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A Capacity Approach to Syntactic Comprehension Disorders: Making Normal Adults Perform Like Aphasic Patients

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This paper presents a theory of syntactic comprehension disorders in aphasic patients. In line with some recent proposals, the current theory assumes that aphasic patients still possess the structural (syntactic) and procedural knowledge necessary to perform syntactic analysis. This paper, however, postulates that patients' comprehension deficits originate, at least in part, from reductions in working memory capacity for language. Based on a recently developed theory of capacity constraints in normal language comprehension (Just & Carpenter, 1992), the theory explains how reductions in working memory capacity can lead to the pattern of comprehension breakdown in aphasics, which can be characterised as a conjoint function of the patient's severity level and the structural complexity of the sentence. As supporting evidence for the theory, we report two "simulation" experiments in which we increased the computational demands on normal adults of varying working memory capacities and thereby induced in them the interaction of "severity" by complexity usually observed among aphasic patients.

INTRODUCTION

Syntactic organisation allows a listener or reader to recover, from a linear sequence of words, the underlying interrelations of concepts that a speaker or writer intends to convey. Consider, for example, the following sentence:

The boy that the girl is chasing is tall. (1)

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In this sentence, it is *the boy*, and not *the girl*, who is tall, even though the noun phrase *the girl* is closer to the predicate *is tall* in the linear sequence of the words. Without syntactic analysis, sentences like (1), which lack semantic and pragmatic cues to guide their interpretation, might not be comprehensible. Although such analysis seems relatively effortless for most adults, it is often a source of difficulty in aphasic patients, a point frequently documented ever since a seminal study on Broca's aphasics reported that they were unable to recover reliably the relational structure of the sentences like (1) (Caramazza & Zurif, 1976).

A number of proposals have been made to account for the possible locus (or loci) of such syntactic comprehension problems in aphasic patients, especially in Broca's aphasics whose speech output is "agrammatic" and frequently lacks function words and morphological inflections. A dominant theory in the late 1970s and early 1980s, for example, characterised the problem as a central syntactic deficit (i.e. a loss of syntactic knowledge) that manifests itself in both language production and comprehension (Berndt & Caramazza, 1980). More recent proposals have attributed the comprehension problems of Broca's aphasics to more specific types of disturbances such as the inability to construct hierarchically organised phrase structures (Caplan, 1985); the inability to co-index "traces" (Grodzinsky, 1986); and the inability to map syntactic structures onto thematic relations (Linebarger, Schwartz, & Saffran, 1983). Note that these accounts assume a loss of either structural (syntactic) or procedural knowledge that is critical to perform complete syntactic analysis.

More recently, however, an increasing number of researchers have started to view the disorders of syntactic comprehension as a manifestation of severe limitations in processing capacity or efficiency (e.g. Frazier & Friederici, 1991; Friederici, 1988; Haarmann & Kolk, 1991; Kilborn, 1991; Kolk & van Grunsven, 1985). In contrast to the earlier proposals, the recent accounts do not assume that patients have lost some of their structural or procedural knowledge necessary for syntactic processing. Instead, they posit that the syntactic comprehension impairments arise from temporal or computational constraints imposed by severely reduced processing capacity or efficiency.

This paper presents a theory of the disorders of syntactic comprehension along this line. Specifically, it proposes that reductions in working memory resources are implicated, at least in part, in the comprehension problems of aphasic patients. By "working memory," we do not mean a phonological short-term storage system (Baddeley's [1986] "articulatory loop") that includes a phonological buffer and a subvocal rehearsal process.[1] Rather,

[1]For a recent review of the impairment of phonological short-term memory and its consequences on language comprehension, see Caplan and Waters (1990), Martin (1993), and Saffran (1990).

our view construes working memory as "a computational arena," the site both for executing various language processes and for storing intermediate and/or final products of the computation, supported by a flexibly deployable pool of limited resources (Carpenter & Just, 1989). Thus, in terms of Baddeley's model, the "working memory" that we focus on in this paper better corresponds to the "central executive" system, particularly that part of the central executive that is responsible for language processing (Just & Carpenter, 1992).

