

Aphasic Sentence Comprehension as a Resource Deficit: A Computational Approach

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This article describes a new computational model of aphasic sentence comprehension. The model is based on the premise that all aphasics, however different, share a common deficit which determines a considerable amount of the individual variation observed in their sentence comprehension performance. This common deficit is construed as a pathological reduction in the activation resources of a working memory system that subserves sentence comprehension (Miyake, Carpenter, & Just, 1994). To test the theoretical feasibility of the resource reduction hypothesis, a new computer model of aphasic sentence comprehension was developed and tested. We describe the model as well as some initial simulation results, indicating that the model can account for some of the sentence complexity and severity effects that have been reported in the aphasia literature. © 1997 Academic Press

INTRODUCTION

It is a well-known phenomenon that aphasics from all major syndrome types have a problem with the comprehension of sentences, particularly if the meaning interpretation is dependent on structural cues rather than on the meanings of the individual lexical items (e.g., Caplan & Hildebrandt, 1988; Naeser et al., 1987). Within the context of a capacity theory of normal sentence comprehension (Just & Carpenter, 1992), it has been recently suggested that a considerable amount of the variance observed in aphasics' sentence comprehension performance might be due to a pathological reduction in working memory capacity for language (Miyake, Carpenter, & Just, 1994). In this article, we present a computer simulation model that instantiates this hypothesis in a quantitative manner.

The computer simulation model was implemented with three major goals

This work was supported in part by a fellowship from the McDonnell-Pew Program in Cognitive Neuroscience, the Office of Naval Research Contract N00014-92-J-1209, National Institute of Mental Health grant MH29617, and Research Scientist Awards MH-00661 and MH-00662 from NIMH.

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in mind. The first goal was to determine whether the resource reduction could account for two basic properties of aphasics' sentence comprehension performance, namely, its modulation by sentence complexity and by the severity of the deficit (Caplan, Baker, & Dehaut, 1985; Caplan & Hildebrandt, 1988; Kolk & van Grunsven, 1985; Naeser et al., 1987). A second goal was to develop a more complete computational model of syntactic analysis and thematic role analysis than had been offered in previous cognitive simulations. A third goal was to contribute to empirical aphasia research by proposing specific testable hypotheses concerning aphasic sentence comprehension.

The article is organized as follows. In the remainder of this introduction, we introduce the capacity theory and the resource reduction hypothesis, which extends the theory into the realm of aphasic sentence comprehension. In the next section, we discuss the lasting contributions of three previous models of aphasic sentence comprehension as well as the CC READER model of normal sentence comprehension indicating which of their properties were incorporated in the new model. A subsequent section introduces the new computer model of aphasic sentence comprehension in two steps. First, we describe the psychological assumptions behind 3CAPS, the cognitive architecture that was used to implement the CC READER model as well as the new model. Second, we describe the major structural components of the new model and indicate how they work together. A simple processing example involving comprehension of a sentence in a high and low capacity case has been included in an appendix. We then present the results of three simulation studies with the new model. In the first simulation study, we examine the effects of sentence complexity as reported in a study by Caplan, Baker, and Dehaut (1985). In the second simulation study, we also consider the effects of severity of the deficit. In the third simulation study, we illustrate the model's value in generating predictions for new research. In particular, we explore the effect of adjective padding (i.e., addition of an adjective to a noun phrase) on sentences varying in complexity (or demand they place on working memory). Finally, in the discussion section, we summarize the major conclusions of our computer simulation study and discuss some of the model's implications for a number of issues that are frequently discussed in the literature on aphasic sentence comprehension. Throughout the article, we focus on those properties of the model that are critical for its understanding as a theory of aphasic sentence comprehension. The article does not include technical implementation details, except for an Appendix describing the formulas implementing the model's activation allocation schema.

Capacity Theory

The capacity theory was originally proposed as a theory of sentence comprehension in normal adults, in particular, to account for the effects of both

individual differences in the working memory capacity for language and of processing load (Just & Carpenter, 1992; see also Carpenter, Miyake, & Just, 1994, 1995). Individual differences in working memory for language were assessed by subjects' performance on the reading span task (Daneman & Carpenter, 1980). A subject's reading span is measured by the number of sentence-final words that can be retained while reading a set of sentences. Unlike more traditional short-term memory measures, such as word span, reading span has both a storage component and a processing component which involves the combination of words at post-lexical levels, that is, syntactic, semantic and inferential levels of processing. Processing load was manipulated in a number of different studies by varying sentence complexity and the presence or absence of a lexical ambiguity, syntactic ambiguity, or extraneous memory load.

The major finding was that high span normals often showed better performance (i.e., faster word reading times and higher accuracy) than low span normals, particularly in the conditions with a high processing load (Just & Carpenter, 1992). For example, high spans seemed to have a better ability to hold onto the multiple semantic (Miyake, Just, & Carpenter, 1994) or syntactic interpretations (MacDonald, Just, & Carpenter, 1992) of a temporarily ambiguous word. Also, unlike low span subjects, high span subjects seemed to be capable of considering additional pragmatic information (i.e., regarding subject animacy) in their on-line decision to maintain the various interpretations of a temporarily ambiguous verb (Just & Carpenter, 1992). Furthermore, the reading time differences between high and low span subjects were exacerbated on syntactically complex subject-object relatives compared to their more simple subject-subject relative counterparts, particularly at the computationally more demanding regions of the verbs (King & Just, 1991). The latter three findings were simulated successfully by a computer model, called CC READER, which formed an instantiation of the key assumptions of the capacity theory (Just & Carpenter, 1992).

In order to account for these effects, the capacity theory proposed that an individual's sentence comprehension performance is determined by the relation between the individual's working memory capacity for language and the demand that a particular processing load places on that working memory. Working memory capacity for language is viewed as a finite activation resource that mediates both the storage and computation of information during sentence comprehension. And the processing load imposed by the comprehension of a particular sentence is given by the total amount of the activation resource consumed by the storage and computation at the lexical, syntactic, semantic, and inferential levels of sentence processing. Furthermore, when the processing load exceeds the working memory capacity for language, the activation demands for storage and computation are only partially met, such that forgetting of previously computed products and slowing of processing occur. A situation of activation shortage and its negative effects are more

likely to occur when the working memory capacity for language is low and the processing load is high. As demonstrated by the CC READER model, these assumptions explain why low span normals perform more poorly than high span normals especially in the demanding regions of a sentence. In CC READER, the concept of working memory capacity received an exact quantitative definition, namely, the number of activation units available for the maintenance of activation of stored elements and for the propagation of activation among elements (i.e., computation). In a situation of activation shortage, individual requests for activation for storage and computation of elements were scaled down in proportion to their size, allocating all of the available resources evenhandedly. Thus, this resource theory does not simply attribute better performance to the availability of more resources. It also specifies precisely how the resource availability (or unavailability) enters into the cognitive processing, permitting precise predictions and tests of the theory.

Resource Reduction Hypothesis

Recently, Miyake, Carpenter, and Just (1994) proposed to extend the capacity theory of normal sentence comprehension into the realm of aphasic sentence comprehension. They proposed that the continuum of working memory capacity, which originally ranged from high span normal to low span normal, could be extended further to include mildly and severely impaired aphasic patients whose working memory capacity for language may have been pathologically reduced by brain damage such as that caused by CVA. While working memory capacity for language can be measured by a normal subject's performance on the reading span task, severity in an aphasic patient is measured by the overall score on an aphasia battery. In more general terms, the Miyake et al. hypothesis amounts to the claim that aphasic sentence comprehension involves a pathological reduction in processing resources, a claim that has been made before by other investigators (Caplan, Baker, & Dehaut, 1985; Caplan & Hildebrandt, 1988; Frazier & Friederici, 1991; Kilborn, 1991; Linebarger, 1990). Another claim associated with the Miyake et al. hypothesis is that all aphasic patients, however different they are from each other, share a common deficit. This claim in its general form is not new and has been made throughout the history of aphasia research (e.g., Caplan, Baker, & Dehaut, 1985; Caplan & Hildebrandt, 1988; Jackson, 1878; Marie, 1906; Schuell & Jenkins, 1959; McNeil, Odell, & Tseng, 1991). What is new about the Miyake et al. resource reduction hypothesis is its precise quantitative instantiation in the context of the capacity theory, in which resources are conceptualized as the finite amount of activation that is available for the maintenance and computation of sentence representational elements in working memory for language. As the simulation results of the CC READER model suggest, this concept of resources lends itself to implementation in a computer model.

Several lines of evidence support the resource reduction hypothesis. At a purely behavioral level, such a deficit is suggested by considering the effects of severity and complexity. First, severity explains a considerable amount of the variance observed among aphasics' sentence comprehension performance: between 60 and 81 percent of the variance is accounted for by severity (Caplan, Baker, & Dehaut, 1985; Caplan & Hildebrandt, 1988; Naeser et al., 1987). Such findings can be accounted for in terms of different degrees of reduction in working memory capacity for language. The less activation is available for the storage and processing of sentence representational elements, the lower the quality of the end result of the comprehension process. Second, aphasics tend to show decreasing comprehension as sentence complexity increases (Caplan, Baker, & Dehaut, 1985; Caplan & Hildebrandt, 1988; Naeser et al., 1987; see also the combined results of Schwartz, Saffran, & Marin, 1980, and Kolk & van Grunsven, 1985). The activation shortage is more likely to occur in the course of processing for sentences that are complex, because complexity is associated with high storage and processing demands. Third, the effects of severity are exacerbated for more complex sentences (Caplan & Hildebrandt, 1988; Miyake et al., 1994; Naeser et al., 1987). The chance of an activation shortage is the greatest when the capacity is low and when, at the same time, the resource demand imposed by the sentence material is high.

A further line of evidence supporting the resource reduction hypothesis comes from studies of normal subjects that manipulated the word input rate, attempting to vary the demand on resources. As each new word is presented, it creates new activation demands for both storage and processing. Therefore, the faster the word input rate, the more activation resources the sentence comprehension system has to mobilize and the more likely it is to reach a situation of activation shortage, especially when the working memory capacity is low to begin with. Following this line of reasoning one would expect normal subjects to show very similar effects of sentence complexity as aphasic patients when the normal subjects are confronted with an unusually rapid word input rate. This is indeed what Miyake, Carpenter, & Just (1994) found in a rapid serial visual presentation (RSVP) experiment that included some of the same sentence types as Caplan, Baker, & Dehaut (1985) had presented in a sentence comprehension study with aphasic patients. Further supporting the capacity theory, Miyake et al. found that low span subjects showed larger sentence complexity effects than medium span subjects, who in turn showed larger effects than high span subjects. The results of Miyake et al. also support the hypothesis that there is a continuum of working memory capacity encompassing both normal and aphasic subjects.

Further supporting the resource reduction proposal, it has been observed repeatedly both in the clinic (Rosenbek et al., 1989) and in experiments (Lasky, Weidner, & Johnson, 1976; Liles & Brookshire, 1975; Pashek & Brookshire, 1982; Poeck & Pietron, 1981; Weidner & Lasky, 1976)

that a slower than normal speech rate often, but not always (Blumstein, Katz, Goodglass, Shrier, & Dvoretzky, 1985; and Brookshire & Nicholas, 1984), facilitates sentence comprehension performance in aphasic patients.

