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Studying the Grammatical Aspects of Word Recognition: Lexical Priming, Parsing, and Syntactic Ambiguity Resolution

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Two experiments are reported examining the relationship between lexical and syntactic processing during language comprehension, combining techniques common to the on-line study of syntactic ambiguity resolution with priming techniques common to the study of lexical processing. By manipulating grammatical properties of lexical primes, we explore how lexically based knowledge is activated and guides combinatory sentence processing. Particularly, we find that nouns (like verbs, see Trueswell & Kim, 1998) can activate detailed lexically specific syntactic information and that these representations guide the resolution of relevant syntactic ambiguities pertaining to verb argument structure. These findings suggest that certain principles of knowledge representation common to theories of lexical knowledge—such as overlapping and distributed representations—also characterize grammatical knowledge. Additionally, observations from an auditory comprehension study suggest similar conclusions about the lexical nature of parsing in spoken language comprehension. They also suggest that thematic role and syntactic preferences are activated during word recognition and that both influence combinatory processing.

KEY WORDS: On-line language comprehension; grammatical knowledge; lexical priming; word recognition; syntactic processing; parsing.

INTRODUCTION

As part of the process of comprehending speech or text, the language system must achieve two important goals: (1) the recognition of individual

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words and the meaning that they convey, and (2) the linking of these words together to form phrases, which convey further combinatory meaning. Most psycholinguistic theories have assumed that these processes are instantiated within separate subsystems that involve diametrically opposed sorts of computations. When comprehending sentences, we *recognize* words but *build* phrase structure.

Recent developments in psycholinguistic theorizing have led many to question this supposed dissimilarity between lexical and phrasal processing. Many have begun to ask: What if we also recognize the presence of phrases? And what if the detection of these phrases triggers the conveyance of combinatory meaning? Such assumptions might provide continuity within theories of language comprehension because the system would become a probabilistic pattern recognition device *through and through,* detecting linguistic events of various sorts at multiple levels (phonemes, words, phrases). These assumptions might also change what is thought to be involved in lexical and phrasal processing. As we discuss below, these assumptions imply a notion of lexical processing that bears considerably more responsibility for the combinatory analysis of language.

Psycholinguistics has not been alone in this focus on the lexical aspects of combinatory processing. Syntactic theory has increasingly moved detailed combinatory information into the lexicon, where individual lexical items are associated directly with their syntactic and semantic combinatory options (e.g., Chomsky's 1993 Minimalist Program, and grammatical formalisms such as Lexicalized Tree Adjoining Grammar (LTAG; Joshi & Schabes, 1996) and Combinatory Categorial Grammar (CCG; Steedman, 2000)). The field of applied parsing in computational linguistics has also seen a shift toward lexicalization (Srinivas & Joshi, 1999). Many have recognized the effectiveness of coding these syntactic options as tendencies (i.e., the probability of each option given a word and its local context). In doing so, statistical natural language processing systems have begun to be able to recover the grammatical structure of novel sentences with astonishing accuracy (Collins, 2000; Marcus *et al.,* 1993; see also Jurafsky & Martin, 2000).

These movements in linguistics and computational linguistics touch on many of the same issues that have given rise to the development of constraint-based lexicalist theories of parsing in psycholinguistics (e.g., Kim *et al.,* 2002; MacDonald *et al.,* 1994; Trueswell & Tanenhaus, 1994). In ways similar to the statistical NLP systems, these theories propose that the recognition of a word involves the relative activation of detailed grammatical options, which are used to guide further combinatory processes. As a result, the frequency-based activation of lexical alternatives becomes the basis for the resolution of many syntactic ambiguities.

Some of the best support for this view has come from on-line studies of reading, which have shown that the subcategorization and thematic role tendencies of individual verbs can guide the resolution of local syntactic ambiguity (e.g., Britt, 1994; Holmes *et al.,* 1989; Garnsey *et al.*, 1997; Trueswell *et al.,* 1993; Trueswell *et al.*, 1994). For instance, Garnsey *et al.* (1997) examined readers' abilities to resolve temporary syntactic ambiguities involving classic Direct Object / Sentence Complement ambiguity, illustrated in Example (1).

(1) The talented photographer accepted the fire could not have been prevented.

Here the noun phrase (NP) *the fire* could be temporarily considered as the direct object of the verb *accepted* or as the subject of a sentence complement. Garnsey *et al.* found that readers' initial commitment to an interpretation of this ambiguous phrase was determined not only by the grammatical tendency of the verb to take a direct object or sentence complement (e.g., *accepted* vs. *insisted*) but also by the semantic fit of the NP as a Theme for the event (e.g., *fire* vs. *prize*). Thus, in a manner consistent with constraint-based lexicalist accounts, a verb's detailed syntactic and thematic preferences played an important role in guiding the syntactic processing of the sentence.

