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Structural Priming as Implicit Learning: A Comparison of Models of Sentence Production

Franklin Chang,[1,3] Gary S. Dell,[1] Kathryn Bock,[1] and Zenzi M. Griffin[2]

Structural priming reflects a tendency to generalize recently spoken or heard syntactic structures to different utterances. We propose that it is a form of implicit learning. To explore this hypothesis, we developed and tested a connectionist model of language production that incorporated mechanisms previously used to simulate implicit learning. In the model, the mechanism that learned to produce structured sequences of phrases from messages also exhibited structural priming. The ability of the model to account for structural priming depended on representational assumptions about the nature of messages and the relationship between comprehension and production. Modeling experiments showed that comprehension-based representations were important for the model's generalizations in production and that nonatomic message representations allowed a better fit to existing data on structural priming than traditional thematic-role representations.

When we talk, we have to create syntactic structures. How we do this is important for understanding sentence production. In this paper, we argue that the process of creating structure is affected by adaptations to experience within the production system. That is, the production system learns. We address this claim through the computational modeling of structural priming, looking at how alternative representations influence structural variations.

Structural priming is a tendency to use similar syntactic structures in successive clauses or sentences (Bock, 1986; Bock & Loebell, 1990). For example, in primed picture description, speakers who first produce a prepositional-dative sentence (e.g., "The girl showed a picture to the teacher")

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[1] Beckman Institute, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801.
[2] Stanford University, Stanford, California 94305.
[3] Author to whom all correspondence should be sent. Email: fchang@s.psych.uiuc.edu.

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tend to describe subsequent events like the one in Fig. 1 as “The boy is giving a guitar to the singer.” Speakers who first produce a double-object structure (“The girl showed the teacher a picture”) are later likely to say “The boy is giving the singer a guitar” (see Fig. 2, left side). Structural priming also occurs with active and passive transitive sentences (see Fig. 2, right side).

Structural priming has been attributed to some kind of syntactic process (e.g., Bock & Loebell, 1990; Hartsuiker, Kolk, & Huiskamp, 1999; Pickering & Branigan, 1998). By syntactic, we mean the processes responsible for mapping the elements of messages into linguistically coded structures and sequences. Some evidence for the syntactic nature of structural priming comes from comparisons of sentences with similar surface configurations, but different thematic compositions (Bock & Loebell, 1990, Experiments 1 and 2). Prepositional locatives (e.g., “The wealthy woman drove the Mercedes to the church”) are as effective as prepositional datives (“The wealthy woman gave the Mercedes to the church”) at priming prepositional datives (see Fig. 2, left side), and intransitive locatives (e.g., “The 747 was landing by the control tower”) are as effective as passives (“The 747 was alerted by the control tower”) at priming passives (see Fig. 2, right side). In both cases, although the primes differ thematically, their syntactic structures are the same. Priming also occurs despite differences between primes and targets in function words (Bock, 1989) and differences in the

Fig. 1. Example dative picture.

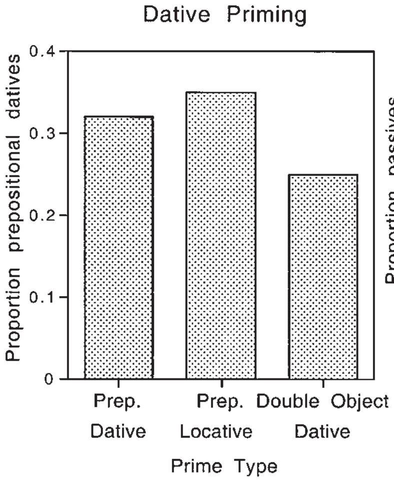

Fig. 2. Structural priming in Bock and Loebell (1990, Experiments 1 and 2).

animacy of subjects and objects (Bock, Loebell, & Morey, 1992). It does not occur when the structure of the prime changes, even if the order of words in the prime stays the same (Bock & Loebell, 1990, Experiment 3). A parsimonious explanation for all of these results is that structural priming involves the surface syntactic configuration.

In the present work, we address the mechanism that leads to structural priming. One hypothesis is that it is a short-term memory or activation effect. If so, structural priming should dissipate with time or interference. However, it lasts a fairly long time: Bock and Griffin (in press) found structural priming over 10 intervening sentences, Boyland and Anderson (1992) found priming when primes and targets were separated by 20 min, and Saffran and Martin (1997) found structural priming over as long as a week for aphasic patients. There is some evidence that priming is sometimes short-lived (Branigan, Pickering, & Cleland, in press; Levelt & Kelter, 1982), but insofar as its effects can persist, activation cannot be the only mechanism at work.