A final line of evidence for the resource reduction hypothesis comes from studies that correlated behavioral measures of sentence comprehension performance with measures obtained through brain imaging techniques, namely, CT (computerized tomography) and PET (Positron Emission Tomography) (Karbe et al., 1989; Kempler, Curtiss, Metter, Jackson, & Hanson, 1991). There is evidence that over 95% of aphasic patients have a common region of decreased metabolic activity (as established with PET) in an area in the temporoparietal region of the left hemisphere, in spite of great variation in their clinical syndrome type and in the site of the focal structural lesion (as established with CT) (Karbe et al., 1989; Kempler, Curtiss, Metter, Jackson, & Hanson, 1991; see also Kuhl, Phelps, Kowell, Metter, Selin, & Winter, 1980; Metter, 1987). Furthermore, the degree of severity of the metabolic decrease in the common area accounts for a considerable amount of the variation in the patients' sentence comprehension performance. Karbe et al. report that the level of brain metabolic activity in relevant regions of the brain accounts for over 80% of the variance in Token Test performance (DeRenzi & Vignolo, 1962). Furthermore, Kempler et al. reported numerous significant correlations between the regional cerebral metabolism in several posterior brain areas (temporal, parietal, and occipital) and patients' morpho-syntactic abilities, ranging from .34 to .54. These PET findings support the concept of a deficit that is common across patients and a deficit that varies continuously across patients, two fundamental assumptions of the resource reduction hypothesis.

A few common misunderstandings concerning the resource reduction hypothesis should be dispelled at this point. First, the phrase *working memory for language* does not refer to verbal short-term memory (vSTM) or to the phonological loop. Rather it refers to the component of the cognitive architecture that is involved with the storage and processing of sentence representational elements at the lexical, syntactic, semantic, and referential levels. This proposed working memory for language is consistent with the neuropsychological evidence which suggests that problems with the phonological loop and sentence comprehension are dissociated from one another (Martin & Romani, 1994). Furthermore, working memory for language should also not be confused with the central executive in Baddeley's (1986) theory of working memory, although it may be considered a special part of it, supporting language comprehension (Just & Carpenter, 1992). Finally, the hypothesis that all patients share a common deficit in the form of a reduction in the capacity of a working memory for language also allows for qualitative differences among patients that may be superimposed on top of the common deficit (Miyake, Carpenter, & Just, 1995; see also Discussion).

PREVIOUS MODELS

Previously, three different computer models of aphasic sentence comprehension have been proposed in the literature: the HOPE model (Gigley, 1982, 1983, 1988), the UNIFICATION SPACE model (Kempen & Vosse, 1989), and the SYNCHRON model (Haarmann & Kolk, 1991a) (for a comparison of the latter two models see Haarmann, 1993, pp. 63–66). While these three models vary greatly in their details of operation, they all have share a number of key properties which we regard as strengths and have retained in our new model. At the same time, the previous models suffer from several limitations which we have tried to overcome. In the section below, we do not describe these three previous models but rather focus on what can be learned from them.

All three previous models (as well as the new model) share the common assumptions that (i) that knowledge representation and processing are *activation driven*, (ii) that successful sentence comprehension requires the *co-activation* of certain critical representational elements, and (iii) that in aphasia, co-activation is disturbed by an immediate or emergent *timing deficit*. The activation assumption entails that representational elements have an associated activation value that can lie at any point on a continuous dimension, making the representation graded rather than all-or-none. The elements' activation level determines their accessibility during sentence comprehension. Similarly the processing is graded, such that the computations underlying comprehension are presumed to be executed incrementally, rather than in an all-or-none fashion. The activation and, therefore, the accessibility of representational elements is temporally constrained, that is, each representational element takes time to build up activation and, once it has accumulated activation, loses it again, either as a result of time-based decay (previous models) or as a result of competition for limited activation resources (CC READER and the new model). Different representational elements may have different time courses of activation, for example, due to different points of entry.

For successful comprehension, certain representational elements originating in various points in a sentence, need to be co-active, that is, they need to have overlapping time periods during which their activation levels are above some threshold. In all models, co-activation of already active elements (e.g., determiner and noun) is a necessary requirement for the introduction and activation of new elements (e.g., noun phrase). In the new model, this co-activation requirement is implemented in a uniform way. All processing is achieved through the application of if-then or condition-action rules. Such rules are applied only when all condition elements on the "if"-side of the rule are co-active above a certain threshold.

Finally, in all models co-activation can be disturbed by a timing deficit involving either a slower than normal rate of processing or a faster than

normal rate of forgetting (see Friederici & Kilborn, 1989; Haarmann & Kolk, 1991a & 1994, for empirical evidence). In the HOPE and SYNCHRON model, both temporal changes are induced directly by changes in corresponding parameters (i.e., for decay and activation rate). In the UNIFICATION SPACE and new model, both temporal changes are the emergent property of a deeper underlying deficit, an increase in chaos and a decrease in capacity, respectively. It should be noted that all models are congruent with the commonly held view that aphasic sentence comprehension is not the result of an all-or-none loss of some supporting linguistic knowledge but rather of a more graded deficit in the processing of this knowledge (Miyake, Carpenter, & Just, 1994). At the same time, these models progress beyond proclaiming a graded deficit by specifying a precise hypothesis about the nature of the underlying impairment, namely, as a direct or emergent timing deficit resulting in co-activation problems (for similar proposals see Friederici, 1988; Friederici & Kilborn, 1989; Kolk & van Grunsven, 1985).

In designing the new model, we made an attempt to overcome various limitations of the three previous models of aphasic sentence comprehension. One limitation concerned the number of different sentence types included in the simulations. One of the advantages of a computational approach to aphasic sentence comprehension is the ability to test a particular theory on a large variety of sentence types. However, previous modeling efforts made only limited use of this potential. The HOPE model dealt with only simple active SV(O) sentences, and attempts to fit the performance of the model to quantitative human data have not been reported. Both the UNIFICATION SPACE and SYNCHRON model went a step further by successfully simulating the combined effects of sentence complexity and severity that were reported in a study with agrammatics by Schwartz, Saffran, and Marin (1980) and a replication study by Kolk and van Grunsven (1985). In both studies, actives were easier to process than their passive counterparts and locatives, with passives and locatives being about equally difficult. As a group, the agrammatic aphasics in the Kolk and van Grunsven study performed at a higher average level than those in the Schwartz et al. study, possibly reflecting a severity factor. However, no attempt has been reported to use the UNIFICATION SPACE model to simulate aphasic performance on more complex sentences, such as the various double verb sentences included in a study by Caplan, Baker, and Dehaut (1985). While the SYNCHRON model simulated performance on relatively simple sentence types such as actives, passives and locatives, the model had difficulty in dealing with more complex sentence types. This limitation was largely due to the absence of a parsing scheme that would have permitted immediate integration of an incoming word into the evolving syntactic and semantic representation (Just & Carpenter, 1980; Marslen-Wilson & Tyler, 1980). As a consequence, SYNCHRON's time-constraints on co-activation were too severe.

Another limitation of previous models of aphasic sentence comprehen-

sion was that the process of thematic role assignment was altogether absent (UNIFICATION SPACE, SYNCHRON) or inadequate to deal with more complex sentence types (HOPE). There are several closely related reasons for including an adequate process of thematic role assignment. First, it makes for a more complete model of aphasic sentence comprehension, since subjects' responses in a test of aphasic sentence comprehension typically require some demonstration that thematic-role bindings (i.e., who did what to whom) are understood. Second, co-activation problems can in principle occur not only at a purely syntactic level but also at a post-syntactic level where syntactic structure is mapped onto thematic roles. This might occur when verb argument structure elements (providing the recipe for thematic role mapping) have already decayed when parse tree elements become activated, either due to fast forgetting of the former type of element or slow activation of the latter type of element (cf. Haarmann, 1993). The assumption of the UNIFICATION SPACE and SYNCHRON models that a complete parse tree representation is sufficient for correct performance might therefore be wrong. Third, co-activation problems at the post-syntactic level of thematic role assignment might be more likely than co-activation problems at a purely syntactic level. The thematic-role assignment requires more elements to be co-active: elements specifying parse tree relations, lexical meaning elements, and verb argument structure elements, specifying bindings between thematic roles and meaning elements in particular structural positions. Indeed aphasics seem to have more problems when the task not only involves syntactic analysis (as in syntactic judgment) but also thematic role assignment (as in sentence picture matching) (Linebarger, Schwartz, & Saffran, 1983).

A final property of the previous models of aphasic sentence comprehension concerns the ungraded quality of their comprehension performance measure. On any particular trial these models either succeeded or did not succeed in deriving a representation that was assumed to be critical for the comprehension of a particular sentence. Success was defined in an all-or-none manner. For the HOPE model the criterion of success was the presence of all thematic role bindings contained in the sentence. And for the UNIFICATION SPACE and SYNCHRON model the criterion of success was the presence of a complete parse tree representation with no unattached constituents. Percentages correct were obtained by assuming stochastic variation in activation properties across trials, such that the model would fail on some trials while succeeding on others in deriving the critical representation. Although this approach may be adequate for fitting percentages correct, the all-or-none criterion for success of sentence comprehension on a single trial seems counterintuitive. Rather than completely succeeding or failing to derive the meaning of a sentence on a particular trial, one might expect an aphasic subject to have more or less confidence in the correctness of a meaning representation depending on task load and impairment severity. This notion could be further supported by asking aphasic patients to give a confidence rating of

their response on a trial-by-trial basis. To our knowledge this has not been attempted in empirical research. Nevertheless, we defined a level-of-confidence index of sentence comprehension performance in the model which we measured as the average level of activation of critical meaning elements after the sentence had been processed.

The capacity theory of normal sentence comprehension was originally implemented in the form of a computer model, called CC READER (for Capacity Constrained Reader) (Just & Carpenter, 1992), which successfully simulated the conjoint effects of processing load (e.g., syntactic complexity) and reading span on the word-by-word reading times of normal college-age students. However, in extending the capacity theory into the realm of aphasic sentence comprehension, a new model was constructed rather than simply modifying CC READER, for several reasons. First, the CC READER model had a tendency to abort parsing when a particular part of a sentence could not be analyzed due to a severe activation shortage. However, it is conceivable that an aphasic patient, while not being able to analyze a more demanding part of a sentence, may still be able to analyze several of its less demanding parts. This is certainly the intuition of most people comprehending in a weak second language. The parsing algorithm of the new model has therefore been given a more distributed form of control so that it better captures this kind of partial comprehension. Second, the CC READER model was limited in its ability to do thematic role assignment because thematic role assignment was not constrained by lexically activated knowledge regarding the permissible argument structures of a verb. Third, it was difficult to expand the grammar of the CC READER model to incorporate the various sentence types that occur in aphasia research.

Several properties of the CC READER model have been retained in the new model. First, both models are instantiations of the capacity theory and have been implemented by means of a cognitive architecture that embodies those assumptions, called 3CAPS (Just & Carpenter, 1992), described in the next section. Furthermore, both the CC READER model and the new model assume immediacy of processing in comprehension, that is, each word is integrated into the evolving syntactic and semantic representation as soon as possible after its occurrence in the input stream. Consistent with the empirical evidence it is assumed that immediacy of processing is a property of the sentence comprehension of both normals (Just & Carpenter, 1980; and Marslen-Wilson & Tyler, 1980) and aphasics.

THE NEW MODEL

The task we have given the new model of aphasic sentence comprehension is to derive the meaning relations among the words of a sentence as they come in from left to right. In particular, the model's focus is on deriving the thematic roles that the verb assigns to the nouns in the sentence, such

as agent, theme, and goal. In this section, we introduce the model, by describing the computer 3CAPS architecture (Just & Carpenter, 1992) that embodies the assumptions of the capacity theory about the storage and processing properties of working memory. Then, we provide an overview of how the major components of the model work together to derive the meaning of a sentence and focus in particular on the processing principles that determine parse tree construction and thematic role assignment. In Appendix A, we offer a simple example of how the model processes a sentence under conditions which we hypothesize to resemble the situation of a normal and aphasic patient, that is, involving a normal versus reduced working memory capacity for language.

