization.

Procedure

Before familiarization, participants were instructed that they would hear utterances consisting of one or more words from a "made-up" language. Speech materials were presented binaurally over headphones. The familiarization phase consisted of 10 blocks. During each block, participants heard all four short utterances and all four long utterances for their group, as well as four utterances from the practice item sets. In the first 2 blocks, each utterance was presented twice in a row, and participants were asked to repeat it aloud after each presentation. In the remaining 8 blocks, each utterance was presented once, and participants were asked to listen and try to remember. Thus, each of the four short and four long utterances was presented 12 times, 4 with repetitions aloud and 8 without. The order of utterances within blocks was determined by generating a large number of random orders and discarding those in which two utterances from the same item set (e.g., *ab* and *abcde*) were presented adjacent to one another. Familiarization lasted about 12 min.

After familiarization, participants heard "bits of speech" and had to decide for each whether it was a word of the made-up language.⁵ To make the instructions as explicit as possible, an example was given in which new syllables were used: "For instance, if *voguki* is a word, *chivoguki* is not, nor is *guki*." Participants were asked to decide as quickly as possible and to press one of two buttons labeled *yes* and *no* even if they were not quite sure of their response. The *yes* button was always controlled by the participant's dominant hand. Each participant was presented with six "bits of speech," two practice items followed by four test items. The response type and response latency for each item were collected by a computer, with reaction times measured from timing pulses aligned with item onset and inaudible to the participants.

Results

Only response types are reported here, because the response latencies did not show any effect. Test items in the word condition were judged to be a word (yes response) 62% of the time (59 of 96); in the nonword condition, they were judged to be a word 45% of the time (43 of 96). Given the discrete nature of the data, a chi-square test was required to assess the difference between the two conditions directly. However, the chi-square test requires that all data points be statistically independent, so it is not applicable to a table in which some cells contain multiple responses from the same participant. We therefore computed the number of participants who answered yes zero times, one time, and two times to items tested in the word condition. The maximum was two, because each participant was tested on only two items in the word condition (and two in the nonword condition). This resulted in an exhaustive classification of participants into three categories. We made the same computations for items presented in the nonword condition, yielding a second exhaustive classification of participants. For each classification, we excluded participants who failed to respond to one or more test items (1 participant in the nonword condition and 3 in the word condition). Table 3 presents the classifications of participants by number of yes responses to test items in the word and nonword conditions.

A chi-square test revealed the two classifications to be reliably different, $\chi^2(2, N = 90) = 12.68, p < .002$. This difference is reflected by the fact that more participants gave two yes responses in the word condition than in the nonword condition (16 vs. 12), and more participants gave zero yes

⁵ This task was favored against a two-alternative forced-choice test (as used by Saffran, Newport, and Aslin, 1996) in which each word was paired with each nonword. In such a task, participants may learn from the test itself and may thus entertain hypotheses that they would not have entertained otherwise. For instance, for each pair, participants would know that one of the items is a word and that the other is not a word (see Valian & Coulson, 1988, for a similar argument). Moreover, multiple presentations of a nonword, paired with all of the different possible words, might cause the nonword to become increasingly familiar and therefore influence responses.

Table 3
Experiment 1: Participant Classification as a Function of the Number of Yes Responses to Test Items in the Nonword or Word Condition

| No. of yes responses | Nonword | Word |
|----------------------|---------|------|
| 0 | 16 | 4 |
| 1 | 19 | 25 |
| 2 | 12 | 16 |
| Total | 47 | 45 |

responses in the nonword condition than in the word condition (16 vs. 4).⁶

Additional analyses were conducted, distinguishing the test items as a function of their previous location in the long utterance: at the left edge (e.g., *ab/abc* in *abcde*) or at the right edge (e.g., *cde/de* in *abcde*). Each participant was tested on two test items from each location, of which one was in the word condition and the other in the nonword condition. Table 4 presents the classifications of participants by number of yes responses (zero or one) to test items in the word and nonword conditions, broken down by location of the test item.

For each classification, we excluded participants who failed to respond to the test item. Although the participant classifications for items in the nonword and word conditions differed significantly both for items on the left, $\chi^2(1, N = 93) = 3.69, p = .055$, and for items on the right, $\chi^2(1, N = 94) = 10.53, p = .001$, the effect of word versus nonword seemed greater for items on the right. To test a possible interaction between the effect of the condition and the location of the test items, we computed, for each participant, the number of correct responses (i.e., the number of yes responses to items in the word condition and no responses to items in the nonword condition); we classified participants by the number of correct responses they gave (zero, one, or two) separately for the test items on the left and the test items on the right (see Table 5). As before, we excluded participants who failed to respond to one or more items. The two distributions were not reliably different, $\chi^2(2, N = 92) = 4.2, p = .12$.⁷

We also classified participants according to the number of yes responses (zero or one) in nonword and word conditions broken down by number of syllables in the test item (Table 6). For each category, we excluded participants who failed to

Table 4
Experiment 1: Participant Classification as a Function of the Number of Yes Responses to Test Items in the Nonword or Word Condition, by Location (Left or Right Edge)

| No. of yes responses | Test item on the left edge | | Test item on the right edge | |
|----------------------|----------------------------|------|-----------------------------|------|
| | Nonword | Word | Nonword | Word |
| 0 | 25 | 17 | 27 | 16 |
| 1 | 23 | 28 | 20 | 31 |
| Total | 48 | 45 | 47 | 47 |

Table 5
Experiment 1: Participant Classification as a Function of the Number of Correct Responses to Test Items at the Left or Right Edge of the Long Utterance

| No. of correct responses | Left edge | Right edge |
|--------------------------|-----------|------------|
| 0 | 10 | 6 |
| 1 | 19 | 25 |
| 2 | 16 | 16 |
| Total | 45 | 47 |

respond to the test item. The participant classifications in nonword and word conditions differed significantly when the test items were two syllables long, $\chi^2(1, N = 95) = 15.96, p < .0001$, but did not differ significantly when the test items were three syllables long, $\chi^2(1, N = 92) = 1.44, p = .23$. To test a possible interaction between the effect of the condition and the number of syllables of the test items, we computed, for each participant, the number of correct responses (i.e., the number of yes responses to items in the word condition and no responses to items in the nonword condition); we classified participants by the number of correct responses they gave (zero, one, or two) separately for the two-syllable test items and the three-syllable test items (Table 7). As before, we excluded participants who failed to respond to one or more items. The two distributions were not reliably different, $\chi^2(2, N = 91) = 0.15$.