Evidence of this sort, although consistent with lexicalist theories, raises important questions about the relationship between lexical and syntactic processing and crucially leaves key elements of such a theory unexplored. For instance, what is the time-course with which subcategorization and thematic information are activated? Is verb-specific syntactic and semantic combinatory information activated during the recognition of the verb, as constraint-based lexicalist theories would predict? Findings from verb reading-time studies have been especially equivocal on this issue (e.g., Schmauder, 1991; Shapiro *et al.,* 1991). In addition, questions remain about the nature of combinatory information associated with lexical items. Is detailed combinatory information restricted to verbs, or do other lexical classes activate similar information, making this, as should be the case, a general claim about the lexical system? And, in relation to the nature of lexical representations, should lexically specific combinatory information be thought of as prestored lexical entries, or as shared distributed representations, reflecting the history of lexico-syntactic regularities?

In this paper, we present the results of two experiments, which are part of a line of research from our lab that is designed to explore answers to these questions. In particular, the experiments make use of two different lexical priming techniques that are employed during the collection of on-line measures of sentence comprehension and syntactic ambiguity resolution. These

experiments differ from most studies of syntactic ambiguity resolution because we have opted to intervene in the ongoing comprehension process, typically covertly, via the brief / attenuated presentation of a lexical prime. Because our primes are rarely identified by readers and listeners, we are free to manipulate the properties of our primes quite severely, often using words that would be completely inappropriate in the target sentence if they were perceptually identified. In spite of this, our priming interventions influence comprehension processes in ways anticipated by lexicalist parsing theories. As we attempt to illustrate here, these priming patterns tell us a great deal about the role of lexical processing in the combinatory analysis of language.

Background: Lexical Priming and Syntactic Ambiguity Resolution

The use of lexical priming techniques in psycholinguistics has arguably been a highly effective tool for studying both the content of lexical representations and the time-course with which such information is activated (e.g., Foss, 1988). For example, priming has been used to map the time-course of activation of phonological and orthographic information during word recognition (e.g., Forster & Taft, 1994; Kouider & Dupoux, 2001) as well as the activation of the alternative meanings of ambiguous words (e.g., Simpson & Burgess, 1985). In most cases, however, the tasks used in these studies to measure participants' reaction to target words (i.e., naming and lexical decision) are unlikely to be influenced by any hypothesized coactivation of subcategorization or thematic role information, because such information is typically not relevant to successful execution of these tasks. Moreover, tasks that are sensitive to this sort of information, such as the collection of reading times on individual words during sentence comprehension, have not been amenable to lexical priming techniques because the introduction of a consciously perceived prime word, midsentence, would catastrophically disrupt the ongoing comprehension of the sentence as a whole.

In the early 1990s, however, Rayner and colleagues (Rayner *et al.*, 1995; Sereno & Rayner, 1992) introduced a covert lexical intervention technique, dubbed fast priming, which allowed for the study of lexical priming effects during the free reading of continuous text. In these studies, the eye movements of readers were tracked and used to contingently update the presentation of text on the computer screen. When the eyes landed on a target word, a prime word was presented for approximately 30 ms, followed by the target word. Although such events were typically perceived as a flicker, it was found that reading times were systematically influenced by the orthographic, phonological, and even semantic relationships between the prime–target pair (e.g., Rayner *et al.*, 1995; Sereno & Rayner, 1992; Sereno, 1995). Taken together, these data are highly consistent with theories of word recognition that allow

for the parallel activation of orthographic, phonological, and semantic information associated with a letter string.

A clear prediction of lexicalist parsing theories is that word recognition also includes the activation of detailed combinatory information, in the form of possible complements that a word may take. It is this activation process that ought to influence the relative availability of alternative syntactic analyses. If this is the case, the syntactic preferences of a briefly presented prime word ought to have a direct impact on a reader's parsing preferences of a syntactically ambiguous phrase. Trueswell and Kim (1998) tested these predictions in a series of experiments using a self-paced reading version of fast priming. In the study, they examined how the fast priming of verbs can influence the way in which readers process sentences containing the Direct Object/Sentence Complement ambiguity in (1) above. Like Garnsey *et al.* (1997), Trueswell and Kim (1998) compared the reading times of temporarily ambiguous sentences (e.g., Example 1) to unambiguous versions that included a "that" (e.g., . . . *accepted that the* . . .). Increased reading times at the disambiguating phrase (e.g., . . . *would go* . . .) were taken as signs of misanalysis of the ambiguous NP (e.g., *the fire*) as the direct object of the verb.