The Cognitive Architecture: 3CAPS

Like its predecessor, the CC READER model, the new model has been implemented in 3CAPS (Just & Carpenter, 1992). 3CAPS is an activation-driven production system that has been put forward as a model of the human cognitive architecture, that is, having properties that hold across cognitive domains. Thus, 3CAPS has been used successfully to model working memory related phenomena in a variety of domains including sentence comprehension (Just & Carpenter, 1992), story comprehension (Goldman & Varma, 1995) and human-computer interaction (Huguenard, Lerch, Junker, Patz, & Kass, 1993). 3CAPS combines symbolic computation (i.e., production rule application) with connectionist properties (i.e., activation propagation). The symbolic component provides the computational power that is necessary to do sentence processing (Fodor & Pylyshyn, 1988) as it permits the composition of higher order representations (e.g., parse trees) out of individual elements (e.g., word class information) as specified in production rules, which enable variable binding. The connectionist component provides a way to capture the graded quality that seems typical of normal and aphasic sentence comprehension, such that activation propagation and storage modulate the efficacy of the symbolic component.

In 3CAPS all processing takes place in cycles. A cycle constitutes a discrete time unit during which a set of production rules, also called condition-action rules, is matched against the contents of working memory (e.g., for language comprehension) and long term memory (e.g., a mental lexicon and grammar). The condition side of such a rule specifies a configuration of elements that needs to be present in memory for the rule to match and to be evoked (e.g., noun phrase followed by finite verb). The action side of a production rule specifies a modification to the contents of working memory (e.g., add subject relation). In the case of 3CAPS, the prototypical action involves one of directing activation, where activation is directed from a condition element (i.e., source element) already in working memory to a new element (i.e., the target element), until some prespecified target level of activation has been reached. In order to reach this target level, the same production

rule usually needs to fire and direct activation to its target for several cycles. The reason for this iterative behavior is that not all but only a proportion (i.e., determined by a factor called weight) of the activation of the source element is propagated to the target element. An important boundary condition on the application of a production rule involves a co-activation requirement, which specifies that the activation level of each matching source/condition element in working memory must surpass a certain critical threshold value, called the condition threshold. Elements that are target elements (e.g., noun phrase is subject) in one production can be source elements in another production and cause the activation of new elements (e.g., noun phrase is agent) in working memory.

An important property of 3CAPS as an architecture for human working memory is that the activation demands that are associated with both storage and processing on any given cycle, cannot always be fulfilled completely but instead are constrained by working memory capacity. The activation demand associated with storage is given by the sum of the activation of all elements in working memory. On any one cycle several production rules may match and direct activation in parallel. The sum of the individual propagated amounts (i.e., source activation \times weight factor) determines the processing demand. Whether or not these activation demands can be met is dependent on the working memory capacity, which is defined quantitatively by the number of activation units available for storage and processing per cycle (e.g., 30 units). Since activation is treated as a finite commodity, a situation of activation shortage arises when the combined storage and processing demands exceed the capacity. In such a situation, the activations that are associated with individual working memory elements and with individual propagation amounts are scaled down so that the total activation (i.e., the capacity) is allocated (see Just & Carpenter, 1992, p. 135, for a numerical example). This results in both forgetting and slower processing. Also, some of the processing may never become initiated or may be halted prematurely, since forgetting interferes with the co-activation requirement on production rule matching. The consequence for sentence processing is partial comprehension, that is, some of the elements that represent the final interpretation of the sentence are either partially activated (i.e., below target level) or are completely absent. Aphasics, whom we hypothesize to suffer from a pathological reduction in working memory capacity due to brain damage, are more likely to show partial comprehension than normals, especially when the deficit is severe and the processing load is high.

Model Components and Information Flow

To accomplish its task of deriving the thematic role relations among the words of a sentence, the model uses three major component subsystems that perform three functions: lexical access, parse tree construction and thematic

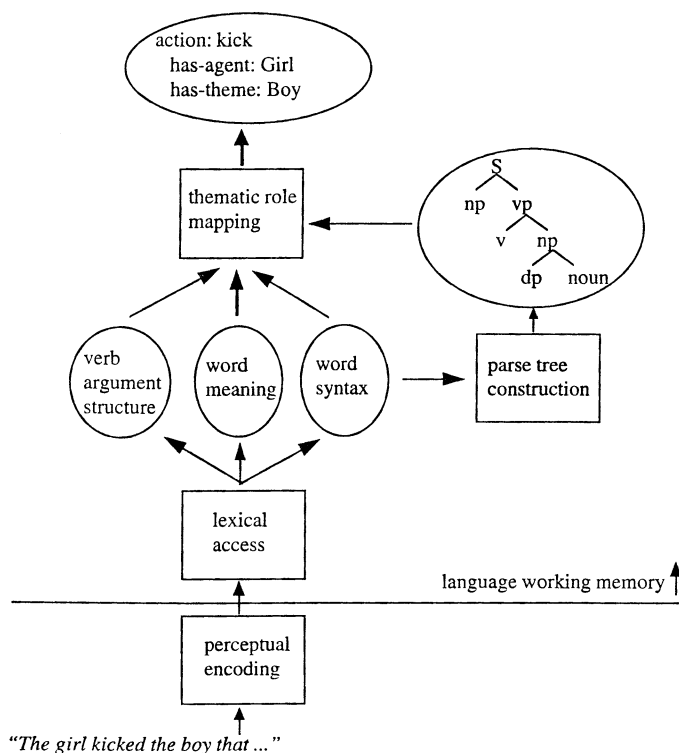


FIG. 1. Overview of the model. As each word comes in, the model attempts to incorporate it as much as possible into the evolving syntactic and semantic representation. First, the word is perceptually encoded. Then, lexical access makes available its meaning and syntactic class and, in the case of verbs, also its argument structure. Based on its word class and a grammar, the word is integrated into a parse tree representation. The thematic role mapping component computes thematic-role bindings.

role mapping. These three components as well as the information flow among them are depicted in Fig. 1. Each model component is implemented in the form of a set of production rules which temporarily activate sentence representational elements in working memory for language. Rather than describing these production rules in detail, we will focus on the processing principles that are embedded in their design.

Immediately after a word has been encountered in the input stream, it is perceptually encoded, that is, a working memory element representing its abstract word form becomes activated. After perceptual encoding, the lexical access component activates three types of information associated with the representation of an individual word in a mental lexicon in long term mem-

ory: its core meaning, its syntactic class, and, in the case of verbs, its argument structure. Most aspects of perceptual encoding and lexical access are performed similarly to the CC READER model (see Just & Carpenter, 1992). A new aspect of lexical access is the activation of a verb's argument structure, described below.

Post-lexical integration of a word meaning into the evolving syntactic and semantic representation occurs as soon and as much as possible after the word has been encountered in the input stream, following the principle of immediacy of interpretation (Just & Carpenter, 1980; Marslen-Wilson & Tyler, 1980; Just & Carpenter, 1992), that is, without any knowledge of the remaining words in the sentence. Based on syntactic word class information and access of a grammar in long-term memory, the parse tree component constructs a temporary parse tree which indicates the hierarchical relations among the constituents in the sentence as well as some long distance dependencies, namely those between so called traces of moved NPs and their antecedents. The thematic role mapping component computes a temporary meaning representation consisting of the thematic roles that a verb assigns to the nouns in the sentence, such as agent, theme, and goal. In the example in Fig. 1, the model derives the two thematic role bindings associated with the sentence "*The girl kicked the boy,*" each of which is represented by a working memory element that encodes a proposition of the form (concept: relation concept): (kicked has-agent girl) and (kicked has-object boy). We will now describe the representational assumptions and processing principles that are involved in the model's parse-tree activation and thematic role mapping in more detail.

Parse Tree Activation

An important intermediate representation in the mapping of words onto thematic roles is the parse tree. The structural properties of a typical parse tree are illustrated in Fig. 2. The parse tree consists of two types of working memory elements, constituent-head elements and constituent-relation elements. A constituent-head element specifies the head relation between the lexical¹ syntactic category of a word (i.e., word class information) and its maximal phrasal projection, for example (VERB head VP). A constituent-relation element specifies which grammatical relation one constituent-head element assigns to another, for example (VP assigns-complement PP). To-

¹ A few constituent-head elements are not lexically realized but must instead be inferred and projected from the surface structure of the sentence. In the model, a (CP head COMP) element is projected in the case of a reduced relative, which lacks an overt complementizer *that*. Furthermore, an (IP head INFL) element is projected when verb finiteness is not realized through a separate auxiliary verb (i.e., a verb of category INFL) but rather through a tensed main verb (i.e., a verb of category VERB) (cf. Gibson, 1991). Finally, the model projects trace elements (see subsection on thematic role mapping).

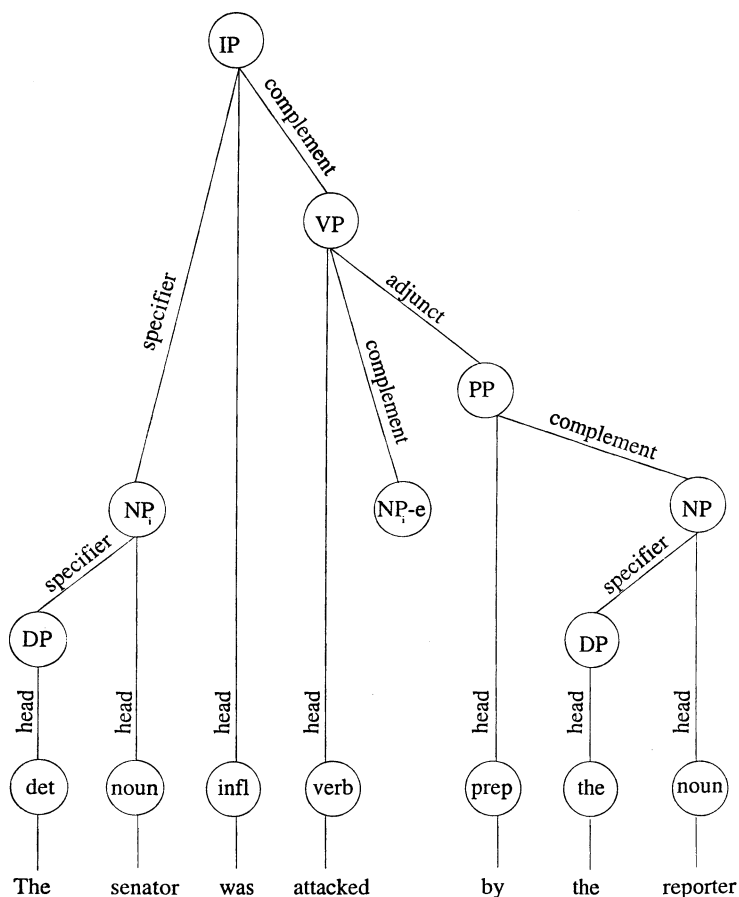


FIG. 2. A sample parse tree representation of a passive sentence showing the hierarchical relations among the major constituents in the sentence as a set of syntactic categories inter-linked by grammatical roles. The parse tree is constructed word by word by a set of production rules that access a grammar.

gether, the set of constituent-head and constituent-relation elements specify a hierarchical network of syntactic categories interconnected by grammatical relations (cf. Kempen & Vosse, 1989).

A grammar specifies for each constituent-head which configuration(s) (i.e., order and kind) of constituent-relation elements may surround it. As illustrated in Fig. 2, the head of the auxiliary phrase IP may be preceded by an NP, which receives the grammatical role of specifier and by a VP which receives the grammatical role of complement. The complete grammar used

in the simulations is shown in Fig. 3. The grammar formalism obeys the constraints of the X-bar theory of syntax (Chomsky, 1970; 1986b; Jackendoff, 1977),² which provides an adequate structural description of many sentence types including the ones used in our simulations (see e.g., Haegeman, 1991; Radford, 1988). The latter is important since the model's predictions regarding the effects of sentence complexity are to some extent dependent on the details of the assumed underlying representation.