We begin by examining the evidence indicative of reduced working memory resources among aphasic patients. The subsequent section describes a capacity theory of syntactic comprehension deficits and specifies how reductions in working memory capacity can lead to the pattern of comprehension breakdown revealed by the literature. A third section describes two "simulation" experiments in which we increased the computational demands on normal adults and thereby induced them to perform comprehension tasks in a manner similar to aphasic patients. The final section discusses further implications of the theory and places it within a broader computational framework.

WORKING MEMORY CONSTRAINTS IN NORMALS AND APHASICS

The theory that we describe focuses on reduced working memory resources as a major source of syntactic comprehension disorders in aphasic patients. Because of this emphasis of the theory on the quantitative, rather than qualitative, differences between normal adults and aphasic patients, we will first review the recent psycholinguistic and neuropsychological literature to show that similar working memory constraints operate in the language comprehension processes of the two populations. We will do so by focusing on the effects of syntactic complexity and individual differences in both populations.

Working Memory Constraints in Normal Adults

One of the factors that strongly influences the demand on working memory capacity is the syntactic complexity of the sentence to be comprehended. Sentences with a centre-embedded relative clause, for example, have been known to be demanding not just for aphasics but also for normal adults. Centre-embedded sentences are capacity-demanding partly because the embedded clause interrupts the constituents in the main clause, and the initial noun phrase must be maintained in working memory while the comprehender is processing the embedded clause. Not all centre-embedded sentences are equally capacity-demanding, however. When compared to subject-relative sentences like (2), object-relative sentences like (3) are more difficult to repeat (Kemper, 1986; Larkin & Burns, 1977), interfere more with maintaining an extrinsic memory load (Wanner & Maratsos, 1978), and induce longer reading times and more regressive eye movements (Ford, 1983; Holmes & O'Regan, 1981). In addition, object-relative sentences elicit larger changes in pupil diameter during reading (Just & Carpenter, 1993), which may be an index of the capacity demand (Beatty, 1982; Kahneman, 1973).

The reporter that attacked the senator admitted the error. (2)

The reporter that the senator attacked admitted the error. (3)

The additional difficulty of the object-relative sentence may derive from at least two sources. First, the order in which the thematic roles are assigned in the relative clause is not canonical because the agent role comes after the patient role (Caplan & Hildebrandt, 1988). Second, the first noun phrase (such as *the reporter*) plays two different roles (agent of the main clause and patient of the relative clause), and such conflicting assignments may be particularly difficult to compute and/or maintain (Bever, 1970; Sheldon, 1974). Supporting this analysis, the performance differences between the two constructions have been found to be particularly large on or around the two verbs, the words that trigger a large number of computations (Ford, 1983; Holmes & O'Regan, 1981; Just & Carpenter, 1993).

Using sentences like (2) and (3), a recent study examined how working memory capacity constrains the syntactic comprehension of normal adults (King & Just, 1991). In this study, readers with different working memory capacities read centre-embedded sentences in a self-paced, word-by-word reading paradigm. Working memory capacity was assessed by the Reading Span test, a test that was designed to measure the subject's capacity to process and maintain verbal information simultaneously (Daneman & Carpenter, 1980). The reading-time data, presented in Fig. 1, suggest that each reader's working memory capacity had a strong influence on the relative difficulty of the sentences. Although all three groups of readers took more time to process object-relative than subject-relative sentences, there were large individual differences in reading times, which were found mainly for the more demanding object-relative sentences. Consistent with the results from other studies mentioned earlier, such an increase in reading times for object-relative sentences was localised primarily to the two verbs, where the critical syntactic information became available. As the right-hand panel shows, the three curves diverge at the location where the processing load is at its peak, suggesting that working memory constraints are most evident when capacity demands are high and resources are depleted.