Prior to reading each sentence, the words of the sentence were masked with each character in a word covered by an equal sign ('='). Each press of the button uncovered a word and replaced the previous word with equal signs. On critical trials however, when the participant reached the matrix verb (e.g., *accepted*), a prime word was displayed in its place for 39 ms. The prime verb was then replaced by the target verb, which remained on the screen until the next press of the button. This event was typically perceived as a flicker on the screen, with participants reporting in a detailed post-experiment questionnaire that they rarely identified any prime words. Two different types of prime words were compared, which had been selected based on their argument-taking properties as measured from a separate sentence completion study. DO-Primes (e.g., "obtained") were verbs that strongly prefer a direct object and do not permit a sentence complement. SC-Primes (e.g., "realized") were verbs that strongly prefer a sentence complement and rarely use a direct object. If the recognition of a verb includes the activation of its possible argument structures, we might expect that the argument preferences of the "flicker" (the prime) would influence the size of the garden-path effect; DO-Primes should induce a large garden-path effect, whereas SC-Primes should reduce the garden-path effect.

Indeed, the experiments showed the expected pattern of priming. In particular, Trueswell and Kim (1998) observed that the processing difficulty usually found in the disambiguating region of ambiguous (no-that) sentences was significantly decreased when the matrix verb had been primed with a SC-Prime as compared to when it had been primed with a DO-Prime. That is, dif-

ficulty that stems from readers erroneously committing to a direct object analysis, due to their detecting the implausibility of the noun as the direct object and having to revise this syntactic commitment, was far less likely to occur when the prime provided argument structure information that could help the reader avoid this misinterpretation. Crucially, the priming had its influence only on the ambiguous conditions and not the unambiguous conditions, implicating the primes' influence on avoiding the garden-path and not the general fit of the prime into the sentence. One other observation from Trueswell and Kim (1998) is also worth mentioning, because we will be comparing it to the findings of Experiment 1 reported here. In both of their experiments, they observed a 30 ms effect of priming at the verb, with SC-Primes being faster than DO-Primes. This effect may suggest a partial role for semantic priming in this process, a point we return to later in this paper.

In sum, the Trueswell and Kim (1998) findings show that garden-path effects can be considerably mitigated by a briefly displayed prime verb, even though the primes were rarely identifiable to the readers. Prime verbs that prefer to take a sentence complement reliably reduced the garden-path typically associated with ambiguous sentence complement constructions. Moreover, the timing of these primes, as well as their subjective perception by participants, strongly suggests that verb combinatory information of this sort is automatically activated during word recognition.

EXPERIMENT 1: FAST PRIMING OF NOUN ARGUMENT STRUCTURE

The Trueswell and Kim (1998) results contribute to a debate on the lexicon's role in comprehension that has focused heavily on the combinatory properties of verbs. This focus on verbs makes sense, given the wide range of research assuming an anchorlike status of verbs in the syntactic and thematic organization of language. Although verbs may be the obvious starting point for the study of lexically based combinatory knowledge, lexicalist proposals clearly hypothesize that other types of words share the burden of combinatory knowledge representation (e.g., Kim *et al.,* 2002).

Perhaps the simplest reason for an account that extends beyond verbs alone is that grammatical phenomena suggest it. For instance, nouns like *opinion* can, like the verb *accepted* in (1), combine with a finite clause (e.g., *we should go*), as in (2):

(2) (She expressed) the **opinion** that we should go.

If the knowledge that drives combinatory processing is lexically generated, then nouns like *opinion* ought to encode knowledge about the complements

they can occur with. This same construction illustrates another reason to extend the inquiry beyond verbs: The syntactic similarity between nouns like *opinion* and verbs like *accepted* (in (1)) suggests an underlying connection between their lexical representations. Specifically, the representations of words like *opinion* and *accepted* may contain shared components, even though the words belong to different basic grammatical categories. That is, knowledge of sentential complements is encoded by overlapping distributed lexical representations.

As reported here, we conducted an experiment to investigate the hypothesis that the comprehension of sentential complement constructions is driven by lexical knowledge representations that are shared by both nouns and verbs. We used an experimental approach that was similar to that used by Trueswell and Kim (1998), except that the prime words were nouns rather than verbs.

Methods

Participants

Thirty-six adults from the University of Pennsylvania community volunteered for the experiment. Participants received course credit or were paid for their participation. All were native speakers of English.