An important property of the model's parsing algorithm that is related to its ability to capture aphasic sentence comprehension, is its distributed control scheme. What makes the control scheme distributed is that the various constituent-relation elements, each of which interlinks two constituent-head elements, are derived and activated fairly independently from one another. A dependency arises only within constituents, when the order constraints imposed by the grammar must be obeyed. A separate control element, which becomes activated as a by-product of constituent-head element activation, keeps track of the order constraints and licensing conditions (i.e., what category assigns what role to what other category) within each constituent. As long as these order constraints and licensing conditions are obeyed, the presence of a pair of two constituent-head elements automatically results in the activation of a constituent-relation element (cf. the unification scheme used by Kempen & Vosse, 1989).

A consequence of the distributed control scheme for the simulation of aphasic sentence comprehension is that a failure to derive and activate the parse tree representation of one constituent (or parts thereof) does not necessarily imply a failure to derive and activate the parse tree representation of another constituent, and use that part successfully in subsequent thematic role mapping. And indeed, when sentence comprehension performance is evaluated not merely on a pass/fail basis but also in terms of what parts of the sentence have been understood (e.g., Caplan & Hildebrandt, 1988; McNeil & Prescott, 1978), this kind of partial comprehension seems to be characteristic of the aphasic patient. For example, when presented with a conjoined sentence like "*The monkey hit the bear and kissed the rabbit*," an aphasic patient may correctly analyze and interpret the subparts "*The monkey hit the bear*" and "*kissed the rabbit*" but fail to interpret "*The monkey (. . .) kissed*" (example from Caplan & Hildebrandt, 1988, p. 119). We refer to this phenomenon as partial comprehension. We further note that partial com-

² Congruent with the X-bar theory of syntax, we assume (1) that each constituent XP consists of only a single phrasal head X flanked to its left and right by other attached constituents (e.g., YP) and (2) that each phrasal head X may assign a predetermined set of grammatical roles (e.g., specifier, complement, and adjunct) according to a language-specific canonical scheme. The various bar levels assumed in X-bar theory have been recoded in our representation. Thus, the path XP-X'-X'-ZP with ZP as sister of X has been represented as XP-complement-ZP, while the path XP-X'-YP with YP as sister of X' has been represented as XP-adjunct-YP.

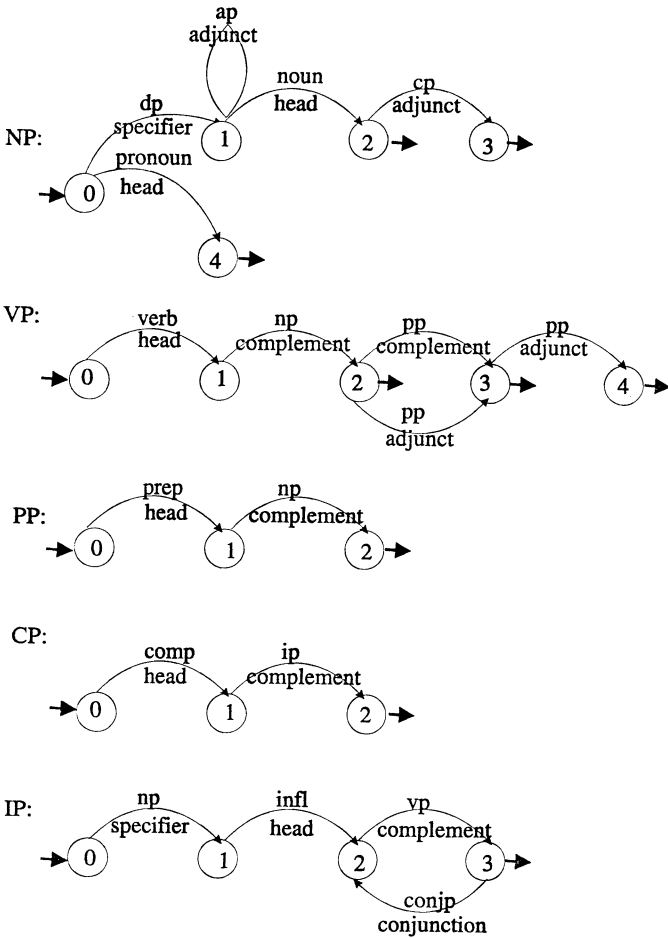


FIG. 3. The model's grammar. The model's distributed parsing scheme derives a syntactic structure as a path through a series of states (numbered circles). Each constituent as well as its pre- and post-head part adjuncts are parsed independently of each other. The distributed parsing scheme ensures that the capacity reduced model is capable of partial comprehension, in that, a failure to derive a demanding part of a parse tree representation does not have a negative effect on the parsing of another less demanding part and its subsequent semantic interpretation.

prehension can occur even in normal subjects when available resources are insufficient (Miyake et al., 1994).

Meaning Representation and Thematic Role Mapping

The model's meaning representation of a sentence includes two types of working memory elements: those that represent individual word meanings

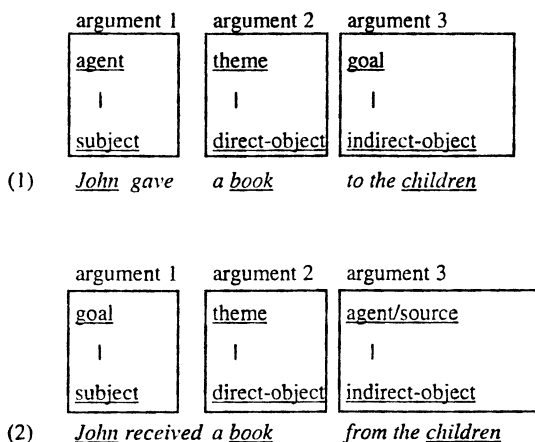


FIG. 4. Examples of verb argument structure. The verbs *give* and *receive* each have their own unique argument structure consisting of three elements correlating a grammatical role (e.g., subject) with a thematic role (e.g., agent). Presentation of a verb to the model results in activation of such elements which provide the schema for thematic role mapping.

and those that represent meaning relations among words. For example, the sentence “*The young man greeted the woman*” would be represented by individual meaning elements (young), (man) and (woman) and by the meaning-relation elements (man has-attribute young), (greeted has-agent man) and (greeted has-theme woman). The individual meaning elements represent temporarily activated knowledge from the mental lexicon in long-term memory. The meaning-relation elements, on the other hand, rather than being pre-stored in long-term memory, represent newly constructed knowledge. In the case of thematic role bindings, that is, meaning-relations among a verb and its arguments, these elements are created by the thematic role mapping component.

The thematic role component maps words or groups of words in the parse tree representation onto thematic roles in the sentence meaning representation. This mapping is many-to-many and its details are dependent on which verb is involved, specifically on its verb argument structure (e.g., Chomsky, 1986a; Pollard & Sag, 1987; Gibson, 1991). The concept of verb argument structure is illustrated in Fig. 4 with two sample sentences involving the verbs *give* and *receive*, respectively. The argument structure associated with these verbs is similar in that both involve a mapping of the roles of agent, theme and goal onto the parse tree positions of subject, direct object and indirect object, albeit a different mapping for the two verbs. Thus, the noun in subject position is the agent of the verb *give* but the goal of the verb *receive*, while the noun in indirect object position is the goal of the verb *give* but the agent (and source) of the verb *receive*. Both verbs assign the

theme to the noun in object position. In the model, a verb's argument structure is stored in the mental lexicon and consists of one or more elements, called arguments. Each such argument specifies in what parse tree position to expect what thematic role (as indicated by the boxes in Fig. 4) and also whether or not the occurrence of that argument in a sentence is obligatory or optional. Each argument is furthermore indexed to indicate to which verb argument structure alternative it belongs, because a verb may have more than one argument structure associated with it (cf. "*John give the book to the children*" versus "*John gave the children a book*") and because several verbs may share the same argument structure (cf. "*John gave/handed the children a book*"). Several instantiations of the same production rule result in the parallel activation of the different arguments of a verb's argument structure during lexical access (i.e., through activation spread from the word form representation), one instantiation per argument. Because of the associated processing and storage costs, verbs with more arguments and/or argument structure alternatives impose a greater processing and storage demand on the model.

Thematic role assignment is a relatively demanding process. The computation of a thematic role binding requires the application of one production rule. There is one such production rule for every possible parse tree position that an argument can refer to. The successful application of this production rule requires the co-activation of different kinds of working memory elements, all of which require activation for their maintenance. To begin with, the production rule needs to have access to the lexically activated verb argument. In addition, the production rule needs to have access to the subset of parse tree elements that specify the particular parse tree position of that argument. For example, to locate the indirect object, two connected constituent-elements are required: (VP assigns-complement PP) and (PP assigns-complement NP), where depending on the verb, the PP must be headed by a particular preposition (as specified in the argument) (e.g., *to* or *from*). Finally, a thematic role binding connects the meaning of the verb with the meaning of its argument. Therefore, the working memory elements representing these two meanings must be active as well.

That thematic role mapping is a relatively demanding process in human beings is indicated by the finding that sentence comprehension is relatively more impaired than syntactic judgment, which for the most part relies on syntactic analysis only (Linebarger, Schwartz, & Saffran, 1983). However, as Linebarger et al. point out, syntactic analysis may also suffer from a reduction in processing resources, especially when the relevant grammatical relations involved span a larger distance across the sentence (see also Baum, 1989). In the model, syntactic errors would result from the activation costs associated with the computation and storage demands of the intermediate representations.

Another factor determining processing load involves the need to compute

and represent a so called trace as part of the parse tree representation of a sentence (for a linguistic motivation of the trace concept see Chomsky, 1981; see also introduction by Haegeman, 1991). This trace represents the canonical verb argument position of a noun phrase that has been realized somewhere else. By virtue of being coindexed with the trace, the noun phrase can be assigned a thematic role by the regular thematic role assignment process, which takes into consideration only the canonical verb argument structure positions. To illustrate, consider the following three sentences with the verb *to attack*, whose argument structure requires the agent and theme roles to be in the canonical subject and direct object position, respectively.

(1) [The reporter]_i that *t_i* attacked the senator admitted the error.

(2) [The reporter]_j that the senator attacked *t_j* admitted the error.

(3) [The senator]_k was attacked *t_k* by the reporter.

In the subject-subject relative (1), the bracketed noun phrase *the reporter* receives the agent role from the verb *to attack* by virtue of being coindexed with the trace *t_i*, which occurs in the subject position of the relative clause. In the subject-object relative (2), the bracketed noun phrase *the reporter* receives the theme role from the verb *to attack* by virtue of being coindexed with the trace *t_j*, which occurs in direct object position (i.e., immediately postverbal) of the relative clause. And, finally, in the passive sentence (3), the bracketed noun phrase *the senator* receives the theme role from the verb *to attack* by virtue of being coindexed with the trace *t_k*, which also occurs in direct object position. The model has three trace-creating productions, one for each of the three sentence types (1), (2), and (3). The model represents a trace as a constituent-head element (NP head NOUN), itself lexically unfilled but coindexed with and therefore pointing to the appropriate noun antecedent. The need to compute and store traces for these sentence types puts an additional demand on working memory for language (cf. Haarmann & Kolk, 1991a). It might be noted that the correct interpretation of passives requires two extra ingredients (cf. Haegeman, 1991). The first ingredient is the assignment of the agent to the by-phrase, which is accomplished by a separate thematic role assigning production. The second ingredient is the suppression of agent assignment to the subject, which is accomplished by requiring that the regular agent assigning production rule be not applied in case of passive verb morphology.