Discussion

Experiment 1 aimed to test whether a sequence of syllables presented in isolation (the short utterance) could be extracted from the edge of a longer utterance, yielding the inference of a new unit, the remainder of the utterance. We exposed different groups of participants to the same long utterances but with short utterances of different length, yielding different predicted segmentation points and different predicted inferred units. Then we presented participants with test items and asked them to decide, for each test item, whether it was a word from the artificial language they had just heard. Across participants, the same test items were either in the word or nonword condition, depending on the

⁶ At the suggestion of an anonymous referee, we also performed a matched-pairs *t* test comparing participants' accuracy at responding to items in the word condition and their accuracy at responding to items in the nonword condition. This test showed a significant difference as well, $t(47) = 2.18, p < .05$, two-tailed. We also compared the percentage of yes responses in each condition with 50% and found that the difference was significant in the word condition, $t(47) = 2.58, p < .01$, but not in the nonword condition.

⁷ At the suggestion of an anonymous referee, a 2 (word vs. nonword) \times 2 (left vs. right) ANOVA with the percentage of yes responses (0% or 100%) as the dependent variable was conducted. Like the chi-square analysis, it did not show an interaction, $F(1, 47) = 0.86$. However, this ANOVA must be interpreted cautiously because each participant contributed either zero or one yes response in each cell, making this an extreme case of discrete data.

Table 6
Experiment 1: Participant Classification as a Function of the Number of Yes Responses to Two-Syllable or Three-Syllable Test Items in the Nonword or Word Condition

| No. of yes responses | Two-syllable items | | Three-syllable items | |
|----------------------|--------------------|------|----------------------|------|
| | Nonword | Word | Nonword | Word |
| 0 | 29 | 15 | 23 | 18 |
| 1 | 19 | 32 | 24 | 27 |
| Total | 48 | 47 | 47 | 45 |

length of the short utterance to which participants had been exposed. The results showed a clear effect of the condition on the participants' responses: Participants classified a test item as being a word more frequently when it corresponded to the predicted inferred unit, showing a higher familiarity with this item than with a shorter or longer fragment of the long utterance. This suggests that the short utterance was extracted out of the long utterance and that a new unit was isolated and stored in memory. Extraction of a familiar unit seems to have occurred both when the unit was located at the beginning of the long utterance and when it was located at the end.

However, this task appeared unsatisfactory in two ways. First, the task involved a metalinguistic judgment that was quite opaque for the participants: Being a word for language users is much more than showing some degree of familiarity. Second, this task does not prevent a conscious strategy from playing a role. Even though they were not instructed about the task until after familiarization, some participants could have noticed the short utterances occurring in the long utterances and later guessed that this pattern was related to what we meant when we asked them whether an item was a "word." Such a conscious guess at the meaning of the task is presumably not at work in early language acquisition. Experiment 2 thus replicated Experiment 1 using the same materials but a task that was not subject to conscious word-discovery strategies.

Experiment 2

The aim of Experiment 2 was to investigate, without requiring metalinguistic judgments to be made, whether participants automatically segment long utterances by extracting a familiar unit at the edge and store the remainder of the utterance in memory. For this purpose, we used a recognition-memory task. After a short familiarization like that of Experiment 1, participants were presented with sequences of syllables and asked to decide, for each sequence, whether they had heard it during the familiarization phase. The sequences consisted of test items and distractors. The test items were all fragments of the long utterances presented during familiarization, as in Experiment 1, so the correct answer was always yes. The distractors included sequences of syllables that had not been heard during familiarization, so the correct answer was no. As in Experiment 1, we describe test items as being in the word condition when they

exactly match the remainder of the long utterance after the short utterance presented to the participant has been extracted from it; otherwise, we describe them as being in the nonword condition. We expected participants to show a high overall accuracy level at distinguishing sequences of syllables they had heard during familiarization from those they had not. However, we had specific predictions about the pattern of errors they would make on the test items and about their speed at responding to them that were independent of the overall accuracy. We predicted that participants would be more accurate and perhaps faster at remembering that they had heard test items in the word condition relative to test items in the nonword condition, even though they had heard both the same number of times and in the exact same context within the long utterance. This prediction depends on the hypothesis that the memory trace of a sequence that has been stored as a unit is more accessible than the memory trace of a sequence that has not been stored as a unit. This paradigm is less subject to conscious word-discovery strategies than the paradigm used in Experiment 1, because the task does not refer to words at all.

Method

Participants

Twenty-six students from Johns Hopkins University volunteered and were paid \$5 for their participation. They were all native speakers of English and were tested individually in a sound-attenuated booth.

Materials

The materials were quite similar to the materials used in Experiment 1. The same four item sets were used. However, as a means of simplifying the design, the location of the short utterance in the long utterance (either at the left or the right edge) was varied across rather than within item sets: For the item sets *abcde* and *klmno*, the short utterance was located at the left edge; for the item sets *fghij* and *pqrst*, it was located at the right edge. For each item set, two short utterances of different lengths were presented to different participant groups. The same two test items were presented to all groups. In addition to the 8 test items (2 for each item set) for which the correct response was yes, 12 distractors were constructed for which the correct answer was no. They were of three types: 4 were composed of two syllables drawn from different item sets (e.g., *ai*), 4 were composed of a pair of adjacent syllables and an additional syllable from the same set that never followed or preceded the pair during familiarization (e.g., *fgi* and *ade*), and 4

Table 7
Experiment 1: Participant Classification as a Function of the Number of Correct Responses to Two-Syllable and Three-Syllable Test Items

| No. of correct responses | Two-syllable items | Three-syllable items |
|--------------------------|--------------------|----------------------|
| 0 | 8 | 8 |
| 1 | 27 | 24 |
| 2 | 12 | 12 |
| Total | 47 | 44 |

were composed of three syllables from the same set that never occurred successively (e.g., *jgi* and *adc*). To balance the number of correct yes and no responses in the test phase, we added 4 distractors that had been heard during familiarization. Two of these distractors were bisyllabic, and 2 were trisyllabic. They were fragments of the long utterance that either contained or were contained in the short utterance (e.g., *ab* for the group familiarized with *abc* and *abc* for the group familiarized with *ab*). The exact same materials as in Experiment 1 were used for the familiarization phase. To reduce the memory burden, we used only one of the two practice item sets (*/muzibo/* and */bo/*). All of the materials presented in the test phase were recorded by the same female speaker as in Experiment 1, during a single session.