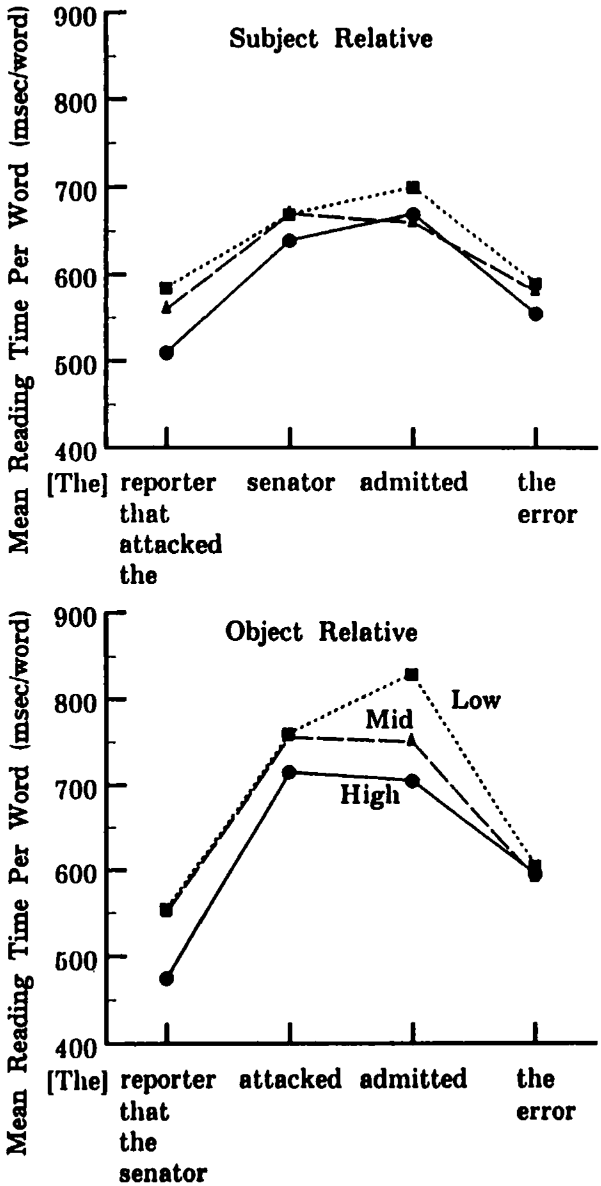

FIG. 1 Reading time per word for successive regions of subject-relative and object-relative sentences, for high-span, mid-span, and low-span readers. The differences among the span groups are greater for the more complex object-relative sentences than for the subject-relative sentences. In addition, the differences are greater at the two verbs, which are the points of major processing difficulty that are expected to tax working memory capacity. The figure is based on the data reported in King and Just, 1991; Fig. 3, p. 589.

The Effects of Severity and Syntactic Complexity in Aphasics

Just as normal adults differ among themselves in their language comprehension capabilities, so do aphasic patients. The range of individual differences, however, may be greater in the aphasic patients, from those with only mild comprehension deficits to those with severe impairments who cannot comprehend even simple sentences reliably. If this difference in comprehension performance among patients reflects, at least in part, individual differences in residual working memory capacity for language, then aphasic patients should show an analogous pattern of performance deterioration as normals do when the difficulty level of the sentence increases. That is, they should be able to comprehend sentences without much difficulty as long as they have enough working memory resources available; however, the more resources that the comprehension of the sentence requires, the more their performance should deteriorate.

One such demonstration of the effects of severity and sentence difficulty comes from a study of the auditory syntactic/morphological comprehension abilities of 60 aphasic patients, who were classified into different clinical syndromes (Naeser et al., 1987). In this study, the patients were given a sentence–picture matching task, called the Palo Alto Syntax Test (PAST), which tested their ability to discriminate 10 different types of syntactic and morphological constrasts by choosing among 4 alternative pictures for each sentence. Although this study is not exclusively directed at the structural level of comprehension, the results nicely illustrate one important aspect of aphasic patients' comprehension performance (i.e. "differences in degree but not order of difficulty," as the title of the Naeser et al. article suggests), using a relatively large number of patients and two independent measures of the degrees of severity of their comprehension ability. Moreover, our own analysis of the data suggests an interaction between severity and sentence difficulty that we argue is also characteristic of more structural aspects of syntactic comprehension.

Figure 2 presents the comprehension accuracy data, excluding the two most severe groups that performed poorly on even the simplest items. The 10 sentence types are ordered along the x-axis in terms of increasing difficulty, based on the mean comprehension scores from the 60 patients. Added to the figure is a linear regression line calculated for each syndrome group, treating the difficulty ordering of the 10 sentence types as if it were a ratio scale (i.e. M/F as 1, O/U as 2, etc.). Although this informal application of regression equation is unjustified from a statistical point of view, it nonetheless graphically illustrates the relationship between severity and sentence difficulty.