SIMULATION STUDIES

A central prediction of the capacity theory is that the relation between the capacity of working memory for language and the demand of the comprehension task determines the success of the comprehension in normals and aphasics. In this section, we report the results of three simulation studies in which this relation has been manipulated in different ways. The first simulation study represents an initial attempt to simulate the sentence complexity effects

that Caplan et al. (1985) obtained in aphasics using nine different sentence types which vary in the demand they impose on working memory for language. The second simulation study concerns the interaction between the severity of aphasia and the complexity of two types of sentences, namely actives and passives (e.g., Kolk & van Grunsven, 1985; Schwartz et al., 1980). The third simulation study demonstrates the use of the model in generating predictions for new research by exploring the effect of adjective padding (i.e., adding one or more adjectives to a noun phrase) on the sentence complexity effect as observed for actives, passives, subject relatives and object relatives.

All the simulation studies used the same format. For every unique sentence type, the model was run once. At the end of a run when there was no more processing (i.e., no productions that "fired"), we recorded the activation levels of those working memory elements that are critical for responding with the correct thematic roles in the sentence comprehension task, namely, the working elements that represent the thematic role bindings (i.e., not the isolated word meanings). We then computed the average activation value of these elements as an index of sentence comprehension accuracy. For example, after having finished the processing of the sentence "The rat was hit by the dog," the model may have activated two working memory elements representing semantic role bindings, namely (hit has-agent dog) and (hit has-theme rat), at activation levels of 2.18 and 1.82, respectively, yielding an average value of 2.00. Note that the model is deterministic,³ that is, for a particular set of parameters and input sentence, every run of the model yields the same activation-based index of comprehension accuracy. We assume that there exists some monotonic function that maps the activation-based index of comprehension accuracy to error percentages, with lower activation values resulting in more errors and with failures to retrieve any thematic role at all as the extreme case of a long retrieval time (Anderson, 1993). The exact form of this function is left for future exploration.

Values for the model's parameters were obtained as follows. We first determined the lowest capacity value at which the model performed perfectly on all nine sentence types used in the Caplan et al. (1985) study. This working memory capacity turned out to be 30 units of activation. The hypothesized resource reduction in aphasia was then induced by decreasing the model's working memory capacity considerably, reducing it by half to a level of 15 activation units, to optimize the fit with the Caplan et al. data. An even

³ Simulation studies using the model can include a stochastic component to correspond to variation in the size of the resource pool. The notion of stochastic variation in impairment level (Haarmann & Kolk, 1991), for example, due to physiological factors, is compatible with our approach. In addition, a stochastic component seems necessary to simulate not only how often a particular noun is interpreted the wrong way (i.e., inversely related to the activation of the correct thematic role binding) but also which particular error is made in such cases.

more severe reduction to a level of 12 activation units was added as a separate condition in the second simulation study. Several other parameters were set by hand and kept constant across the simulation studies. These included the resting level, condition threshold, and target activation level of working memory elements, the weight factor, the word introduction rate and, finally, an activation allocation bias parameter whose function is explained in the appendix. For each simulation, we verified that minor fluctuations in their values did not change the ordinal pattern in the simulation results. The target level for activating thematic role bindings was chosen to be higher than that of other elements to reflect their importance for the ultimate goal of sentence comprehension, that is, meaning interpretation.

Simulation Study 1

The goal of the first simulation study was to explore to what extent the model can capture sentence complexity effects reported in the literature in aphasia. We chose to simulate the data from a study of aphasic sentence comprehension reported by Caplan et al. (1985) for several reasons. First, their study included a large number of aphasic patients from all major syndrome types. This was important because our model, contrary to earlier models, which simulated sentence comprehension performance in agrammatic aphasics, (Kempen & Vosse, 1989; Haarmann & Kolk, 1991a), represents a claim about a component of aphasic comprehension deficits which we hypothesize to be common to all aphasic patients. Second, the Caplan et al. study included a relatively large number (nine) of different sentence types, which would provide for a stronger test of the new model's ability to capture sentence complexity effects (see Table 1). Third, Caplan et al.'s patients showed consistent sentence complexity effects across three different studies (for data see Table 4.19, p. 22 in Caplan & Hildebrandt, 1988), indicating that the data represent a reliable phenomenon. To obtain the most reliable estimate for comparison with the simulation results, we took the average group performance per sentence type across these three studies.⁴

Aphasic sentence comprehension was simulated by reducing the resources available for storage and processing in working memory for language to 15

⁴ Within each study, average percentages correct per sentence type were obtained by collapsing performance across different patient clusters. Caplan et al. found that the sentence complexity patterns of these patient clusters were determined by a common factor, which loaded about equal on all sentence types and accounted for almost 65% of the variance, and by cluster-specific effects, which accounted for less than 20% of the variance. By collapsing across the sentence complexity patterns of different patient clusters, the present simulation study focuses on the effect of the common factor and treats cluster-specific sentence complexity effects as a source of random error. However, future studies with the model may attempt to simulate cluster-specific sentence complexity effects by considering various potential sources of cluster-specific variation, such as variation in additional impairments and processing strategies (cf. discussion).

TABLE 1
Sentence Types Used in the Caplan et al. (1985) Study

Sentence types
Active (A) The rat hit the dog.
Passive (P) The rat was hit by the dog.
Cleft-Subject (CS) It was the rat that hit the dog.
Cleft-Object (CO) It was the rat that the dog hit.
Dative (D) The rat gave the dog to the cow.
Dative Passive (DP) The rat was given to the dog by the cow.
Conjoined (C) The rat hit the dog and kissed the cow.
Right-Branching Subject Relative or Object-Subject relative (OS) The rat hit the dog that kissed the cow.
Center-Embedded Object Relative or Subject-Subject relative (SO) The rat that the dog hit kissed the cow.

units of activation, (half the amount required for perfect comprehension). Figure 5 shows the aphasic data from the Caplan et al. (1985) studies, plotted together with the simulation results. The ordinal pattern in the simulation data mirrors the human data in various respects. Actives and cleft subjects are about equally easy to process. Passives, datives, and cleft objects are more difficult. Still more difficult than passives and datives are the right branching object-subject relative sentence and the conjoined sentence. And the center embedded subject-object relative sentence is the most difficult. Datives fit quite well within the overall order of difficulty obtained by Caplan et al. However, compared to passives, datives seem somewhat too easy for the model. We could perhaps remedy this discrepancy by increasing the target activation level of verb arguments, causing a disproportionate increase in the activation demands for datives which have one more verb argument than passives. However, this relative discrepancy between the model and the data should not be overinterpreted, as Caplan et al. report minor variations in the order of difficulty between datives and passives across their three studies. Finally, although the model captures the fact that cleft objects are more difficult to process than actives and cleft subjects, cleft objects seem to be too difficult for the model when compared to passives. This is possibly due to the fact that the model does not have enough time to complete all of the processing associated with the computationally demanding object-relative verb (see below) before the next word comes in. Spillover of processing to

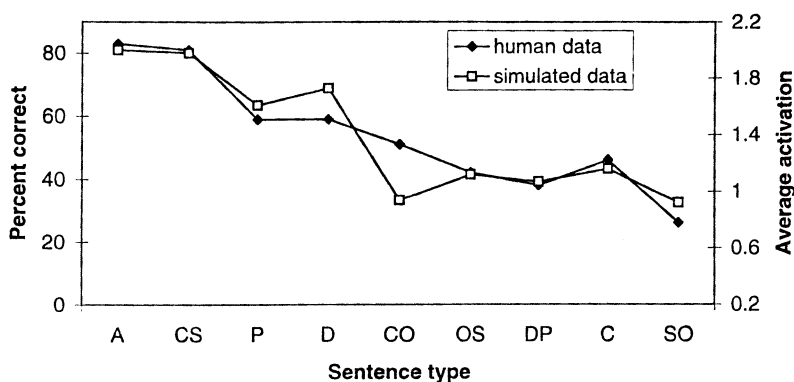


FIG. 5. Mean comprehension performance of aphasics for nine sentence types: human versus simulated data: Active (A), Cleft-Subject (CS), Passive (P), Dative (D), Cleft-Object (CO), Object-Subject-Relative (OS), Conjoined (C), Dative Passive (DP), and Subject-Object-Relative (SO). The human and simulated data reveal a similar ordering of difficulty across the nine sentence types. The human data represent percent correct comprehension and are based on the data reported in *Disorders of syntactic comprehension* by D. Caplan & N. Hildebrandt, 1988, Table 4.19, p. 122. The simulation data represent the average final activation of the thematic role bindings after one run of the model with reduced capacity.

the next word, which is not part of the current model, might remedy this problem.

The model's ability to simulate most of the sentence complexity effect that was obtained by Caplan et al. (1985) is dependent on two sentence properties, (1) the number of working memory elements associated with the internal representation of a sentence and (2) their distribution across the sentence. To begin with the first factor, the greater the number of working memory elements that need to be generated and maintained during the processing of a particular sentence, the more likely the system is to encounter resource demands that exceed the supply. Consequently, the model has more difficulties with the interpretation of sentences that contain more verbs and associated noun phrases (e.g., conjoined versus active sentences), and more verb argument structure elements (e.g., datives with three-place argument verbs versus actives with two-place argument verbs). The model also has more difficulties with the interpretation of sentences that contain more parse tree elements due to length (e.g., conjoined versus actives) or depth of embedding (e.g., subject-subject relatives versus conjoined, see also Haarmann & Kolk, 1994; Kolk & Weijts, in press). To mention one more example, the presence of a trace is another factor that adds to interpretation difficulty (e.g., actives versus passives or subject-object relatives).

The second sentence property determining the model's sentence comprehension performance is the distribution of the storage and processing load across a sentence. The effect of this variable can be best illustrated by consid-

ering the contrast between subject and object relative sentences. The model has more difficulties with object than with subject relative sentences, not just in the case of clefts (average thematic role binding activations of 1.98 for CS vs. 0.94 for CO) but also in the case of center embedded (1.16 for SS vs. 0.92 for SO) and right branching sentences (1.12 for OS vs. 0.74 for OO).⁵ This is a robust sentence contrast that has been obtained in several studies of normal comprehension (for review see MacWhinney & Pleh, 1988) and aphasic sentence comprehension (for a review see Grodzinsky, 1989; Miyake et al., 1994). Hakuta (1981) has reported evidence from Japanese children suggesting that the stacking of noun phrases prior to the verb (e.g., *'the senator that the reporter attacked'*) makes object relative sentences more difficult than subject relative sentences (e.g., *'the senator that attacked the reporter'*). And indeed this particular factor explains the model's ability to capture the subject-object relative contrast. This factor also enabled the CC READER model to simulate capacity-related individual differences in the time course of reading in normal subjects (Just & Carpenter, 1992). Thematic role assignment at the location of the verb is more activation-demanding in an object- than subject-relative because it involves the maintenance and assignment of an extra argument in case of an object relative. Besides the stacking of noun phrases, there might be other factors that contribute to the greater difficulty of object relatives, such as their non-canonical word order or the need to change the initially preferred active interpretation of the first noun phrase from agent to theme (for a discussion of this and other factors see MacWhinney & Pleh, 1988). While such a shift in perspective may place an increased burden on the inferential-pragmatic aspect of language working memory, and thus could be especially problematic for low capacity subjects, it falls outside the scope of the current model.

The first simulation study revealed two unexpected consequences of the capacity theory as implemented in the model. To begin with, a prior version of the model, while producing the advantage of subject- over object-relative sentences at the location of the embedded verb (i.e., a more highly activated agent binding than in the object-relative), was not able to hold onto the agent binding until the end of the sentence due to its below-normal capacity. This illustrates that it is not just the local load but the cumulative load across the course of sentence comprehension that determines the model's success rate. To remedy the model's problem with the retention of already computed thematic role bindings, we included a bias parameter in the activation allocation mechanism of the 3CAPS system that could be set to favor the storage of thematic role bindings. Rather than scaling down all activation demands in an evenhanded manner, the activation associated with the storage of thematic role bindings was scaled back less (i.e., approximately 7.5% less on

⁵ Performance on SS and OO was not graphed in Fig. 5 because these two sentence types were not included in the Caplan et al. (1985) study which we attempted to simulate.

average; see Appendix B for more details). This seemed a reasonable choice given that an aphasic's ultimate task in a test of sentence comprehension is to indicate the understanding of thematic role bindings.