STRUCTURAL PRIMING AS IMPLICIT LEARNING

We hypothesize that structural priming is a form of implicit learning. The persistence of priming over intervening sentences implicates a longer-term change to the production system whose function may be to tune the

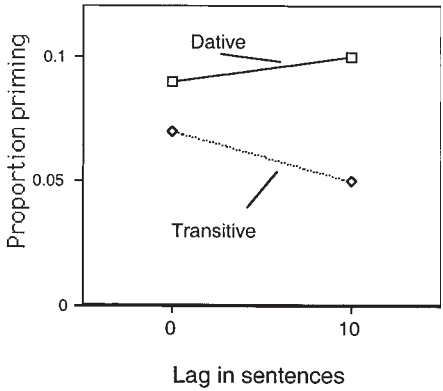

Fig. 3. Structural priming over lags of 0 and 10 intervening sentences (from Bock & Griffin, in press).

system to experience. The learning is implicit, because it involves incidental learning of complex, abstract relations during the performance of a task, yielding knowledge that is inaccessible to consciousness (Seger, 1994).

The model of structural priming that we are developing reflects this hypothesis. The best models of implicit learning of sequences are a class of connectionist models called simple recurrent networks (Cleeremans & McClelland, 1991; Seger, 1994). Experimentally, implicit sequential learning is tested by having people respond quickly to series of stimuli that follow certain patterns. Like people, the models learn to be sensitive to the patterns. The models do so because they can use their past states as the context for predictions. When the predictions fail, the models make changes to the weights in the network by backpropagation. These weight changes are the hypothetical basis for implicit learning.

Because simple recurrent networks have also been used to model the learning of structural dependencies (Elman, 1990, 1993), our first step in implementing the learning account of structural priming was to adapt a simple recurrent network to the task of sentence production. We focused on one of the likely components of priming. The component has to do with the order of constituents in sentences, or what plays the role of subject, direct object, prepositional object, etc. (Bock, Loebell, & Morey, 1992). We explored two questions about the nature of the representations and mappings that guide this process. The first concerns the relationship between comprehension and production. What representations or processes, if any, do they have in common? The second question is about the conceptual input to production, sometimes called the message. Although the message gets production started, it has rarely been studied (but see Griffin & Bock, in press).

The model was taught to map a message into a sequence of words, one word at a time, and trained to produce sequences analogous to those used in structural priming experiments. Table I shows the types of sequences, an example of each type, the frames that the sequences adhered to, and the percentage of each sequence in training. The verbs associated with each sequence type are given as well. The nouns were restricted in three ways. First, recipients in dative sequences were animate (or construable as sentient; Gropen *et al*., 1989). Second, agents in passive sequences were predominantly inanimate and patients were predominantly animate (Bock, 1986; Ferreira, 1994). Third, experiencers in theme-experiencer sequences were predominantly animate (Ferreira, 1994).

A backpropagation algorithm was used both to train the model and to implement priming. The model was first trained to produce many examples

Table I. Sequences in the Training Corpus

Sequence structure	Frequency in training (%)[a]	Sentence construction Example sentence Verb set
Intransitives	16	AGENT VERB cats walk. walk live see hear
Active transitives	16	AGENT VERB PATIENT cats chase dogs. chase feed see hear make write
Passive transitives	4	PATIENT AUX PASTPART by AGENT dogs are chased by cats. chase feed see hear make write
Locative	16	AGENT AUX PRESPART PREP LOCATION cats are walking near dogs. walk live see hear
Active theme-experiencer	8	THEME VERB EXPERIENCER. cats scare dogs. scare thrill
Passive theme-experiencer	8	EXPERIENCER AUX PASTPART by THEME. dogs are scared by cats. scare thrill
Prepositional dative	8	AGENT VERB PATIENT PREP GOAL. girls give cats to boys. give make show write
Double-object dative	16	AGENT VERB GOAL PATIENT. girls give boys cats. give make show write
Prepositional locative	8	AGENT VERB PATIENT PREP LOCATION. cats chase dogs near cars. chase feed see hear

[a] Frequency in training approximated real-world frequencies.

of each sequence type. Then, to simulate priming, we had the model produce a prime sequence with learning "on," leading to weight changes in the network. These weight changes subsequently biased the production of a similar structure, yielding priming. So the same mechanism, weight change, supported both the learning of the mapping system and the priming of sequences.

Important to the performance of the model were two representational assumptions embedded in the model architecture. We will discuss these assumptions before reporting the model's performance.