Materials and Procedure

Participants read sentences like (3), which were structurally identical to the sentences of Trueswell and Kim (1998).

(3) The ice skater doubted (that) the judges would keep her from competing.
   a. opinion (SC-bias prime)
   b. freedom (Abstract prime)
   c. machine (Concrete prime)

In each sentence, the target verb (e.g., *doubted*), could occur with either a direct object or a sentential complement. Unlike Trueswell and Kim (1998), however, the potentially ambiguous noun (e.g., *judges*) was always a good direct object of the target verb. This was done to eliminate a potential confound that existed in the previous experiments, in which increased reading times in the ambiguous conditions could be attributed either to the semantic anomaly of the noun (and its spillover) or to effects of garden-pathing.

Syntactic ambiguity was again manipulated by including or excluding the complementizer *that.* Sentences were read in a self-paced moving window

presentation. When readers encountered the position of the target verb, a prime noun was first presented for 39 ms and was then replaced by the target verb. Three levels of Prime-Type were crossed factorially with the Ambiguity factor: (a) "SC-bias" primes, nouns that frequently take a sentential complement (e.g., *opinion*); (b) "Abstract" primes, nouns that are semantically abstract, but which do not take sentential complements (e.g., *freedom*); (c) "Concrete" primes, semantically concrete nouns that never take sentential complements (e.g., *machine*). The syntactic properties of the prime nouns were determined in a separate norming study. SC-bias verbs were those that occurred with at least 30% SC-completions in the data set of Argaman and Pearlmutter (2002). Concreteness and Abstractness of primes was defined in terms of concreteness and imageability scores in the MRC Psycholinguistic Database (Coltheart, 1981). Concrete primes had high scores for concreteness and imageability. Both Abstract and SC-bias primes had low scores. Mean scores are included in Table I (scores are on a scale from 100 to 700).

Predictions

As in Trueswell and Kim (1998), priming effects were measured in the form of modulations of processing difficulty in the disambiguating region of the sentence, associated with the different levels of Prime Type. The use of two levels of control prime, Abstract and Concrete, allowed us to address the possibility that priming effects might be mediated by broad semantic similarities between SC-bias nouns and sentential-complement verbs, rather than by specifically combinatory representations. That is, SC-bias nouns such as *opinion* tend to denote abstract, relational concepts, as do sentential complement verbs. Priming effects between SC-bias nouns and sentential complement verbs could conceivably be mediated by this dimension of similarity. Abstract primes share the semantic abstractness of the SC-bias primes but not the tendency to occur with finite sentential complements. Thus, if SC-bias primes yield an effect while Abstract primes do not, then specifically combinatory knowledge is implicated over simple abstractness.

Table I. Concreteness and Imageability Ratings for Noun Primes from MRC Psycholinguistic Database (Coltheart, 1981)

	Characteristics		
Prime type	Frequency	Concreteness	Imageability
S-Comp primes	100.67	310.38	363.5
Abstract primes	115.83	293.4	424.1
Concrete primes	110.83	590.82	579.64

Table II. Fast Priming with Nouns, Mean Reading Times in Milliseconds for Each Word Position

		Word position					
Prime Type	Ambiguity	*doubted*	*(that)*	*the*	*judges*	*would*	*keep*
SC-Noun	No-that	378		387	366	359	323
	That	383	397	328	353	334	314
	Difference	−5		+59	+13	+25	+9
Abst./Conc.	No-that	410		389	380	397	344
	That	428	383	326	360	358	318
	Difference	−18		+62	+20	+39	+26

Results

Mean reading times are presented in Table II. Reading times for Abstract and Concrete primes are collapsed, because whenever effects of Prime Type occurred, planned comparisons showed that these two levels of Prime Type were not distinguishable, as discussed later. Figure 1 plots Ambiguity Effects (as a function of word position), i.e., the difference in reading times between the ambiguous and the unambiguous conditions.

In the disambiguating region (*would keep*), a main effect of Ambiguity was evident ($F1(1,35) = 13.83$, $p < .001$; $F2(1,23) = 14.66$, $p < 0.001$), indicating processing difficulty connected with syntactic misanalysis. Ambiguity effects were also seen in the determiner that followed the main verb ($F1 = 26.16$, $p < .001$; $F2 = 47.45$, $p < .001$). A similar effect of ambiguity was observed in Trueswell and Kim (1998) and may in part be the result of slight disruptions in processing due to the priming event.[4] Main effects of Prime Type were also seen, both in the disambiguating region ($F1(2,70) = 6.63$, $p < .005$; $F2(2,46) = 4.42$, $p < .05$) and also earlier, at the ambiguous verb (e.g., *doubted*) ($F1(2,70) = 5.11$, $p < .01$; $F2(2,46)$, $p < .05$).