Another unexpected consequence of the capacity theory as implemented in the model was the simulation result that center embedded sentences (i.e., SS and SO) were no more difficult and in fact slightly easier to process for the low capacity model than their right branching counterparts (OS and OO). In the former but not the latter type of sentence, the relative clause postpones the moment of syntactic-semantic integration of the subject and predicate of the matrix clause. Due to interference from the intervening sentence constituents one might therefore expect center-embedded sentences to be more difficult to understand than right branching ones (cf. Miller & Isard, 1964; Yngve, 1960). However, while the model's performance does indeed suffer from interference by an intervening relative clause, there is another counter-vailing factor. Recall from the model section that sentences with a relative clause require the derivation of a trace for their interpretation. Trace derivation is more vulnerable in sentences with a right branching as opposed to center embedded relative clause due its late occurrence, that is, when more activation resources have been consumed. Again, this illustrates that it is not just the local load but the cumulative load across the course of sentence comprehension that determines the model's comprehension. In fact, the model's performance turns out to be consistent with the empirical evidence from normal adults (Baird & Koslick, 1974; Hakes, Evans, & Brannon, 1976; Holmes, 1973; but see Miyake et al., 1994), normal children (for review see MacWhinney & Pleh, 1988) and aphasics (Grodzinsky, 1989), which indicates that center-embedded SS and SO sentences are either no more difficult or easier to process than their right branching counterparts OS and OO. Unfortunately, the evidence from Grodzinsky's aphasia study is somewhat weak. Agrammatic patients performed at chance on both center embedded SO sentences and right branching OO sentences, possibly due to the fact that the critical test of sentence comprehension was restricted to the same relative clause in both sentence types (cf. Haarmann & Kolk, 1994, Footnote 1).

In sum, the results of the first simulation study show that the model can account for most of the sentence complexity effects that were obtained in a study of aphasic sentence comprehension by Caplan et al. (1985), involving as many as nine different sentence types. Furthermore, the model consistently produced the subject-object relative contrast, that aphasics show in the context of cleft sentences, center-embedded sentences and right branching sentences (Grodzinsky, 1989; Miyake et al., 1994). Comprehension of complex sentences requires the storage of many working memory elements and also tends to involve computations which are less spread out across different sentence positions but instead are concentrated in one region of the sentence. This makes the competition for the limited resource pool more intense and explains the model's ability to capture sentence complexity effects.

Simulation Study 2

The goal of our second simulation study was to explore to what extent the new model can capture the combined effect of sentence complexity and severity. A central assumption of the capacity theory, is that the breakdown in sentence comprehension performance is a function of the relation between capacity and demand. Indeed, the underlying 3CAPS architecture scales down on the activations used for storage and processing when their combined demand surpasses the model's working memory capacity. A more complex sentence makes a larger demand, and increased aphasic severity is presumed to be associated with a smaller resource supply. Together, these considerations might lead one to expect an interaction between sentence complexity and severity, such that an increase in sentence complexity has a stronger deleterious effect on sentence comprehension performance when the capacity of the system is low to begin with (Miyake et al., 1988).

We choose to simulate the sentence comprehension accuracy of two aphasic patients, *la* and *roo*, on simple active SVO sentences and their passive counterparts (data from Kolk & van Grunsven, 1985; see Fig. 6a). Overall comprehension accuracy indicated a more severe impairment in patient *roo* than in patient *la*. For both patients, passives were more difficult to process than actives, a pattern which has also been obtained in many group studies (see Haarmann & Kolk, 1991a, p. 65, for a review). However, for the mild patient *la* the difference between actives and passives was relatively small, whereas it was large for the severe patient *roo*.⁶ As can be seen in Fig. 6b, the model captures this particular interaction between sentence complexity and severity quite well.

At the same time, a note of caution is in order regarding the sentence complexity by severity interaction. Ongoing explorations with the model indicate that interaction is not a general property of the current model. In particular when the most simple sentences (i.e., SVO actives) are omitted from consideration, the sentence complexity by severity interaction as discussed above is not guaranteed to be present. Instead additive effects are sometimes obtained, or even an interaction in the opposite direction. One possible explanation for the variation of the interaction is related to the distribution of computational demand and activational resources across a given sentence.

⁶ A qualitatively similar interaction can be observed in the group patient data of Caplan et al. (1985) if one compares the average performance of their 10 mildest and 10 most severely impaired patient clusters on actives and passives. We have not, however, attempted to simulate performance of the different patient clusters on these and the other sentence types in that study. The statistical analyses carried out by Caplan et al. indicate that performance of the different patient clusters is not only a function of the severity of a deficit which is shared across patient clusters but also of effects which are specific to a particular patient cluster. While the latter effects are not incompatible with the current model (cf. discussion), their simulation is left for future exploration.

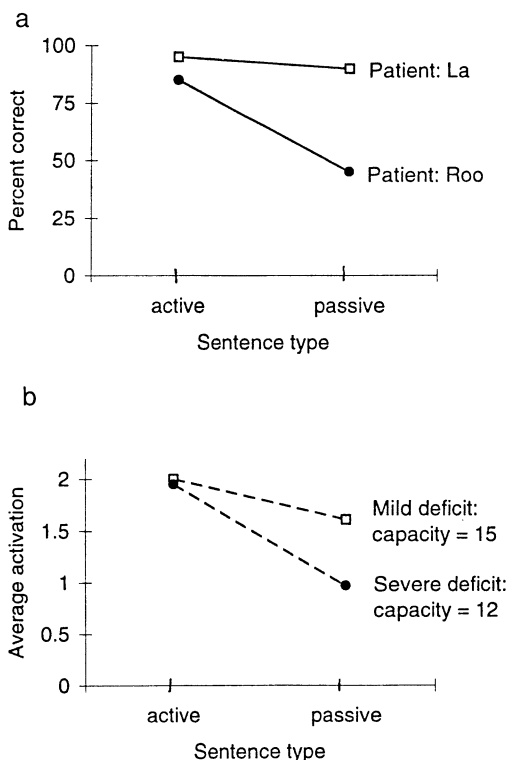


FIG. 6. Interaction between sentence complexity and severity. (a) A passive sentence causes much more difficulty than an active in a moderately impaired aphasic patient Roo, but the effect is much smaller in a mildly impaired aphasic patient La. (b) The same is true for the model with a reduced language WM capacity of 12 or 15 units of activation, which corresponds to a moderate and mild resource reduction, respectively. The human data are based on individual patient data reported by Kolk & van Grunsven, 1985.

The more that the activation cannot be allocated to the most demanding part of a sentence (i.e., due to its complexity and the severity of the capacity decrement), the more the activation becomes available for the processing and representation of a later occurring part of the same sentence. This re-allocation of activation mechanism sometimes counteracts the sentence complexity by severity interaction that one might be led to expect otherwise. More empirical and simulation research is necessary to establish the factors that modulate the relationship between sentence complexity and severity of the deficit. At any rate, the simulation results suggest that the presence or absence of an interaction between sentence complexity and severity across different parts of the complexity and severity spectrum does not necessarily constitute evidence for or against the capacity theory. Instead, the observa-

tions make it clear that the dynamics of sentence comprehension are far too complex to permit precise predictions to be made in the absence of a computational model.

Simulation Study 3

The goal of our third simulation study was to demonstrate the role the computer model can play in generating new predictions for future research. A central claim of the theory is that the availability of working memory resources determines sentence comprehension performance. One way to manipulate the availability of working memory resources is to introduce a secondary task which consumes the resources from the same pool as used by the sentence comprehension system, for example, retention of one or two words that are not a part of the stimulus sentence (Just & Carpenter, 1992). For example, an extrinsic memory load has a negative impact on sentence comprehension accuracy for normal adults, particularly when sentences are complex (i.e., object- instead of subject-relative) and/or subjects' reading span is low (King & Just, 1991). Another way to manipulate the availability of working memory resources is to add extra verbal material to be processed as part of the stimulus sentence in the comprehension task, that is, by a "padding" manipulation. Several studies have shown aphasic sentence comprehension to be negatively affected by padding, for example, by padding with adjectives in the context of the well-known Token Test (e.g., DeRenzi & Vignolo, 1962; McNeil & Prescott, 1978; Orgass, 1976) and by padding with extra verb phrases (Kolk & Weijts, in press; but see Schwartz, Linebarger, Saffran, & Pate, 1987). However, the interaction between a padding manipulation and other ways of manipulating sentence complexity has yet to be explored empirically in aphasics. If, as hypothesized, aphasic patients suffer from a resource reduction, the mere addition of an adjective to one or two noun phrases in the sentence (i.e., adjective padding), could have a negative impact on their sentence comprehension accuracy, especially in case of a more demanding, more complex type of sentence. We therefore used the model to generate predictions about the combined effects of adjective padding and sentence complexity in a low capacity system.

The hypothesized resource reduction was induced as in the first simulation study, that is, by reducing working memory capacity from 30 units of activation (i.e., corresponding to normal) to 15 units of activation (i.e., aphasic). And sentence complexity was manipulated as in the second simulation study, by including actives and their more difficult passive counterparts. Each of these two sentence types occurred in two versions, with and without adjective padding. In the latter condition, an extra adjective was added to each of the two noun phrases in the sentence, expanding a determiner-noun sequence into a determiner-adjective-noun sequence. The addition of the adjective decreased the model's availability of working memory resources by creating

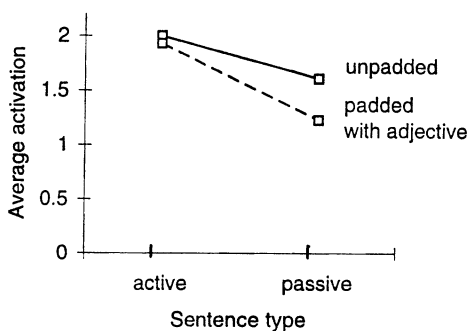


FIG. 7. Model predictions regarding the effect of adjective padding on the comprehension of actives (A) and passives (P). For the reduced capacity model, the poorer performance on passives is exacerbated in the padded condition, where an adjective has been added to each of the two noun phrases.

extra storage and processing demands, involving the lexical access of the adjective and its syntactic and semantic integration with the noun. As before, the average activation of thematic role bindings at the end of the run was taken as an index of the model's sentence comprehension performance.

The results of the adjective padding manipulation are shown in Fig. 7. As expected, adjective padding results in an overall decrease in sentence comprehension for both actives and passives. Furthermore, the negative effect of adjective padding is more pronounced on the passive sentence, where the competition for the model's limited resources is the greater. Further explorations with the model indicated that this interaction between sentence complexity and adjective padding is even more pronounced when meaning retention bias of the model (see Appendix B) includes not only thematic role bindings but also noun-adjective relations, that is, when the task requirements stress the understanding of all meaning relations.