Design

The length of the short utterance for each item set was varied across two groups of participants, yielding different segmentations and different predictions for the test items. An example is the item set *abcde* (with an underscore indicating the predicted segmentation and boldface indicating the predicted inferred units in the test items):

| | | |
|---------|--------------------|----------------|
| | Familiarization | Test |
| Group 1 | <i>ab, ab_cde</i> | <i>cde, de</i> |
| Group 2 | <i>abc, abc_de</i> | <i>cde, de</i> |

For the item set *abcde*, for example, Group 1 heard the short utterance *ab* and the long utterance *abcde*, yielding the predicted segmentation *ab_cde*; conversely, Group 2 heard the short utterance *abc* and the long utterance *abcde*, yielding the predicted segmentation *abc_de*. These two groups yielded different predictions on the same test items. For instance, the test item *cde* corresponded to the inferred unit and was thus in the word condition for Group 1, whereas it straddled the segmentation point and was thus in the nonword condition for Group 2. This design allowed us to compare recognition performance for the same items in both conditions across groups. We predicted that performance would be better for test items in the word condition than for test items in the nonword condition. Participants were assigned to Group 1 for half of the item sets and to Group 2 for the other half.

Procedure

The familiarization phase was very similar to that of Experiment 1. In the test phase, participants were asked to decide, for each sequence of syllables presented, whether they remembered it from the utterances they had just heard. An example was given via sequences of syllables that did not occur in the materials. Participants gave their response by pressing one of two buttons labeled *yes* and *no*; the *yes* button was always controlled by the participant's dominant hand. The instructions emphasized the speed of the response. Twenty-four items (8 test items and 16 distractors) were presented to each participant in a randomized order that was constant across participants. Three practice test items were added at the beginning of the test phase, composed of syllables from the practice item set. Response type (yes or no) and reaction time for each item were collected by a computer, with reaction times measured from timing pulses aligned with item onset and inaudible to the participants. Reaction time was collected during the period of 3,500 ms after the onset of the test item. If the participant did not press one of the two buttons within this temporal window, the trial was considered to be missed.

Results

The overall accuracy for each participant (the proportion of correct responses to the test items and the distractors) was computed. The accuracies and reaction times for the test items only were then examined via an analysis of variance (ANOVA). Throughout this study, the differences tested by items (F_2) were often found to be nonsignificant. This is probably a consequence of the limited number of items used (eight). We did not add more test items because that would have meant presenting more utterances during familiarization, substantially increasing the memory burden and making the task more difficult. Throughout the analyses, our interpretation relies on the significance by participants (F_1), although F_2 values are also reported.

The mean accuracy, that is, the proportion of correct responses to the test items and distractors together, was 73%. This indicates that participants were able to accurately categorize a sequence of syllables as having been heard before or not 73% of the time. The performance on the distractors only was 72%; the distractors consisting of sequences of syllables that had not been heard before were responded to correctly 70% of the time, and the distractors consisting of sequences of syllables that had been heard before were responded to correctly 74% of the time.

Accuracy Analysis

The accuracy analysis was restricted to the test items, all of which had been heard during familiarization and for which the correct response was yes. Percentages of accuracy for each participant and each condition were computed (no responses and missing data were coded as incorrect responses), and a $2 \times 2 \times 2$ (Condition \times Location \times Number of Syllables) ANOVA by participants (F_1) and by items (F_2) was conducted. Table 8 presents the accuracy percentages for each condition (nonword and word) as a function of the number of syllables of the test items.

Condition (word or nonword) was found to have a major impact on accuracy: Mean accuracy rates in responding to the test items were 75% in the nonword condition and 87% in the word condition, $F_1(1, 25) = 8.41, p < .01, F_2(1, 4) = 4.8, p = .09$. No global effect of the number of syllables or the location of the test item in the long utterance was found. None of the two-way interactions among condition, location of test item, and number of syllables were significant.

Table 8
Experiment 2: Mean Accuracy and Reaction Time (RT),
Classified by Number of Syllables and Condition

| No. of syllables | Nonword condition | | Word condition | |
|------------------|-------------------|---------|----------------|---------|
| | Accuracy (%) | RT (ms) | Accuracy (%) | RT (ms) |
| 3 | 73 | 1,715 | 88 | 1,522 |
| 2 | 77 | 1,448 | 85 | 1,454 |

Reaction-Time Analysis

Reaction times for test items that were accurately recognized (yes responses) were analyzed via a $2 \times 2 \times 2$ (Condition \times Location \times Number of Syllables) ANOVA by participants (F_1) and by items (F_2). Table 8 presents the mean reaction times for nonword and word conditions as a function of the number of syllables of the test items. Mean reaction time was longer in the nonword condition (1,578 ms) than in the word condition (1,488 ms), but this effect was not significant, $F_1(1, 25) = 2.55, p = .12, F_2(1, 4) = 1.37, p = .31$. The three-syllable test items showed a longer mean reaction time (1,610 ms) than the two-syllable items (1,463 ms), but the difference was only marginally significant, $F_1(1, 25) = 3.88, p = .06, F_2(1, 4) = 1.68, p = .34$. This difference was probably due to the duration difference between the three-syllable items (1,142 ms) and the two-syllable items (794 ms), reaction times being measured from item onset. No global effect of the location of the test item was found. No interaction was found between condition and location of the test item or its number of syllables. Nor was an interaction found between number of syllables and location of the test items.

Discussion

Experiment 2, like Experiment 1, aimed to test whether a sequence of syllables that was presented in isolation (the short utterance) could be extracted from the edge of a longer utterance, yielding the inference of a new unit, the remainder of the utterance. By contrast with Experiment 1, we used an indirect measure to account for the discovery and storage of new units: participants' accuracy and speed at remembering a sequence of syllables they had heard during familiarization. After a short familiarization phase, we presented participants with test items and asked them to decide whether they remembered having heard the sequences of syllables before. Participants were more accurate at remembering sequences of syllables when these sequences corresponded to the remainder of the utterance after extraction of a familiar unit than when the sequences corresponded to longer or shorter utterance fragments.

Experiment 2 supports INCDROP's predictions, namely, that a familiar unit is extracted from the edge of an utterance and the remainder of the utterance is inferred as a new unit. Inference and storage of new units after extraction of the familiar unit were demonstrated indirectly, by testing participants' performance in accessing the memory traces of sequences of syllables. If the sequence did not correspond to an inferred unit, its retrieval was more prone to failure than the retrieval of a sequence that corresponded to an inferred unit. This suggests that new units can be represented in memory without having been presented in isolation, through the extraction of familiar units. Such a word-discovery mechanism therefore seems to exist and to be automatically applied by listeners engaged in a simple memorization task. The next question, addressed in Experiment 3, was whether the extraction of a familiar unit embedded in the middle of an utterance could be observed under similar conditions.