Planned comparisons revealed that the effect of Prime Type was driven by the difference between the SC-bias condition and the other two Prime Types. In the disambiguating region, reading times for the SC-bias condition were faster than both the Abstract ($F1(1,35) = 8.42$, $p < .01$; $F2(1,23) < 4.06$, $p = .056$) and the Concrete conditions ($F1(1,35) = 12.88$, $p < .01$; $F2(1,23) = 10.14$, $p < .005$), while Abstract and Concrete were indistinguishable (Fs < 1). The same pattern occurred at the target verb, where SC-

[4] However, an ambiguity effect at the determiner has sometimes been found in nonpriming DO/SC studies (Trueswell *et al.*, 1993) and thus may reflect spillover from the complexity of the previous word (in the ambiguous case the previous word is a verb; in the unambiguous case it is the complementizer *that*).

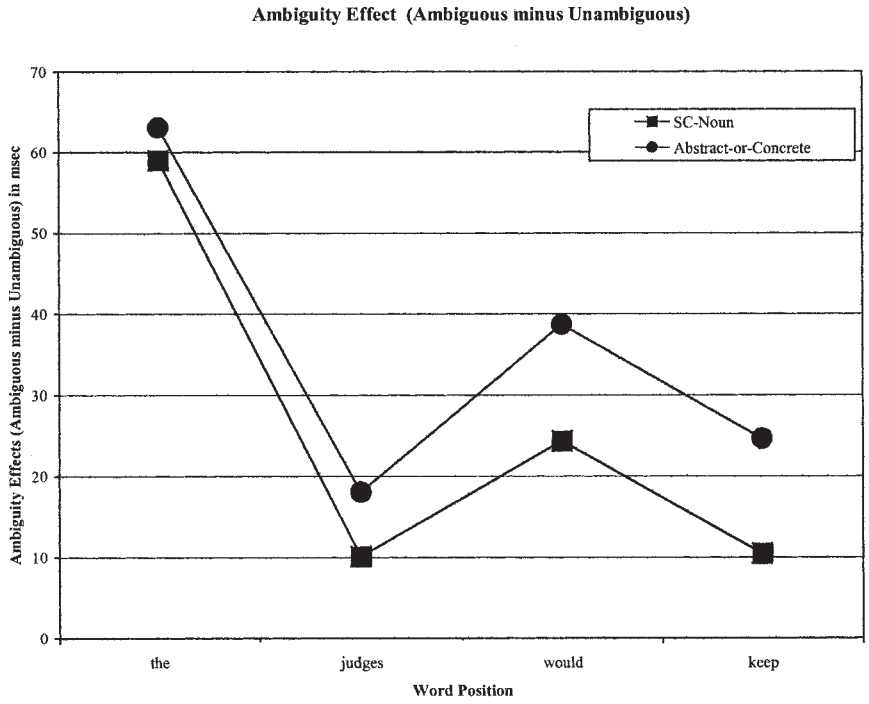

Fig. 1. Mean reading time differences between temporarily ambiguous and unambiguous sentences, as a function of word position.

bias reading times were faster than Abstract ($F1(1,35) = 8.58$, $p < .01$; $F2(1,23) = 7.194$, $p < .05$) and faster than Concrete conditions ($F1(1,35) = 6.00$, $p < .05$; $F2(1,23) = 4.25$, $p = .051$), and the Abstract and Concrete conditions were indistinguishable ($Fs < 1$).

The distinction between SC-bias and other types of prime also existed in Ambiguity effects (see Fig. 1). In the disambiguating region, the effect of Ambiguity was significant for both the Abstract ($F1(1,35) = 6.01$, $p < .05$; $F2(1,23) = 7.29$, $p < .05$) and Concrete ($F1(1,35) = 4.14$, $p < .05$; $F2(1,23) = 5.60$, $p < .05$) conditions, but not for SC-bias primes ($F1(1,35) = 2.8$, $p = .103$; $F2(1,23) = 3.12$, $p = .091$). Thus, evidence of syntactic misanalysis was observed for Abstract and Concrete primes but not for SC-bias primes. Figure 1 shows ambiguity effects with Abstract and Concrete primes collapsed because there were no statistical differences between these conditions.