The demonstration of an adjective padding effect would have implications for the more traditional neurolinguistic approach to aphasic sentence comprehension (e.g., Grodzinsky, 1986, 1989; Hickok, Zurif, & Canseco-Gonzalez, 1993). While this approach, like ours, emphasizes the importance of structural linguistic properties of the sentence materials, it tends to ignore the more graded effects of processing load and deficit severity on sentence comprehension performance (for an exception, see Caplan & Hildebrandt, 1988). A well-known example is the trace-deletion hypothesis of agrammatic sentence comprehension (e.g., Grodzinsky, 1986, 1989; for a revised version see Hickok et al., 1993), which permits only two performance levels: above-chance (on actives and subject relatives) and chance level (on passives and object relatives). The predictions of the trace-deletion hypothesis follow from the following three assumptions: (i) Moved noun phrases (present in

passives and relative clause sentences) do not receive a thematic role on a structural semantic basis due to the absence of traces in the surface representation of a sentence. (ii) Moved noun phrases in sentence initial position are assigned the agent role on the basis of a non-syntactic, heuristic agent-first strategy. (iii) When there is a conflict between agent assignment on a structural syntactic and heuristic basis (as in passives and object relative sentences), the patient is forced to guess, resulting in chance performance. Otherwise performance is predicted to be above-chance. The crucial assumption that leads to this dichotomous categorization of sentence comprehension performance to chance and above-chance performance, is that traces are completely absent from the surface representation of the sentence. Our model on the contrary postulates a more graded and less selective deficit, such that the success of trace derivation and storage is dependent on the exact balance between the overall sentence processing load and working memory capacity for language (i.e., corresponding to deficit severity). To give an example, both adjective padding (simulation Study 3) and increase in severity (simulation Study 2) diminish the resources available for deriving the trace in a passive sentence, causing the trace to be less active. This yields an impoverished input to the thematic role mapping component, which does not derail completely, but instead derives the thematic role bindings at a lower level of activation, thereby reducing sentence comprehension accuracy. Depending on the exact balance between processing load and working memory capacity, many different levels of above-chance performance are possible. More generally, according to our model, modulation of sentence comprehension performance as a function of available processing resources is one of the hallmarks of aphasic sentence comprehension and should not be overlooked.

DISCUSSION

This simulation study demonstrates the feasibility of extending the capacity theory (Just & Carpenter, 1992) to the realm of aphasic sentence comprehension and provides support for the resource reduction hypothesis (Miyake et al., 1994). The computational model can account for most of the sentence complexity effects that were obtained in a study of aphasic sentence comprehension by Caplan et al. (1985), involving as many as nine different sentence types. Furthermore, the model consistently produced the subject-object relative contrast, that aphasics show in the context of cleft sentences, center-embedded sentences and right branching sentences (Grodzinsky, 1989; Miyake et al., 1994). Finally, the model provides an account for the severity dimension of the deficit, suggesting that there is a continuum of resource reduction along which patients can be located. These simulation results suggest that the processing principles underlying the capacity theory apply not only in the domain of normal sentence comprehension (Just & Carpenter, 1992) but also in aphasic sentence comprehension.

The model implements the processing principles of the capacity theory in a computationally explicit manner and suggests a mechanism by which a pathological resource reduction causes sentence comprehension difficulty in aphasics, resulting in slowing and a form of partial comprehension, which is characterized by a less complete and less activated meaning representation. The model also suggests how the modulation of processing demand entailed by the construction of a sentence representation may provide a psychological metric for sentence complexity effects. Sentence complexity effects are explained by the fact that more complex sentences tend to require the processing and storage of more working memory elements and also require more massed, less distributed computations, making the competition for the limited resource pool more intense.

The model shares with its predecessors the notion that aphasic sentence comprehension results from a direct (Gigley, 1982, 1983, 1988; Haarmann & Kolk, 1991) or emergent timing deficit (Kempen & Vosse, 1989, and current model) disrupting the co-activation among sentence representational elements (cf. Kolk & van Grunsven, 1985). However, the new model (i) has been tested on a larger number of sentences types, (ii) provides a more complete theory of sentence comprehension by including a linguistically well-defined component for thematic role mapping, and, finally, (iii) more fully exploits the notion of activation-driven processing by providing a graded measure of comprehension performance on a single sentence presentation.

The extension of the capacity theory of sentence comprehension into the domain of aphasia suggests a new perspective in cognitive neuropsychology that focusses on the continuities between normal and abnormal performance. One of the goals of cognitive neuropsychology is to make inferences about the global functional architecture of the normal cognitive system through the study of neuropsychological deficits (e.g., Coltheart, Sartori, & Job, 1987; Patterson, Marshall, & Coltheart, 1985; Shallice, 1988). From this conventional perspective, the emphasis is on trying to explain neuropsychological deficits in terms of an impaired isolable component subsystem (or transmission route) of the normal cognitive architecture, thereby confirming the psychological reality of the component subsystem in question. Whereas a particular component subsystem is considered to be intact in the normal case, it is considered to be impaired in the neurologically impaired case. The focus within this conventional perspective is therefore on differences, rather than on similarities between normals and neurologically impaired individuals. Indeed, it is possible to view the resource reduction hypothesis in this light, with working memory capacity for language at sufficient and pathologically much reduced levels in normals and aphasics, respectively.

However, the resource reduction hypothesis may be viewed in a different light as well. In spite of differences in the amount of available resources between normals and aphasics, the capacity theory assumes that, at least in the case of light to moderate aphasia, the same processing mechanisms are

operating in both cases. For example, a central assumption is that forgetting and slowing occur in both normals and aphasics, when in the course of performing a task the available supply of working resources is outstripped by the sum of all activation demands. Because of the postulated difference in working memory capacity, this capacity constraint on storage and processing operates under different boundary conditions in normals and aphasics. For example, for the capacity constraint to be evoked in normals, a task must make much greater activation demands than for aphasics. Such high demands can be imposed by presenting the words of a sentence at an unusually rapid rate (Miyake et al., 1994) or by presenting complex relative clause sentences together with an extrinsic memory load (King & Just, 1991). For aphasics, on the other hand, relatively small increases in activation demand, such as created by adjective padding, may be sufficient for the capacity constraint to be evoked, as suggested by the results from our third simulation study. Viewed from this perspective then, the study of normal and neurologically impaired individuals provides an opportunity to demonstrate the generality of a particular processing mechanism within the cognitive system, exactly because it can be observed under different boundary conditions. Such an emphasis has implications for empirical research as it can seek out similarities, as well as differences in the underlying processing mechanisms and principles governing the behavior of normals and aphasics.

Another new perspective our approach offers concerns the traditional neuropsychology practice of describing individual variation among patients in terms of differences in specific impairments affecting different component subsystems. The resource reduction hypothesis offers a different perspective by postulating a common component in the aphasic comprehension deficit that varies continuously rather than qualitatively among patients. In the introduction, we reviewed evidence from both behavioral and brain imaging studies suggesting that the severity of such a common deficit can explain a considerable amount of the individual variation in the sentence comprehension performance of aphasic patients. However, it is important to note that the resource reduction hypothesis, as instantiated in the new model, is compatible with individual variation based on other factors.

There are at least two sources of individual variation which may be superimposed on the common deficit (Miyake et al., 1995). First, there might be premorbid differences in processing strategy that become exacerbated in aphasia, due to the need to compensate for the effects of brain damage on the sentence comprehension system (cf. Kolk & Friederici, 1985). Such differences in processing strategy may create stable differences among patients' performance profiles, which take the appearance of double dissociations due to individual variation in specific impairment. This possibility is supported by the observation that normal adults, with no history of neurological impairment, may show similar "dissociations" as aphasic patients when a high demand is imposed on their comprehension system, as is the case with rapid

serial visual presentation (RSVP) (Miyake et al., 1994). To explore this possibility, a model like ours could be augmented with adaptive processing strategies that are evoked when the outcome of the comprehension system is partial.

A second way of handling individual variation superimposed on the common deficit is related to the observation that CVA patients with aphasia show two lesion types: a structural, focal lesion with different sites in different patients and a metabolic lesion (area of hypometabolism) involving the same left temporoparietal area of almost all patients (Karbe et al., 1989; Kempler et al., 1991). While the common metabolic lesion may be responsible for inducing a resource reduction in the working memory capacity for language, the structural focal lesion may superimpose additional impairments. For example, a more posterior structural lesion involving the secondary auditory cortex, such as in Wernicke's aphasia, might make the comprehension of the afflicted patients especially vulnerable when sentences are presented in the auditory modality (Goodglass & Kaplan, 1983). In our model, this would correspond to modality-specific problems with perceptual encoding. Another example is the observation that Broca's aphasics have more problems with the processing of the syntactic information associated with function words, while Wernicke's have more problems with the processing of the lexical-semantic information associated with this class of words (Friederici, 1982). In our model, such additional problems could be simulated by lowering the resting level of each of the two types of information in the model's mental lexicon, which would result in longer times for the elements to reach a target level and make the information more vulnerable to forgetting. In addition, in such an expanded model, Broca's and Wernicke's respective weaknesses with different aspects of closed class information would not be treated as an isolated problem. Rather the model would predict that these problems are modulated by the availability of working memory resources for language, which might be experimentally manipulated, for example, by variation in sentence complexity (cf. Grossman & Haberman, 1982). This suggests the possibility of a synergy between two approaches, combining the accounts of both qualitative and quantitative differences among aphasic patients.

Another new perspective offered by our approach concerns the tendency to decompose the cognitive architecture into many different isolable subsystems (e.g., Coltheart, Sartori, & Job, 1987; Patterson, Marshall, & Coltheart, 1985; Shallice, 1988). At a gross scale, our model certainly fits within this tradition by assuming a separate working memory for sentence comprehension as opposed to other working memory systems, for example, one for the storage and processing of visual-spatial information (Isaak & Just, in press; Just & Carpenter, 1992). However, at a more fine-grained level of analysis, the capacity theory does not further decompose working memory for sentence comprehension and assumes that both syntactic and semantic processing are subserved by a single resource pool. This is a controversial claim

in view of a tendency, also evident in the aphasia literature, to treat syntactic processing as a modular subsystem that operates independently of semantic considerations (Caplan & Hildebrandt, 1988; Caplan & Waters, 1995; Grodzinsky, 1986, 1989). However, there is evidence from both normals and aphasics that is consistent with the view that a single resource pool supports both syntactic and semantic processing. Reading span, which provides an index of working memory capacity for language in normals, appears to modulate the ability of normal adults to retain not only multiple syntactic (King & Just, 1991; MacDonald et al., 1992) but also multiple semantic interpretations (Miyake, Just, & Carpenter, 1994) of an ambiguous word. In addition, in normal adults, reading span modulates the effect of semantic information on syntactic disambiguation decisions, a topdown semantic influence being present in high but not low span subjects. Furthermore, the ability of semantic information to influence syntactic attachment decision (Taraban & McClelland, 1990) points to the real-time integration of syntactic and semantic processing (cf. models of Cottrell, 1989; and Cottrell & Small, 1983) and is, therefore, consistent with the notion of a single resource pool supporting both types of processing. In aphasics who suffer from "asyntactic comprehension," sentence comprehension performance improves for sentence materials in which lexical-semantic cues have been added to syntactic information. However, the fact that aphasics' performance does not reach normal level under favorable processing conditions (Blumstein, Goodglass, Statlender, & Biber, 1983; Heeschen, 1980; Kolk & Friederici, 1985) does indicate the presence of additional problems of a semantic nature. Finally, most aphasics experience problems on the Token Test (DeRenzi & Vignolo, 1962; McNeil & Prescott, 1978; Orgass, 1976), even when all items involve a syntactically simple noun phrase that refers to a shape and its color and size attributes (e.g., "*the large red circle*") (Gutbrod, Mager, Meier, & Cohen, 1985). The latter finding seems to reflect a problem not so much with syntactic analysis but with semantic integration of feature information. In sum, it seems plausible to assume, as we do in the model, that syntactic and semantic processing are subserved by a single resource pool in normals and aphasics.