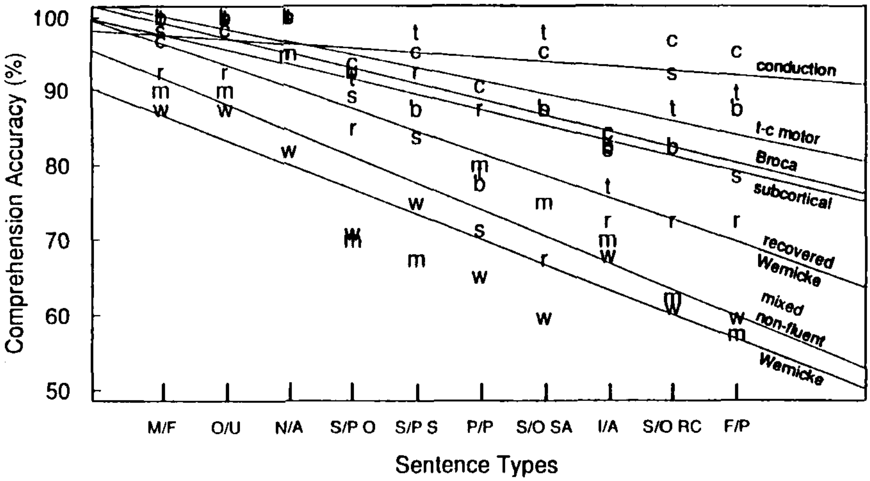

FIG. 2 Comprehension performance of 7 clinical syndrome groups of aphasic patients with different degrees of severity for 10 different syntactic and morphological contrasts: Male/Female (M/F), On/Under (O/U), Negative/Affirmative (N/A), Singular/Plural Object (S/P O), Singular/Plural Subject (S/P S), Past/Present Progressive Tense (P/P), Subject/Object in Simple Active Sentences (S/O SA), Is/Are (I/A), Subject/Object Relative Clause (S/O RC), and Future/Present Progressive Tense (F/P). The straight lines are the best-fitting linear regressions, which treat the difficulty ordering of the 10 sentence types as though it were a ratio scale. As the diverging lines suggest, all groups are able to comprehend the easiest syntactic items, whereas the groups with more severe deficits have numerous errors as the difficulty level of the sentence types increases. The difficulty ordering of the sentences, however, is generally preserved under various levels of severity. The graph is based on the data reported in Naeser et al., 1987; Table III, p. 368.

Demonstrating the effects of severity, the patients' performance on the PAST correlated with two independent measures of general (as opposed to specifically syntactic and/or morphological) comprehension ability, namely the auditory comprehension section of the Boston Diagnostic Aphasia Examination (+0.91) and the Token Test (+0.88). In addition, the patients showed a remarkably similar rank order of sentence difficulty; sentence types that were difficult for one group of patients tended to be difficult for other groups of patients also, as indicated by the high Spearman rank-order correlations among the seven aphasia subgroups (+0.57 to +0.92). The effects of severity and sentence difficulty were not simply additive, however, as shown by the gradual divergence of the seven regression lines as the difficulty level of the sentences increases. Although all the groups performed well on the easiest items, there were large group differences for the most difficult ones. We do not claim that reductions in working memory resources necessarily underlie all of the comprehension problems in these 10 contrasts, particularly the non-structural ones. In addition, no theoretically meaningful metric seems to be able to account for this particular ordering of difficulty. Nevertheless, these data illustrate how a difficulty ordering can generally be preserved under various levels of severity, a prediction consistent with a capacity-reduction view of syntactic comprehension disorders that we will present shortly.

A series of studies that is more directly relevant to syntactic comprehension shows a similar interaction between degrees of severity and the difficulty level of the sentence, the latter of which corresponds to syntactic complexity (Caplan, Baker, & Dehaut, 1985; see also Caplan & Hildebrandt, 1988). In this series of studies, aphasic patients were tested on their comprehension of nine syntactic constructions, using an object-manipulation task, in which patients indicated the thematic roles of the participants in the sentence by acting out the event(s) with animal dolls. Figure 3 presents the mean comprehension accuracy for each of the 9 sentence types in 3 studies (with 56, 37, and 49 aphasic patients, respectively). Revealing a strong effect of syntactic complexity on comprehension, the three studies yielded almost the same ordering of difficulty. Several