Discussion and Summary

We found that fast priming effects generalize beyond verbs to another part of the lexicon, nouns. The short-lived processing of SC-bias noun primes influenced the syntactic processing of the host sentences in a manner that supports the sentential-complement interpretation. We claim that (even partial) processing of SC-bias nouns activates predictive knowledge about sentential complements. The representations that encode this knowledge are shared with sentential-complement verbs, and their preactivation influences the recognition of the target verb. By supporting the sentential-complement sense of the ambiguous target verb, the priming pushes the processing system toward the correct grammatical analysis of the sentence.

The similarity of Abstract and Concrete prime conditions constrains our interpretations. We mentioned the possibility that priming effects might arise from semantic abstractness in the primes. However, Abstract primes behaved differently from SC-bias primes and indistinguishably from Concrete primes. Thus, specifically combinatory knowledge is implicated over simple abstractness. It is intriguing to note that many of the Abstract primes were even capable of taking complements of some sorts (e.g., *the freedom to leave*). Thus, it appears that something quite specific is at work here.

These results demonstrate that nouns can project syntactic structure in a way that plays an active role in the guidance of sentence interpretation (see also Schütze & Gibson, 1999). This contribution of noun argument structure is expected under lexicalist proposals, given the need to specify combinatory information specific to these items. Furthermore, the facts from other languages support the need for a system that hypothesizes detailed structural information based on words other than verbs. For instance, if processing is to be incremental in verb-final languages, syntactic hypotheses must be based on evidence stemming from the distributional probabilities of preverbal nouns and their morphological markers (see, e.g., Kamide *et al.*, 2001; Kamide, *et al.*, 2002).

These results also demonstrate that the representations of nouns and verbs are, in some cases, related through the sharing of representational mechanisms. The sharing of this representational machinery is the basis of the observed priming effects. This may reflect a general and powerful principle of the organization of grammatical knowledge: It is distributed across representational mechanisms, which are shared by many elements of the lexicon, often across category boundaries. The principle of distributed knowledge representation is a fundamental claim of constraint-based proposals in language processing (e.g., Seidenberg & McClelland, 1989) and has been proposed specifically for lexically based parsing by, for example, Juliano & Tanenhaus (1994) and Kim *et al.* (2002).

EXPERIMENT 2: LEXICAL PRIMING IN ON-LINE SPOKEN LANGUAGE COMPREHENSION

Recently, our lab has been exploring the extent to which similar lexical priming effects can be observed during on-line spoken language comprehension. The study of spoken sentence comprehension has seen renewed interest in recent years with the advent of an innovative technique for studying real-time spoken language comprehension, in which listeners' eye movements are recorded as they hear spoken descriptions of a scene or spoken instructions to move real objects about (e.g., Tanenhaus *et al.,* 1995; cf. Cooper, 1974). Studies of this sort have shown that listeners' eye movements to potential referents are closely time locked with their linguistic instantiation in the speech stream (e.g., Allopenna *et al.,* 1998). This "visual-world" technique has also been shown to be highly effective for studying on-line parsing decisions in spoken language comprehension, especially when the syntactic alternatives have distinct referential interpretations (e.g., Tanenhaus *et al.,* 1995; Trueswell *et al.,* 1999; Spivey *et al.,* 2002).

In our "fast priming" variant of this task, participants heard prerecorded spoken instructions, uttered by a male, to move objects about on a table. At critical moments in the speech, however, a second audio track was digitally mixed in. This second track played a female voice producing a different lexical item (i.e., a lexical prime), and we were interested in how these lexical primes influenced the ongoing interpretation of the attended utterance. This paradigm takes advantage of a well-known phenomenon in perceptual attention, that during the simultaneous presentation of two spoken stimuli, the attention by the listener to one of these stimuli results in highly attenuated processing of the second stimulus to the point that its content typically cannot be reported (Cherry, 1953), even though the second stimulus could exert partial influence on perception (Treisman, 1960). Indeed, our own technique is reminiscent of the dichotic listening work carried out by Mackay (1973). In a series of experiments, MacKay examined participants' memory of ambiguous sentences, such as those containing lexical and even syntactic ambiguities. In one experiment, participants attended to ambiguous sentences presented in one ear (e.g., *They threw stones toward the* ***bank*** *yesterday*), while a prime was presented in the other ear (e.g., *river* or *money*). At the end of the experiment, subjects were tested on their memory of these sentences, explicitly being asked to choose between the two alternative meanings. MacKay found that participants' memory of a sentence was influenced by the type of prime that had been presented when the participants had originally heard the target sentence. Although MacKay's results are highly suggestive, the use of an off-line measure leaves open the question as to whether the lexical associates influenced the moment-by-moment perception and interpretation of the sentences or the memory representations of these sentences.