The Comprehension Assumption

The comprehension assumption is that the production process uses knowledge from comprehension. A growing body of evidence shows that simply comprehending a sentence creates structural priming in production (see Pickering *et al.*, this issue). This has been found in tasks involving sentence recall (Potter & Lombardi, 1998), dialogue (Pickering *et al.*, this issue), and picture description (Bock, in preparation).

To evaluate the comprehension assumption, we compared a model whose context representation was derived solely from sequence production with a model containing an additional context that came from a separate simple recurrent network trained for comprehension (Fig. 4). The comprehension network was first trained to map sequences of words into a static message representation. The full model was then trained to produce sequences under the influence of the dynamic context from comprehension. For simplicity, separate units were used for comprehension and production, although this does not reflect a commitment to separate representations (see Pickering *et al.*, this issue).

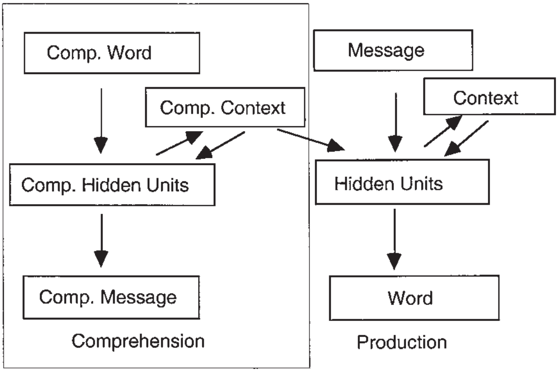

Fig. 4. The architecture of the model with comprehension-based representations. The production-only model excluded the comprehension component (in the box).

The Message Assumption

In the model, messages were framed in terms drawn from theories that represent argument structures with semantic primitives like cause, sentience, motion, and existence (Dowty, 1991). This contrasts with traditional views of thematic roles (Fillmore, 1968), where the arguments of an event are classified into a fixed set of atomic roles like agent, patient, goal, location, and so on.

Three ideas from the nonatomic approach are particularly relevant to the model. First, Jackendoff (1990) argued for a tier account of thematic roles that incorporates both action (causal) and aspect (perspective) components. In this system, in “Sue threw the ball,” *Sue* is simultaneously the agent (the cause of the event) and the source (the initial location of the ball). These two tiers were represented in the model with slots for aspect (source, theme, goal) and features within each slot for action information, like sentience. Concretely, this eliminates atomic roles like location and allows recipients to be distinguished from locations by a feature within the goal slot.

A second important idea is Levin and Hovav’s (1996) distinction between internal and external causes. Roughly speaking, this divides agents into those that act on others (external causes) and those that act on themselves (internal causes). We implemented this by putting internal causes into the theme slot and external causes into the source slot. Concretely, this means that intransitive and locative agents were themes in the model.

Finally, modern theories claim that semantic features guide argument selection (Dowty, 1991). We implemented this by making structure selection dependent on the activation of causal features, such as sentience. With a sentient goal, a double-object dative was produced; otherwise, a prepositional dative was produced. Table II shows the positions of the arguments in

Table II. Nonatomic Message Representation

	Message slot[a]					
Sequence structure	Source[a]		Theme		Goal	
Intransitives			AGENT	SNTI		
Active transitives	AGENT	SNTI	PATIENT	snti		
Passive transitives	AGENT	SNTI	PATIENT	SNTI		
Locative			AGENT	SNTI	LOCATION	
Active theme-experience	THEME	snti	EXPERIENCER	snti		
Passive theme-experience	THEME	snti	EXPERIENCER	SNTI		
Double-object dative	AGENT	SNTI	PATIENT		GOAL	SNTI
Prepositional dative	AGENT	SNTI	PATIENT		GOAL	snti
Prepositional locative	AGENT	SNTI	PATIENT		LOCATION	

[a] SNTI, denotes sentience; upper and lower case represents full and partial activation, respectively.

this kind of representation, with SNTI indicating the sentience of the concept, and upper and lower case indicating more and less activation, respectively.

MODEL TESTS

Six training sets were created, composed of sequences like those in Table I. We manipulated two factors to test the comprehension and message assumptions. The comprehension factor had two levels, one for a model with only a production component and the second for a model with both a comprehension and a production component.

The message factor also had two levels, corresponding to the model with nonatomic message roles and a model with atomic thematic roles. The atomic-role view was instantiated with a separate slot in the message for each thematic role, using the relative activation of the concept in each slot to select structures. For example, if the goal was more active than the patient, a double-object dative was produced; otherwise, a prepositional dative was produced. Table III depicts this kind of representation.