Experiment 3

Experiments 1 and 2 demonstrated that people tend to extract a familiar unit from the edge of an utterance, treating the remainder of the utterance as a novel unit. INCDROP favors this segmentation because it reduces the total length of all novel units in the segmentation, as compared with the alternative in which the entire utterance is treated as a single novel unit. Furthermore, when the familiar unit is at the edge, the number of novel units is one regardless of whether the familiar unit is segmented out or the whole utterance is treated as a long novel unit. However, when a familiar unit is embedded in the middle of an utterance containing no other familiar units, extracting the familiar unit implies two novel units, one to the left of the familiar unit and one to the right. As a result, INCDROP predicts that extracting a familiar unit and inferring the new units should be more difficult when the familiar unit is embedded in the middle of a long utterance, although it should still be possible if the familiar unit is long enough and frequent enough.

There is evidence in the language-acquisition literature that the processing of a word in utterance-medial position is more difficult than the processing of a word in utterance-final position. Young children's comprehension of words seems to be better when the words are in utterance-final position than when they are in utterance-medial position (Fernald, McRoberts, & Herrera, in press; Swingley & Pinto, 1997). Furthermore, adult language learners have been shown to be more efficient at recognizing a word when it occurs at the end of an utterance than when it is embedded in the utterance (Golinkoff & Alioto, 1995). Interestingly, English adult speakers tend to place focused words conveying new information at the end of the utterance in both adult- and child-directed speech, which might be an efficient strategy to optimize the processing of the most informative part of the utterance (Aslin, 1993; Fernald & Mazzie, 1991).

Experiment 3 was designed to test, using the same paradigm as in Experiment 2, whether a familiar unit embedded in the middle of a long utterance would be extracted and new units inferred. We manipulated the short utterances that participants heard during familiarization to see how that would affect the new units they inferred from the long utterances. The following is a sample item set (with the predicted inferred unit for each group shown in bold-face):

| | Familiarization | Test |
|---------|--------------------|-----------------------|
| Group 1 | <i>bc, a_bc_de</i> | <i>cde, de</i> |
| Group 2 | <i>ab, ab_cde</i> | <i>cde, de</i> |

Participants in Group 1 were presented with a short utterance, *bc*, that later occurred embedded in the middle of the long utterance *abcde*. We hypothesized that the short utterance would be recognized in the long utterance and extracted and that two new units would be inferred, *a* and *de*. To assess the extraction of the new unit *de*, we needed to compare participants' performance on the test item *de* with other participants' performance on the same test item when it did not correspond to an inferred unit. Participants in Group

2 were thus familiarized with the short utterance *ab* and the long utterance *abcde*; on the basis of the results from Experiments 1 and 2, the long utterance was predicted to be segmented and the new unit *cde* to be inferred. For the participants in Group 2, the test item *de* did not correspond to the inferred unit, and their ability to remember having heard this item was predicted to be lower than that for the participants in Group 1. The same reasoning was held for the test item *cde*. This design allowed us to compare performance on the same test items across groups as a function of condition.

Method

Participants

Twenty-four students from the University of Maryland at College Park volunteered and received course credit for their participation. They were all native speakers of English and were tested individually in a quiet room.

Materials

Four item sets were used. The syllabic composition of the item sets was different from Experiments 1 and 2. The long utterances were /digufezomul/ (*abcde*), /potekobudol/ (*fg hij*), /kubegifoze/ (*klmno*), and /rubonevoli/ (*pqrst*). Note that the letter code used is similar to the previous experiments. Each item set was composed of one long utterance (e.g., *abcde*); two bisyllabic short utterances, one located at the edge of the long utterance (e.g., *ab*) and the other embedded in the long utterance (e.g., *bc*); and two test items consisting of syllables from the part of the long utterance that did not contain the short utterances (e.g., *cde* and *de*). The location of the short utterance, either at or toward the beginning of the long utterance or at or toward the end, was varied across item sets. To reduce the memory burden, no practice item set was used, because participants missed very few test items in Experiment 2. In addition to the eight test items (two for each of four item sets), eight distractors were constructed, composed of syllables in new sequences; four were bisyllabic, and four were trisyllabic. There were thus eight test items consisting of sequences that occurred during familiarization and for which the correct response was yes and eight distractors consisting of sequences that did not occur during familiarization and for which the correct response was no. The number of two-syllable and three-syllable items was equal. The materials were recorded by the same female speaker as in the previous experiment, and, as before, she was instructed to produce each syllable at a regular pace, with the main stress on the first syllable of the utterance.

Design

For each item set, type of short utterance (at the edge or embedded) was varied across two groups of participants. For the item set *abcde*, for example, Group 1 heard the short utterance *bc* and the long utterance *abcde*, predicting the segmentation *a_bc_de*; conversely, Group 2 heard the short utterance *ab* and the long utterance *abcde*, predicting the segmentation *ab_cde*. In the test phase, the test item *de* was in the word condition for Group 1 but in the nonword condition for Group 2, whereas the test item *cde* was in the nonword condition for Group 1 and in the word condition for Group 2. We thus compared performance on the same test items in

different conditions, across groups. Participants were assigned to Group 1 for half of the item sets and to Group 2 for the other half.

Procedure

Before the familiarization phase, the same instructions as in Experiment 2 were given to participants. The familiarization phase consisted of 30 blocks during which each of the four short utterances and each of the four long utterances were presented. This increase in repetitions relative to Experiment 2 was intended to increase the probability that the short utterance would be remembered, recognized, and extracted. As in Experiment 2, the first 2 blocks were repetition blocks, and the remainder were simple listening blocks. The order of utterances within blocks was determined by generating a large number of random orders and discarding those in which two utterances from the same item set (e.g., *ab* or *bc* and *abcde*) were presented adjacent to one another. Familiarization was about 20 min long. Participants were given a short break after 12 min of listening, to provide them with a rest as well as to restimulate their interest halfway through the listening. The procedures for the test phase and the data collection were identical to those of Experiment 2.

Results

The overall accuracy on test items and distractors was 74% on average. For the distractors only, the accuracy was 73%.

Accuracy Analysis

The accuracy percentages on the test items only were submitted to a $2 \times 2 \times 2$ (Condition \times Location \times Number of Syllables) ANOVA by participants (F_1) and by items (F_2). Table 9 presents the mean percentages.

The accuracies at responding to items in the word and nonword conditions did not differ significantly (76% and 74%, respectively). No effect of the location of the test item in the long utterance (left or right) was found. Accuracy differed between two-syllable and three-syllable items (57% vs. 93%), $F_1(1, 23) = 39.8, p < .0001, F_2(1, 4) = 10.91, p < .05$. No interaction between condition and location of the item was found. Nor was there an interaction between condition and number of syllables or between number of syllables and location of the test items.