Methods

Participants

Sixteen participants from the University of Pennsylvania volunteered for the experiment. They received course credit or were paid for their participation. All participants were native speakers of English and had normal or corrected-to-normal vision.

Materials and Procedure

Like our fast-priming reading experiment, this experiment crucially combined a priming technique with an on-line measure of ongoing sentence processing commitments, so as to uncover how the combinatory preferences of these primes might influence the concurrent syntactic processing of the sentence. In particular, participants' eye movements were recorded as they heard spoken instructions, such as Example (5).

(5) Now I'd like you to turn the bear with the stick.

Target verbs (e.g., *turn*) were selected based on an earlier sentence completion study and dubbed Equi-bias verbs; that is, participants had been equally likely to complete a fragment like *Turn the doll with . . .* with an NP modifier or a VP instrument. Referential scenes in the on-line study contained a potential instrument object (e.g., a full-scale stick), a target animal (e.g., a toy bear holding a miniature replica of the instrument object), a competitor animal (e.g., a toy pig holding a knife), and a distractor item (e.g., a diskette).

One of two types of primes was digitally mixed and aligned with the target onset: Modifier-bias verbs (e.g., *hug*), which, according to previous norming studies, strongly prefer *with the X* as an NP modifier; or Instrument-bias verbs (e.g., *clean*), which strongly prefer to take *with the X* as a VP instrument. Postexperimental questionnaires revealed that listeners were largely unaware of the presence of the primes, and when aware, they were unable to identify what was being said. The consensus among participants was that some nonintrusive background noise was heard, which never disrupted their understanding of the target sentence.

Predictions

It was anticipated from earlier experiments using nonpriming versions of these same stimuli (Snedeker *et al.,* 2001) that listeners' actions and eye movements would reveal the kind of interpretation they assigned the ambiguous phrase. In particular, subjects who took *with the stick* as an instrument ought to look to the potential instrument upon hearing *stick* and use this object to perform the task; participants who took a modifier interpretation ought not to look

at the instrument and carry out the turning using his/her own hands. Critically, if the combinatory preferences of the prime verb influence the interpretation, then we would expect Instrument-bias Primes to increase the rate of instrument looks and responses, whereas Modifier-bias Primes ought to decrease this rate.

Results—Off-line and On-line Measures

The constraint-based lexicalist predictions were supported. As shown in Fig. 2, the proportion of time spent looking at the Potential Instrument (Fig. 2a) and the proportion of trials in which the Potential Instrument was used, were both influenced by the type of prime. The Instrument-Prime condition showed greater instrument looks/actions than the Modifier-Prime condition. The effect of prime type on looks to the instrument was significant in both the subject and item analyses ($F1(1,14) = 7.29$, $p < .05$; $F2(1,6) = 7.39$, $p < .05$). The effect of prime type on instrument actions was marginally significant only in the subject analysis ($F1(1,14) = 4.20$; $p = .06$; $F2 < 1$).

To determine how early this effect was emerging, we took the average onset of the instrument object word (e.g., *stick*) and analyzed differences in looks to the instrument objects over time between the two priming conditions. The results revealed differences in the proportion of looks to the instrument objects as the speech stream temporally unfolded, between 400 and 600 ms after this point in the utterance ($F1(1,14) = 4.71$, $p < .05$; $F2(1,6) = 4.74$, $p = .072$) and thereafter. In other words, over trials, participants launched more eye movements to the instrument object in Instrument-Prime conditions than in Modifier-Prime conditions. Considering that it takes approximately 150 to 200 ms to initiate an eye movement after it has been

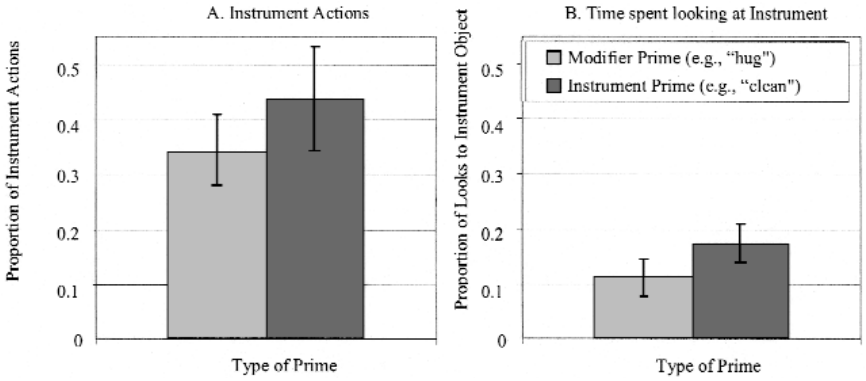

Fig. 2. **A:** Proportion of Instrument Actions as a function of type of prime. **B:** Proportion of time spent looking at the Instrument Object as a function of type of prime.

programmed (Matin *et al.,* 1993), it is quite likely that many participants had begun to consider the instrument objects in the scene before the word referring to it was even complete.