The resulting 2×2 design had six model-subjects per cell. For testing, 192 prime and target pairs were created for each of four priming conditions (dative-dative, prepositional locative-dative, transitive-transitive, locative-transitive). These four conditions include the standard priming tests with dative and transitive primes and targets, as well as two conditions from Bock and Loebell (1990) to assess whether prepositional locatives would prime prepositional datives and passives. In order to measure priming, two criteria had to be met. First, prime sequences had to be produced correctly. To

Table III. Atomic Message Representation

	Message slot[a]			
Sequence structure	Agent	Patient	Goal	Location
Intransitives	AGENT			
Active transitives	AGENT	patient		
Passive transitives	AGENT	PATIENT		
Locative	AGENT			LOCATION
Active theme-experience	THEME	experiencer		
Passive theme-experience	THEME	EXPERIENCER		
Double-object dative	AGENT	PATIENT	GOAL	
Prepositional dative	AGENT	PATIENT	goal	
Prepositional Locative	AGENT	PATIENT		LOCATION

[a] Upper and lower case represents full and partial activation, respectively.

ensure this, primes were generated from a message that forced a particular sequence, relying on the argument selection mechanisms described earlier. Second, target sequences had to permit alternation between different structures. To enable this, messages for the targets were set to a state intermediate between the representations of the two target sequences. For example, with the nonatomic message representation, this meant that the sentience feature of the goal argument for a dative target would have an “activation level” intermediate between the levels for double object and prepositional datives.

Analyses of variance were performed with subject models as the random factor. The dependent measure was the magnitude of the difference between two alternative structures after priming by one of them, which we call a priming score. For instance, dative priming was calculated by first determining the proportion of prepositional-dative target sequences elicited for each test message (relative to the total number of dative targets elicited) when preceded by prepositional-dative primes or double-object-dative primes. These proportions were averaged over items. The proportion of prepositional-dative sequences produced after double-object dative primes was subtracted from the proportion following prepositional dative primes. Thus, a positive priming score means that more prepositional datives were produced after prepositional-dative primes than after double-object primes.

Results

Comparing the models with and without context from comprehension, we found more priming in models that incorporated a comprehension representation of the priming sequences than in models that used only a production representation (Fig. 5). This effect was significant [$F(1, 20) = 5.05$;

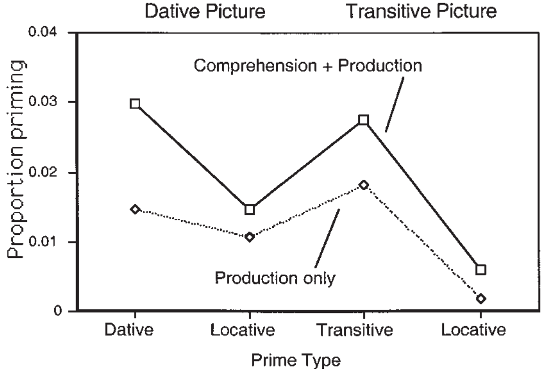

Fig. 5. A comparison of a production-only model with the comprehension-plus-production model.

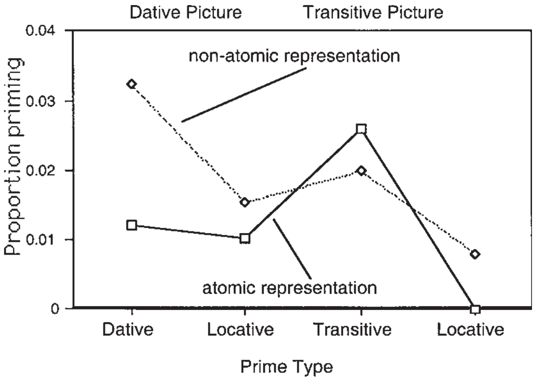

Fig. 6. A comparison of atomic- and nonatomic-role based message representations.

p = .036]. Likewise, models with nonatomic message representations were better at priming in three of the four conditions (Fig. 6), yielding a marginally significant effect [$F(1, 20) = 3.60$; $p = 0.072$].

Despite its marginal statistical significance in the overall analysis, the nonatomic representation was superior to the atomic representation in one crucial respect. It produced significant locative-to-passive priming; the atomic representation did not. We attribute this to the representation of locative agents: In the nonatomic message representation, agents of locatives are internal causes, and therefore more similar to patients in passives. Since locative-to-passive priming is on its face difficult to reconcile with traditional thematic-role representations, the advantage for nonatomic roles in this test offers independent support for nonatomic role theories.