Reaction-Time Analysis

Table 9 also presents the mean reaction times for the yes responses in the nonword and word conditions. These results were analyzed in a $2 \times 2 \times 2$ (Condition \times Location \times

Table 9
Experiment 3: Mean Accuracy and Reaction Time (RT)
Classified by Number of Syllables and Condition

| No. of syllables | Nonword condition | | Word condition | |
|------------------|-------------------|---------|----------------|---------|
| | Accuracy (%) | RT (ms) | Accuracy (%) | RT (ms) |
| 3 | 94 | 1,773 | 92 | 1,736 |
| 2 | 54 | 1,425 | 60 | 1,669 |

Number of Syllables) ANOVA by participants (F_1) and by items (F_2). No significant difference was found between test items in the nonword condition and in the word condition. The two-syllable items were responded to significantly faster than the three-syllable items (1,623 ms vs. 1,732 ms), $F_1(1, 23) = 9.4, p < .01, F_2(1, 4) = 1.43, p = .30$, as a probable consequence of the difference in duration of the test items (762 ms and 1,047 ms on average, respectively). No global effect of location of the test items in the utterance was found. No interactions were found between condition and number of syllables or location of the test item in the long utterance.

Discussion

The accuracy and response-latency analyses failed to show any difference between test items in the word and nonword conditions. Thus, we failed to find any evidence that participants inferred new units by extracting a familiar unit from the midst of an utterance. Although we cannot take this as a confirmation of the null hypothesis, it raises the possibility that the participants in fact did not infer new units in this way.

The one reliable effect in this experiment was that participants remembered having heard three-syllable test items more often than two-syllable test items (93% vs. 57%). There are two compatible explanations for this finding. First, it is possible that three-syllable items in general convey more sequential information than two-syllable items and therefore were less prone to errors. For example, an individual who recognizes one pair of adjacent syllables in a three-syllable item may be able to use that pair to retrieve his or her memory of the entire three-syllable item by association; for two-syllable items, there is no second chance. Likewise, a strongly unfamiliar pair may be enough to cause one to reject a three-syllable distractor one has not heard before. This interpretation is supported by the accuracy advantage for three-syllable distractors relative to two-syllable distractors, although this difference was only marginally significant (78% vs. 68%), $F_1(1, 23) = 3.44, p = .08, F_2 < 1$. A second explanation for participants' greater tendency to recognize three-syllable test items is that these items contain a syllable that occurred more frequently during the familiarization phase than the other syllables of the test items. For example, when *bc* and *abcde* were presented during familiarization, the syllables *b* and *c* occurred twice as often as the syllables *a*, *d*, and *e*. Test items that contained a high-frequency syllable (*c* in the test item *cde* or *m* in the test item *klm*) were three syllables long; they might have been responded to with a higher accuracy because the frequent syllable served as an anchor, activating the memory traces of the sequence where it appeared more efficiently than the less frequent syllables.

The lack of a reliable difference between the word and nonword conditions in Experiment 3 could be due to acoustic factors (see General Discussion). Future experiments using more sensitive methods may reveal that people can infer novel words by extracting a familiar word from the middle of an utterance. Nonetheless, the results of Experi-

ment 3 suggested the possibility that participants might have more difficulty inferring novel wordlike units by extracting familiar units from the middle of an utterance than by extracting familiar units from the edge. Experiment 4 investigated that possibility directly.

Experiment 4

Experiment 4 was designed to show a positive effect if participants had more difficulty inferring new words by extracting *bc* from *abcde* than by extracting *ab* from *abcde*. In this experiment, one group of participants (Group 1) was presented with two short utterances, *ab* and *bc*, and a long utterance, *abcde*. Because these two short utterances share a syllable (*b*), they could not both be extracted within the same segmentation, and hence they competed for the segmentation of the long utterance: The extraction of *ab* would yield the segmentation *ab_cde*, whereas the extraction of *bc* would yield the segmentation *a_bc_de*. INCDROP predicts that *ab*, rather than *bc*, should be extracted, because the extraction of *ab* minimizes the number of novel words. If the extraction of *ab* is favored against the extraction of *bc*, the new unit *cde* should be inferred and stored in memory. To assess this segmentation, we needed to compare the performance on the test item *cde* for this group of participants with the performance of another group, for which that test item would not correspond to an inferred unit. This second group of participants (Group 2) was thus presented with the short utterance *abc*, which should trigger the segmentation *abc_de*. For this group, the test item *cde* is not an inferred unit and thus should be remembered less well than for Group 1; conversely, the test item *de* should be remembered better for Group 2 than for Group 1, for which it is not an inferred unit. The design and predictions for the item set *abcde* were as follows (with predicted inferred units shown in boldface), on the assumption that participants in Group 1 would extract the familiar unit from the edge rather than the middle of the utterance:

| | Familiarization | Inference | Control |
|---------|-----------------------|----------------|----------------|
| Group 1 | <i>ab, bc, ab_cde</i> | <i>cde, de</i> | <i>abc, ab</i> |
| Group 2 | <i>abc, abc_de</i> | <i>cde, de</i> | <i>abc, ab</i> |

As in Experiments 2 and 3, we compared participants' performance in remembering predicted inferred units with their performance in remembering items that were longer or shorter than the predicted inferred unit (inference test items). As a control, we also compared their performance in remembering the short utterances they heard in isolation (e.g., *ab* for Group 1 and *abc* for Group 2) with their performance in remembering items that were one syllable longer or shorter (control test items). This control was meant to ensure, using a simpler test case in which the sequence of syllables was bounded by silence during familiarization, that a sequence of syllables is remembered better when it corresponds to a unit in memory than when it does not.

Method

Participants

Twenty-three students from the University of Maryland at College Park volunteered and received course credit for their participation. They were all native speakers of English and were tested individually in a quiet room.

Materials

Four item sets were used, the same ones used in Experiment 3 (but different from those used in Experiment 2). Each item set was composed of a long utterance (e.g., *abcde*), two bisyllabic short utterances (e.g., *ab* and *bc*), one trisyllabic short utterance (e.g., *abc*), and two test items (e.g., *cde* and *de*). Distractors consisted of bisyllabic and trisyllabic sequences of syllables that did not occur in sequence during the familiarization phase. We used the tokens from Experiment 3, supplemented with new trisyllabic short utterances and additional distractors. The same female speaker recorded the new materials in a single session. In addition, one more token of the short utterances was selected from the previous recording for the control test items (e.g., *ab*), so none of the test items in the test phase were acoustically identical to what had been heard during the familiarization. There were 16 test items consisting of syllable sequences heard during familiarization and 16 distractors consisting of syllable sequences not heard during familiarization. Of the 16 test items, 8 were intended to test whether recognition was facilitated for inferred units as compared with items that were shorter or longer by one syllable (inference test items); the other 8 were controls to check that recognition was facilitated for the short utterances as compared with items that were shorter or longer by one syllable (control test items). Among these 32 items, the number of trisyllabic and bisyllabic items was counterbalanced, as well as the number of times each syllable was presented.