Discussion

The results of this experiment are in many ways similar to the earlier fast-priming studies; the combinatory preferences of an unattended prime word influenced ongoing parsing decisions involving an attended target sentence. Clearly, as one might expect, similar lexically specific parsing operations are at work in auditory language comprehension as in written language comprehension.

Properties of this experimental task, however, as well as properties of the stimuli used in the study, permit us to make observations that go beyond merely replicating the reading findings in a different modality. For instance, the act-out task that is part of the "visual-world" technique allows one to examine in some detail the interpretation that speakers assign to each target utterance. In this regard, it is interesting to note that priming effects appeared to be restricted to the argument preferences of the primes, and not to other aspects of the prime verb meaning, such as the verb's "core meaning." In particular, inspection of the video record revealed no cases of participants acting out the prime verb rather than the target verb (e.g., cleaning the bear that has the stick rather than turning it). Moreover, there appeared to be no blending of the prime and target along these lines. The prime–target pair *clean–turn* did not result in fastidious turning, nor did *hug–turn* result in affectionate turning. Jokes aside, such an observation is important and warrants further investigation. There is no reason to expect that the effects of a prime word should be restricted to the grammatical analysis of the sentence, unless such primes somehow tap only implicit language operations as the grammatical analysis of the sentence. At the moment, such a conclusion would be mere speculation, but clearly, future research with this technique should systematically analyze the contribution of various event features denoted by these verbs (manner, path, etc.).

It is also worth noting that properties of the primes used in this experiment may also speak to the relative contribution of verb-specific syntactic and semantic preferences to parsing decisions. Verbs were selected on the basis of sentence completion norms, in which participants were to complete sentence fragments like (6) with the first continuation that came to mind:

(6) Clean the baby doll with . . .

Completions were categorized on semantic grounds rather than on the basis of syntactic properties, in that only Instrument and Noninstrument completions

served as categories. For instance, a verb was highly regarded to take an instrument role if there were a high number of prepositional phrase completions containing instruments, for example, *Clean the baby doll with a sponge.* Sentences that contained mere VP-attachments like *Clean the baby doll with care* or NP-attachments like *Clean the baby doll with green eyes* were categorized as Noninstruments. This categorization scheme resulted in a large semantic difference between how likely certain verbs took instruments (e.g., *clean,* which approached 100% Instrument completions) or how likely they were not to take instruments (e.g., *hug,* which never took an instrument role), and this is how the prime types were chosen. Contrastingly, inspection of gross *syntactic* differences in continuations for these verbs based on whether they were likely to take VP-attachments or not resulted in very little difference in syntactic preferences. In particular, both Instrument-bias primes and Modifier-bias primes had high VP-attachment preferences (98% and 76%, respectively). Although it is possible that this small difference in VP-attachment rates could be influencing the on-line priming effects, it seems more likely that there is a strong availability of semantic roles rather than syntactic structure during auditory verb recognition. The most plausible conclusion, and the one consistent with most views of argument structure, is that recognition of a verb includes activation of permissible syntactic complements, permissible thematic roles, and the possible mappings between the two (e.g., see Carlson & Tanenhaus, 1988).

CONCLUSIONS

Several conclusions about the nature of sentence comprehension arise from these results:

1. Lexical knowledge encodes detailed information about the syntactic possibilities for words, directly influencing the manner in which words are combined to form sentence-level representations. This is true of verbs and also of other word classes, such as nouns.
2. Those lexical-combinatory representations are encoded in a distributed manner and shared between words in a way that crosses grammatical class boundaries.
3. The lexical representations that guide sentence processing include combinatory information of a sort that may go beyond classical syntactic notions. This information may include event-structural information, including information about which specific classes of arguments a particular word tends to associate with.
4. The findings in general align well with constraint-based lexicalist theories of parsing. Word recognition appears to play an important role in

the grammatical analyses of sentences. It should be made clear, however, that not all grammatical operations can be described as lexical. Supra-lexical operations must exist, for instance, to piece together the syntactic representations that are associated with individual lexical items. These operations are beyond the scope of the current research enterprise (though see Kim *et al.*, 2002, for a detailed discussion).

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