Putting together the comprehension representation and the nonatomic messages yields a model that has at least some priming in all four of the priming tests. The priming effects are small, but are (marginally) significantly different from zero in one-tailed tests: datives [4.04% priming, $t(5) = 4.44$, $p = 0.003$], transitives [2.89%; $t(5) = 1.88$, $p = 0.06$], prepositional locative—prepositional dative [1.77%; $t(5) = 3.31$, $p = 0.01$], locative-transitive [1.25%; $t(5) = 1.90$, $p = 0.06$].

Further Tests

To better understand how the model architecture influenced priming, we tested the models with learning in various sets of connections turned off.

Table IV. Proportion of Total Priming

Network connections	Dative (%)	Transitive (%)
Hidden → lexical	91	100
Message → hidden	13	45
Prod. Context → hidden	14	8
Comp. Context → hidden	91	45

Table IV shows the resulting proportions of total priming. Low proportions mean that turning a connection off had a large effect on priming.

There are two things to note. First, the hidden-to-lexical connections did not exert much influence. This implies that priming in the model did not depend on lexical connections. Second, datives and transitives used the weights differently. Although both structures depended on the production-context-to-hidden weights, transitives relied more on the comprehension-context-to-hidden weights whereas datives relied more on the message-to-hidden weights. This points to different sources of priming for different constructions.

Another test addressed the time course of priming. One of the motivations for an implicit learning account of structural priming is evidence for the persistence of priming over intervening sentences (Bock & Griffin, in press). We evaluated the model's performance over different lags between prime and target sentences; Fig. 7 shows the results. For both datives and transitives, structural priming endured over ten sequences. This lends credence to the view that priming and learning can be rooted in the same mechanisms.

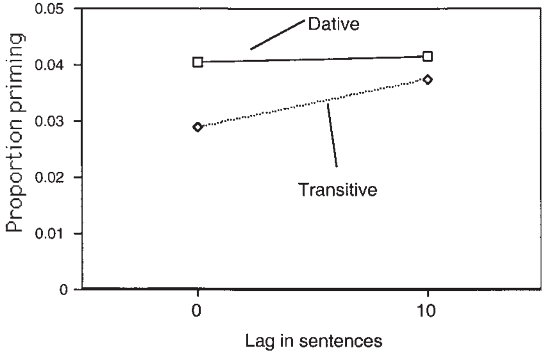

Fig. 7. Modeling priming over intervening sentences for datives and transitives, using nonatomic messages and comprehension-based representations.

DISCUSSION

The connectionist architecture in which our learning and representational hypotheses was tested inherited many of its features from previous accounts of the implicit learning of sequences. The results of our tests suggest that similar architectural features may be applied in accounting for the mechanisms of structural priming in language production. At the same time, we are wary of claims that the entire range of syntactic phenomena in language use can be adequately explained by simple recurrent networks.

The nature of models of this kind makes it difficult to explicitly define the processes by which message representations are mapped into sequences of constituents. Psycholinguistic tests of priming have pointed to influences from the structure of the sequence (Bock & Loebell, 1990), from word order (Hartsuiker, Kolk, & Huiskamp, 1999), from semantic features related to sentience, like animacy (Bock *et al*., 1992), from verb repetition (Pickering & Branigan, 1999), and from thematic roles (Hare & Goldberg, 1999). It is part of the implicit learning hypothesis that multiple routes will show priming so long as those routes are necessary for language learning. In particular, we predict that priming will occur when alternatives share the ordering of syntactic constituents, but differ in the mapping from message roles (as in spray-load constructions; Chang, Bock, & Goldberg, in progress).

As this summary suggests, elections of sentence structures reflect a contest among many factors. This, in turn, helps to explain why the learning associated with producing a single sentence can be responsible for structural priming. Sometimes the contest is close. When it is, the small weight changes associated with learning the prime can tip the balance in favor of the primed structure.

CONCLUSION

In this work, we developed and tested an account of structural priming in terms of mechanisms for implicit learning. A computational model that learned to map from messages to word strings—in other words, that learned a small part of the task of language production—yielded priming from the same mechanisms responsible for learning the mapping in the first place. Two innovations were important to the model's success. It used representations developed in the course of comprehension to help guide production. In addition, it incorporated representations with nonatomic message roles, which provided a better fit to data on structural priming than a more traditional atomic-role representation. Both of these features may help to illuminate the nature of structural generalization, including the restrictions on structural generalization that influence language learning and use.

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