Design

For each item set, one group of participants heard the two overlapping short utterances, and another group heard the single trisyllabic short utterance. Both groups heard the same long utterance. For the item set *abcde*, for example, Group 1 heard the short utterances *bc* and *ab* and the long utterance *abcde*, for which we predicted the segmentation *ab_cde*; Group 2 heard the short utterance *abc* and the long utterance *abcde*, for which we predicted the segmentation *abc_de*. In the test phase, the test item *cde* was in the word condition for Group 1 but in the nonword condition for Group 2; conversely, the test item *de* was in the word condition for Group 2 but in the nonword condition for Group 1. We compared participants' performance on the same items, across groups, and we

predicted better performance for test items when they were in the word condition than when they were in the nonword condition. Such a difference would indicate that the two groups had inferred different new units and, therefore, that the extraction of *ab* was favored against the extraction of *bc*, as predicted. Participants were assigned to Group 1 for half of the item sets and to Group 2 for the other half.

Procedure

The procedure was identical to that of Experiments 2 and 3. During the familiarization phase, each (long and short) utterance in each item set was presented in 2 repetition blocks followed by 28 simple listening blocks. The duration of the familiarization was about 24 min, with a break after 14 min.

Results

The overall accuracy on distractors and test items together was 77% on average. Participants were thus able to accurately remember whether a sequence of syllables had been heard before or not 77% of the time. The accuracy on distractors only was also 77%.

Inference Test Items

Table 10 presents the accuracies and reaction times for inference test items in nonword and word conditions as a function of the number of syllables in the item. Accuracies and reaction times were submitted to separate $2 \times 2 \times 2$ (Condition \times Location \times Number of Syllables) ANOVAs by participants (F_1) and by items (F_2).

Accuracy analysis. Accuracy was higher for test items in the word condition than for items in the nonword condition (73% vs. 60%), $F_1(1, 22) = 5.35, p < .05$, $F_2(1, 4) = 2.74, p = .17$. Accuracy for three-syllable items was higher than that for two-syllable items (83% vs. 50%), $F_1(1, 22) = 26.19, p < .0005$, $F_2(1, 4) = 3.45, p = .14$. No effect of the test-item location in the utterance was found. No significant interactions between condition and number of syllables or location or between number of syllables and location of the test item were found.

Reaction-time analysis. Items in the word condition were responded to faster than items in the nonword condition (1,613 ms vs. 1,791 ms), but the difference was only marginally significant, $F_1(1, 21) = 3.81, p = .06$ (the mean squared error was computed on 22 participants, because of missing data); $F_2 < 1$. Three-syllable items showed longer

Table 10
Experiment 4: Mean Accuracy and Reaction Time (RT) for Inference and Control Test Items,
Classified by Number of Syllables and Condition

| No. of syllables | Inference | | | | Control | | | |
|------------------|--------------|---------|--------------|---------|--------------|---------|--------------|---------|
| | Nonword | | Word | | Nonword | | Word | |
| | Accuracy (%) | RT (ms) | Accuracy (%) | RT (ms) | Accuracy (%) | RT (ms) | Accuracy (%) | RT (ms) |
| 3 | 78 | 1,909 | 87 | 1,658 | 89 | 1,722 | 98 | 1,490 |
| 2 | 41 | 1,566 | 59 | 1,546 | 87 | 1,369 | 98 | 1,304 |

mean reaction times than two-syllable items (1,777 ms vs. 1,554 ms), $F_1(1, 21) = 8.42, p < .01, F_2(1, 4) = 7.51, p = .05$, almost certainly as a result of their duration difference. No global effect of the location of the test items in the long utterance was found, and there were no interactions between condition and number of syllables or location or between number of syllables and location.

Control Test Items

Table 10 also presents accuracy percentages and reaction times for the control test items in nonword and word conditions as a function of the number of syllables in the item. Accuracy percentages and reaction times were submitted to separate $2 \times 2 \times 2$ (Condition \times Location \times Number of Syllables) ANOVAs by participants (F_1) and by items (F_2).

Accuracy analysis. Control test items in the word condition were responded to more accurately than items in the nonword condition (98% vs. 88%), $F_1(1, 22) = 5.75, p < .05, F_2(1, 4) < 1$. No effect of number of syllables or location in the long utterance was found. Also, there were no significant interactions between condition and number of syllables or item location or between number of syllables and location of the test item.

Reaction-time analysis. Control test items were responded to faster in the word condition than in the nonword condition (1,397 ms and 1,548 ms, respectively), $F_1(1, 22) = 9.70, p < .005, F_2(1, 4) = 2.21, p = .21$. Moreover, two-syllable items were responded to faster than three-syllable items (1,334 ms and 1,600 ms, respectively), $F_1(1, 22) = 42.53, p < .00001, F_2(1, 4) = 5.22, p = .08$, which again can easily be explained by the duration difference between these items (820 ms and 1,120 ms, respectively). No effect of the location of the item in the long utterance was found. Also, there were no interactions between condition and location of the test item or between number of syllables and location.

Comparison Between Inference and Control Test Items

Accuracies for and reaction times to both the control test items and the inference test items were analyzed together in a new $2 \times 2 \times 2 \times 2$ ANOVA that included test-item type (control vs. inference) as a variable. Accuracy was higher for control than inference test items (on average, 93% vs. 66%), $F_1(1, 22) = 53.9, p < .0005, F_2(1, 8) = 8.99, p < .05$. A word–nonword difference in accuracy was found for both the control and inference test items (9.8% and 13%, respectively), with no interaction between condition and test-item type (control or inference). As far as the response latencies were concerned, control test items were responded to faster than inference test items (1,468 ms vs. 1,693 ms), $F_1(1, 22) = 16.9, p < .001, F_2(1, 8) = 7.28, p < .05$. Both control and inference test items were responded to faster in word conditions than in nonword conditions (by 151 ms and 178 ms, respectively), with no interaction between condition and test-item type (control or inference).