We see several fruitful lines of future research with our model. For example, aphasics' sentence comprehension performance often improves when the word input rate is slowed (Lasky, Weidner, & Johnson, 1976; Liles & Brookshire, 1975; Pashek & Brookshire, 1982; Poeck & Pietron, 1981; Rosenbek et al., 1989; Weidner & Lasky, 1976), though not always (Blumstein, Katz, Goodglass, Shrier, & Dworetzky, 1985 and Brookshire & Nicholas, 1984). One would expect the model to capture such an effect because it can complete more processing before the next word comes in when the word presentation rate has been slowed, thereby better distributing the processing load across the sentence. Given the activation dynamics of sentence comprehension, it is difficult, however, to predict what the effect of word presentation rate would be in combination with complexity and severity in the ab-

sence of a computational model. Running the actual simulations might result in a further refinement of the resource reduction hypothesis.

The new model integrates several perspectives in the study of aphasic sentence comprehension into a single framework. The model addresses the effect of structural linguistic factors, such as phrase-structure complexity (Caplan & Hildebrandt, 1988) and long-distance dependencies involving traces (e.g., Grodzinsky, 1986, 1989; Hickok et al., 1993), while at the same time taking into account the dynamic factors involving the time course of activation (e.g., Friederici & Kilborn, 1993; Haarmann & Kolk, 1991a, 1991b; Shankweiler et al., 1989) and moment-to-moment availability of processing resources (e.g., Miyake et al., 1994; McNeil et al., 1991). We have developed the model partially in the hope that it will encourage new research that represents a synergy among the different approaches. Such research would contribute to our understanding of aphasia by illuminating which neurological, linguistic and cognitive factors determine the availability of processing resources in working memory for language and, thereby, patients' success in comprehending sentences.

APPENDIX A

Processing Example

To illustrate the operation of the model, this section provides a processing example of a simple active SVO sentence in a high and low capacity case. Consider the situation depicted in Fig. 8A. The model is presented with the sentence "*The man greeted a woman,*" such that each successive word of the sentence enters the model's comprehension system every 13 processing cycles, emulating a computer-controlled presentation duration. Each word results in the introduction of new elements in working memory at different levels of representation. At the syntactic level, constituent-head and constituent-relation elements become activated. At the semantic level, word-meaning and thematic-role-binding elements become activated. And at the level interfacing between syntax and semantics, verb-argument-structure elements become activated. Their level of activation is graphed in Fig. 8A for every cycle during which a new word is presented to the model. We will first consider the time-course of activation of working memory elements in a high capacity case, with a working memory capacity of 30 units of activation.

At cycle 1, the first word, *the*, is presented. During the next few cycles it becomes perceptually encoded and its word class information, that is, a constituent-head element (DP head DETERMINER), is retrieved from the lexicon and activated to target level. At cycle 13, the next word, *man*, is presented. During the next few cycles, *man* becomes perceptually encoded and its word class information and word meaning information are retrieved from the lexicon and activated to target level in the form of two working memory elements (NP head NOUN) and (MAN), respectively. In addition,

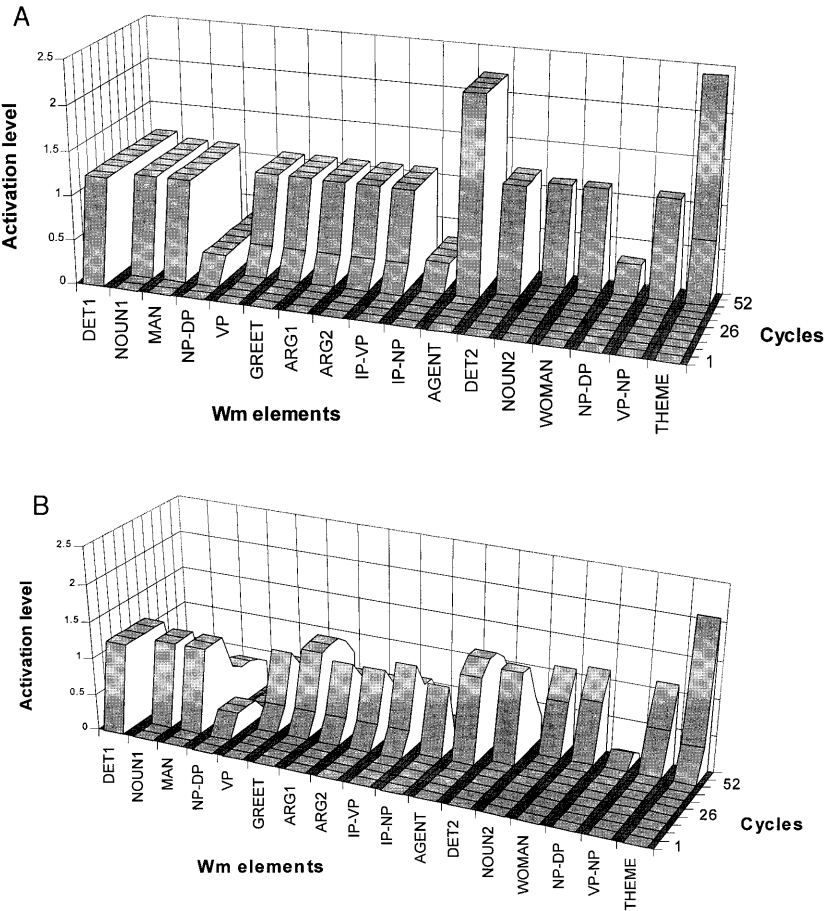


FIG. 8. Example of the model's processing of an active sentence in a high and low capacity case (for explanation see text).

the grammar is accessed, and, a constituent-relation element is computed and activated to target level, namely, (NP assigns-specifier DP), which indicates that the noun phrase headed by *man* assigns the grammatical role of specifier to the determiner phrase headed by *the*. At cycle 26, the next word, *greeted*, is presented. During the next few cycles, *greeted* becomes perceptually encoded and three types of associated lexical information become activated to target level: word class, word meaning and verb argument structure in form of the following working memory elements: (VP head VERB), (GREET), (GREET AGENT SUBJECT), (GREET THEME DIRECT-OBJECT). In Fig. 8A, these working memory elements are indicated in ab-

breviated form as VP, GREET, ARG1, and ARG2, respectively. In addition, the constituent-head element representing the sentence category (IP head INFL), is projected from the verb and activated to target level. Furthermore, at the syntactic level, two parse tree relations are computed and activated to target level in the form of the working memory elements (IP assigns-specifier NP) and (IP assigns-complement VP). Using the verb argument structure element (GREET AGENT SUBJECT) as a schema, the model is now ready to compute and activate a thematic-role binding element (GREET HAS-AGENT MAN). Note that SUBJECT is shorthand for (IP assigns-specifier NP), where (IP assigns-complement VP). At cycle 39, the next word, *a*, is presented. During the next cycles it becomes perceptually encoded after which its word class information, that is, a constituent-head element (DP head DETERMINER) is retrieved from the lexicon and gradually activated to target level. At cycle 52, the final word, *woman*, is presented. During the next few cycles it becomes perceptually encoded after which its word class and word meaning information are retrieved from the lexicon and activated to target level. In addition, at the syntactic level, two parse tree relations are computed and activated to target level in the form of the working memory elements (VP assigns-complement NP) and (NP assigns-specifier DP). Using the verb argument structure element (GREET THEME DIRECT-OBJECT) as a schema, the model is now ready to compute a thematic-role binding element (GREET HAS-THEME MAN) and raise its activation to target level. Note that DIRECT-OBJECT is shorthand for (VP assigns-complement NP).

At cycle 65, all words of the sentence "*The man greeted the woman*" have been presented and both the agent binding (GREET HAS-AGENT MAN) and theme binding (GREET HAS-THEME WOMAN) are active above target level (set at 2.0 activation units), resulting in perfect comprehension, in the sense that all the thematic roles have been appropriately represented.

Next, consider the time-course of working-memory-element activation in the low capacity case, which has a reduced capacity of only 10 units of activation (see Fig. 8B). Since the example sentence is not very complex and does not impose too great of a demand on the model's working memory resources, co-activation is not disrupted and the model can still compute all relevant parse-tree relations and thematic role bindings. However, at the end of the sentence presentation, comprehension is incomplete in that the agent and theme bindings are activated below target level. In particular, at cycle 39, it becomes noticeable that the model's working memory resources can not keep up with the activation demands due to the heavy load that was imposed by the computation of the agent role. As a consequence, all working memory elements lose some of their activation. Due to a bias to retain thematic role bindings (see below), these elements are forgotten somewhat less than other elements. In spite of the capacity reduction, the theme binding

is still activated to target level. On the other hand, the agent-binding which is no longer the target of new input and is merely passively stored when the activation shortage hits, loses some of its initial activation.

For a more complex sentence, such as the passive “*The woman was greeted by the man,*” the effects of an activation shortage would have even greater negative consequences. There are a few extra computations involved in passives making them more demanding than actives. First, there is an extra computation that determines passive voice and suppresses the assignment of the agent role to the subject (*woman*). Second, there is another computation that derives the trace connecting the subject to its canonical verb argument structure position (post-verbal direct-object), enabling assignment of the theme role. Third, there is an extra computation that activates a constituent-relation element, (PP assigns-complement NP), that deals with the extra level of embedding caused by the presence of the by-phrase. All these extra steps make passive sentences more demanding, and this extra demand is especially damaging to performance in the low capacity case.

APPENDIX B

Details of Activation Allocation Mechanism and Bias Schema

The activation allocation mechanism and included bias schema are implemented by the following four formulas.

$$f_m = \frac{\beta C}{\beta m + (1 - \beta)r} \quad (1)$$

$$f_r = \frac{(1 - \beta)C}{\beta m + (1 - \beta)r} \quad (2)$$

$$\text{if } f_m > 1.0 \quad f_{r\text{corrected}} = f_r + \frac{(f_m - 1)m}{r}$$

$$f_{m\text{corrected}} = 1.0 \quad (3)$$

$$\text{if } f_r > 1.0 \quad f_{m\text{corrected}} = f_m + \frac{(f_r - 1)r}{m}$$

$$f_{r\text{corrected}} = 1.0 \quad (4)$$

The activation allocation schema only comes into play when C the capacity is smaller than the sum of m and r , which define the total demand for activation associated with the retention of meaning elements and all remaining activation requests, respectively. Formula 1 defines a factor f_m whose complement $(1 - f_m)$ determines by which proportion an activation request for the storage of meaning elements is scaled down, while formula 2 defines

the factor f_r whose complement $(1 - f_r)$ determines by which proportion an activation request unrelated to meaning retention is scaled down. β is the bias factor and should be chosen in the interval $[0, 1]$ With no bias in place (i.e., $\beta = 0.5$), the factors f_m and f_r are equal so that all activation requests are scaled down by the same proportion. Below this neutral bias value, the factor f_m is smaller than f_r , while above it the factor f_m is larger than f_r . In the simulations the latter was the case (i.e., $\beta = 0.52$) so that activation requests associated with the storage of meaning elements were scaled down less than all remaining activation requests, the difference in the proportion of scale down being on the order of 0.05 to 0.10. Note that only a relatively small increase in bias parameter (i.e., of 0.02) was necessary to achieve this. Occasionally, either one of the factors f_m or f_r (but never both factors simultaneously) may exceed 1 indicating that enough capacity is available to fulfill the type of activation request that is associated with the particular factor. Formulas 3 and 4 prevent over-allocation of activation in such cases and ensure that the excess activation is re-allocated to the activation requests associated with the other factor. Formula 3 has been derived by applying the following constraint.

$$f_{r\text{corrected}}r = f_r r + excess_m$$

$$, \text{ where } excess_m = (f_m - 1)m \quad (5)$$

Formula 4 can be derived in an analogous manner. Finally, it should be noted that Formulas 1 and 2 ensure that all the available capacity is allocated exhaustively and that no activation is wasted.

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