Discussion

Experiment 4 aimed to determine the outcome of a competition between a familiar unit occurring at the edge of an utterance and a familiar unit embedded in the middle of the utterance. INCDROP explicitly predicts that the segmentation involving the extraction of a familiar unit at the edge of the utterance should be favored against the segmentation involving the extraction of a familiar unit embedded in the utterance, because the former implies only one new unit, whereas the latter implies two. To test this prediction, we compared the responses to test items in word and nonword conditions, as predicted by the model. Test items in the word condition were responded to more accurately and tended to be responded to faster than items in the nonword condition, supporting the model's predictions. However, we do not have evidence that the two familiar units actually competed for segmentation. It is possible that the medially embedded familiar unit was perceptually more difficult to recognize and extract than the familiar unit at the edge. We return to this point in the General Discussion section. As in Experiment 3, accuracy for three-syllable inference test items was higher than that for two-syllable inference test items. The presence of a high-frequency syllable or the more informative nature of three-syllable sequences could explain this effect. The fact that participants were better able to recognize that they had not heard three-syllable distractors than two-syllable distractors supports the latter hypothesis (86% vs. 65%), $F_1(1, 22) = 24.38, p < .0005, F_2(1, 14) = 5.64, p < .05$.

In addition to testing the inference test items, we tested the recognition of control test items, which consisted of either the exact short utterance heard in isolation or a sequence that was longer or shorter by one syllable. Accuracy was higher when the control test items corresponded to the exact short utterance. The response latencies showed a clear facilitation for responding to the control test items in the word condition relative to the nonword condition. This nonword–word effect for the control test items confirms that accuracy and response latency in remembering a sequence of syllables are enhanced when the sequence consists of a unit in memory; both the short utterance bounded by silence and the new unit inferred after segmentation showed such a facilitation.

General Discussion

Summary of Predictions and Results

INCDROP is a model put forth to explain how humans at all stages of linguistic knowledge discover new wordlike units from continuous speech (Brent, 1997; see also Brent, 1996, 1999; Brent & Cartwright, 1996). It posits a single mechanism that discovers new units by recognizing familiar units in an utterance, extracting those units, and treating the remaining contiguous stretches of the utterance as novel units. When an utterance contains no familiar units, the whole utterance is treated as a single novel unit, so there is no need to assume a special bootstrapping device that discovers the first units. Like all of the proposed phonologi-

cal strategies for segmentation and word discovery, this mechanism is not expected to be foolproof. Rather, the theory is that this mechanism generates a set of units that are candidates for becoming the sound patterns of words, if an appropriate meaning or syntactic function can be assigned to them.

This series of experiments suggests that new units can be isolated by recognizing familiar units and segmenting them out of the longer context in which they are embedded. The evidence is that participants showed higher familiarity and stronger memory traces for sequences of syllables that corresponded to the new units predicted by this process, as compared with shorter or longer subsequences of the context. However, this does not imply that the new units have acquired the status of words for the participants or that they would automatically acquire lexical status for child learners presented with analogous linguistic stimuli. Conversely, the sequences that violate unit boundaries are not necessarily excluded from acquiring lexical status. Indeed, participants consistently found these latter sequences more familiar than sound patterns formed by syllables that did not occur successively, as shown by the high percentages of yes responses for test items in the nonword condition in all of the experiments presented here. Yet, participants treated sequences of syllables in the word and nonword conditions differently. We interpret participants' greater sense of familiarity with the items in the word condition as evidence that these items are better candidates than items in the nonword condition for binding with meaning or syntactic function to form lexical entries.

At a more detailed level, INCDROP asserts that people segment utterances in such a way as to minimize the number of implied novel wordlike units, minimize the length of the utterance attributed to novel units, and maximize the product of relative frequencies of the segmented units. Brent and Cartwright (1996) showed, using computer simulations, that segmenting according to these criteria was effective at extracting words from broad phonetic transcriptions of child-directed speech. The present study aimed to test whether listeners actually segment utterances and infer new units as predicted by the model. In the experiments reported here, adult participants were exposed to short and long utterances from a miniature artificial language. Some of the short utterances appeared at the edge of a long utterance, and others appeared in the middle of a long utterance. The model predicts that the short utterance will become a familiar unit. Furthermore, when a familiar unit occurs at the edge of the long utterance, the model predicts that it will be extracted and that the remainder of the long utterance will be treated as a novel unit, unless the familiar unit is both very short and very rare. When the familiar unit occurs in the middle of the long utterance, however, segmenting it out implies two novel units, whereas treating the whole utterance as a novel unit implies only one. This cost in more novel words also implies a cost in lowering the product of relative frequencies. Thus, the model predicts that extracting a familiar unit from the middle of a longer utterance will be more difficult than extracting from the edge, although extracting from the

middle should still be possible if the familiar unit is sufficiently long and sufficiently frequent.

Experiments 1 and 2 tested the inference of a new unit after extraction of a familiar unit located at the edge of the long utterance. When asked to judge whether a test item was a word of the made-up language (Experiment 1), participants considered the predicted inferred units to be words more often than fragments of the long utterance that were longer or shorter than the predicted inferred units. When asked whether they had heard a sequence of syllables during the familiarization phase (Experiment 2), participants were more accurate at recognizing the predicted inferred units than fragments of the long utterance that were longer or shorter than the predicted inferred units. Experiment 3 aimed to test whether a familiar unit can be extracted from the middle of the long utterance, causing two new units to be inferred. One group of participants was exposed to a short utterance that appeared at the edge of the long utterance (e.g., *ab* in *abcde*), whereas another group was exposed to a short utterance that appeared in the middle of the long utterance (e.g., *bc* in *abcde*). If both groups segmented out the short utterance and treated the remaining contiguous stretches as new units, we would expect the first group to treat *cde* as a unit but not *de*, and vice-versa for the second group. We did not find a reliable difference between the two groups. This led us to design Experiment 4 in such a way that there would be an effect if participants found it easier to extract a familiar unit from the edge of an utterance than from the middle. In this experiment, we presented both an edge-embedded familiar unit and a medially embedded familiar unit to the same participants. Both familiar units could not be extracted in the same segmentation because they overlapped by one syllable. The results suggested that the familiar unit at the edge, rather than in the middle, was extracted and that the remainder of the utterance was inferred as a new unit.

These results with adult participants suggest that the human mind is capable of the types of computations and behaviors predicted by INCDROP. However, experiments with young children would be required to prove that the same conclusions apply to children in particular.

Possible Explanations for the Difficulty of Extracting From Utterance-Medial Position

The failure to find extraction of a familiar unit from the middle of an utterance may be due to perceptual factors, cognitive factors, or both. One perceptual explanation is that syllables at utterance boundaries are more acoustically salient. Words tend to be longer in utterance-final position and pitch excursions larger in utterance-initial position (Klatt, 1974, 1975, 1976; Oller, 1973; Umeda, 1977). Further support for the influence of utterance position on salience comes from Fernald et al. (in press), who found that 15-month-old infants showed notably enhanced comprehension of utterance-medial words when their duration was increased. A second perceptual explanation depends on the degree of acoustic similarity between the short utterance when it occurs in isolation and the same syllable sequence

when it occurs within the longer utterance. Consider once again the fact that words tend to be longer in utterance-final position, and pitch excursions are larger in utterance-initial position. When *bc* occurs in isolation, its two syllables are initial and final, respectively; when it occurs in *abcde*, both of its syllables are medial. When the short utterance occurs at the edge of the long utterance, however, one of its syllables is in the same position as when the short utterance occurs in isolation. In addition, coarticulation may render medially embedded utterances less acoustically similar to their isolated counterparts. When the short utterance is at the edge of the long utterance, only the medial end of the short utterance (e.g., *b* when *ab* is embedded in *abcde*) is subject to influence by neighboring segments; when the short utterance is in the middle of the long utterance, both ends are.

The relative difficulty of extracting a familiar unit from the middle of an utterance as compared with the edge could also be explained by cognitive factors. Descriptively, better recognition of familiar units at the edges of the utterance could be attributed to recency and primacy effects. However, INCDROP explains this effect in terms of the number and length of novel units; familiar units at the edges of utterances simply happen to imply fewer novel units. The INCDROP explanation therefore makes additional predictions, as described below.

The experiments presented here do not even distinguish between the perceptual and the cognitive account, much less between the various versions of each. However, one can imagine future work that might, in principle, show that the advantage of edge-embedded units over medially embedded units is at least partially explained by INCDROP. A first step would be to relieve the potential perceptual difficulties by making the embedded and isolated occurrences of the short utterance acoustically identical. The chief disadvantage of this approach, and the reason it was not used here, is that the result inevitably sounds unnatural, and this unnaturalness may well wipe out any improvement in recognizability due to acoustic similarity. Another step would be to design materials that could distinguish the INCDROP explanation, which depends on the number of implied novel units, from the perceptual and recency-primacy explanations, which depend directly on the edge of the long utterance. Informally, INCDROP favors extracting familiar units that occur adjacent to other familiar units as well as those that occur at the edge of the utterance. For example, suppose that *ab*, *cd*, and *de* are all familiar units. INCDROP predicts that the utterance *abcdef* will be segmented as *ab_cd_ef*, with the two familiar units *ab* and *cd* adjacent to one another, not as *ab_c_de_f*, with the two familiar units *ab* and *de* separated by the novel unit *c*. The reason is that the segmentation in which the familiar units are adjacent minimizes the number of novel units. In this example, the preference for fewer novel units does not coincide with a preference for extracting familiar units at the edges of the utterance. The chief difficulty of this approach is that both the cognitive and perceptual burdens in this design are substantially greater than those in the designs used so far. Specifically, individuals must learn three familiar units and recognize two of them

in a larger utterance, including one in medial position. Finally, it should be noted that all of the explanations laid out here could contribute to the results we have observed; finding effects that can be explained only by INCDROP would not imply that the other factors cited play no role.

Can These Results Be Explained by Transitional Probabilities Alone?

The results reported are consistent with predictions of the INCDROP model, but we must consider whether they could be explained equally well by a segmentation procedure based solely on transitional probabilities. To answer this question, we must assume a precisely formulated account of transitional-probability segmentation. For this purpose, we adopt the mathematical definition of transitional probability offered by Saffran, Newport, and Aslin (1996), and we assume that segmentation occurs precisely when the transitional probability between two adjacent syllables is lower than the transitional probability between the pairs of syllables on either side. The analysis presented here does not apply to any other segmentation algorithm based on transitional probabilities or any other statistics on the co-occurrence of adjacent syllables that might be proposed.

Saffran, Newport, and Aslin (1996) defined the transitional probability between two syllables *x* and *y* as the proportion of occurrences of *x* that are followed by *y*. Clearly, transitional probabilities are asymmetric, taking account of the proportion of *xs* followed by *y* but not the proportion of *ys* preceded by *x*. One consequence of this asymmetry is that transitional probabilities make the same prediction as INCDROP for Experiments 1 and 2 when the familiar unit is at the beginning of the long utterance but not when it is at the end. For example, consider participants exposed to *ab* and *abcde* with equal frequency. The short utterance *ab* is at the beginning of *abcde*, and the transitional probability is lowest between *b* and *c*; half of the occurrences of *b* were followed by a pause and half by the syllable *c*, whereas the other syllables were consistently followed by the same context. Now consider participants exposed to *de* and *abcde* with equal frequency. The short utterance *de* is at the end of *abcde*, and the transitional probabilities in the long utterance are all equally high, because each syllable is always followed by the same context. Although *d* is preceded by both *c* and silence, it is only the following context that determines transitional probability. Thus, the transitional probabilities do not predict any segmentation when the short utterance is at the end of the long utterance. However, we found segmentation and inference with short utterances at either edge.

In Experiment 4, we found evidence that participants exposed to *ab*, *bc*, and *abcde* with equal frequency inferred that *cde* is a novel unit. This implies that they segmented the utterance between *b* and *c*, as predicted by INCDROP. The only local minimum of transitional probability, however, lies between *c* and *d*. To see this, note that all of the *as* are followed by *b*, two thirds of the *bs* are followed by *c*, only half of the *cs* are followed by *d*, all *ds* are followed by *e*, and all *es* are followed by silence.

These observations seem to suggest that a segmentation strategy based only on transitional probabilities does not accurately predict patterns of segmentation when the input consists of short utterances. Nonetheless, transitional probabilities might work together with lexically driven segmentation. For example, they might serve as a useful measure of whether a hypothesized new word “sounds like” a word of the language being learned, that is, whether it has probabilistic phonotactics appropriate for that language. Furthermore, INCDROP’s prediction that utterances will be stored as a single unit when they contain no familiar units breaks down when all input utterances are very long. INCDROP only models the relative cognitive burden of different ways in which an utterance could be exhaustively divided into familiar words and novel words to be memorized; it does not predict what will happen when the burden becomes so great that it is not possible to process the utterance exhaustively and some parts of it must be abandoned, neither recognized as familiar units nor learned as novel units. In such cases, local statistics such as transitional probabilities may play a dominant role in segmentation.

Language and Memory

The work reported here began with a theory about how children acquire language, and its ultimate aim is still to improve understanding of language acquisition. However, INCDROP can be thought of in more general, cognitive terms, as a model of how people divide up speech and store it in memory. Indeed, what we have shown in these experiments is more directly interpretable in terms of general cognitive strategies than in terms of native-language acquisition. Nonetheless, if children have at their disposal the same types of automatic storage strategies as adults, that could help explain how they accomplish one of the many remarkable feats of language acquisition. One need not be an empiricist about syntax and phonology to believe that word discovery piggybacks on general strategies for storing sequences in memory.

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