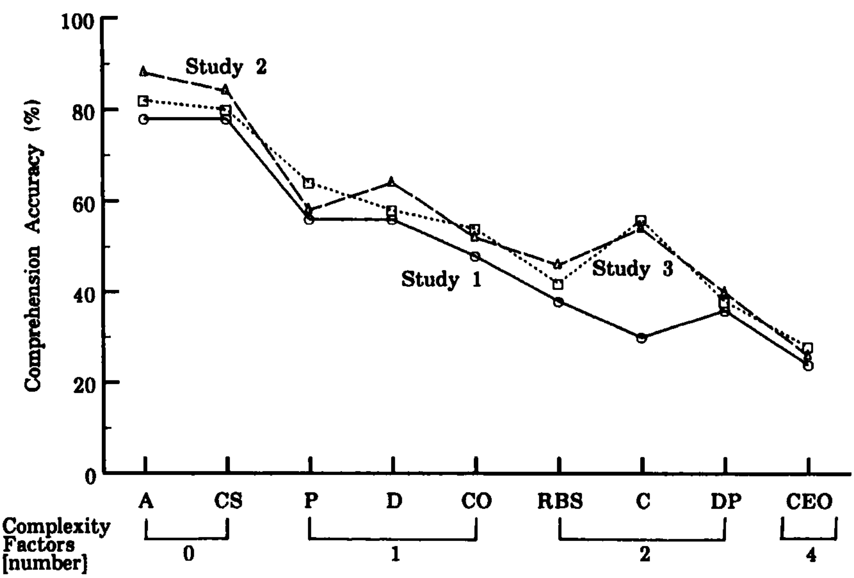

FIG. 3 Mean comprehension performance in three studies of aphasic patients for nine sentence types: Active (A), Cleft-Subject (CS), Passive (P), Dative (D), Cleft-Object (CO), Right-Branching Subject-Relative (RBS), Conjoined (C), Dative Passive (DP), and Centre-Embedded Object (CEO) sentences. The three studies reveal almost the same ordering of difficulty for the nine sentence types, an ordering that is consistent with the complexity metric in Table 1. The graph is based on the data reported in Caplan and Hildebrandt, 1988; Table 4.19, p. 122.

factors, listed in Table 1, may have contributed to this difficulty ranking, as pointed out by Caplan et al. (1985) and other researchers (Bever, 1970; MacWhinney & Pleh, 1988; Sheldon, 1974): (1) the number of thematic roles (two or three) associated with a single verb; (2) the number of verbs (one or two) or, as a correlated factor, the number of pairs of thematic roles (the agent and patient roles) within the sentence; (3) whether or not the order of thematic roles is canonical (i.e. the agent role precedes other

TABLE 1
Factors that Contribute to the Difficulty of Sentences Used in the Caplan et al. (1985) Study

	Contributing Factors					
Sentence Types	*1*	*2*	*3*	*4*	*5*	*Total*
Active (A):						
The rat hit the dog						0
Cleft-Subject (CS):						
It was the rat that hit the dog						0
Passive (P):						
The rat was hit by the dog			×			1
Dative (D):						
The rat gave the dog to the cow	×					1
Cleft-Object (CO):						
It was the rat that the dog hit			×			1
Right-Branching Subject Relative (RBS):						
The rat hit the dog that kissed the cow		×			×	2
Conjoined (C):						
The rat hit the dog and kissed the cow		×		×		2
Dative Passive (DP):						
The rat was given to the dog by the cow	×		×			2
Centre-Embedded Subject Relative (CES)[a]:						
The rat that hit the dog kissed the cow		×		×		2
Right-Branching Object Relative (RBO)[a]:						
The rat hit the dog that the cow kissed		×	×			2
Centre-Embedded Object Relative (CEO):						
The rat that the dog hit kissed the cow		×	×	×	×	4

Contributing Factors:
1. three (as opposed to two) thematic roles for a single verb
2. two (as opposed to one) verbs in a single sentence.
3. non-canonical (as opposed to canonical) order of thematic roles (i.e. the patient role precedes the agent role)
4. the maintenance of the first noun phrase is necessary while another set of thematic roles is computed
5. there is a noun that plays two different thematic roles in different clauses.

[a]These sentence types were not used in the Caplan et al. study, but were included in the experiments reported in this paper.

roles); (4) whether it is necessary to retain the first noun phrase while another set of thematic roles is computed; and (5) whether there is a noun that plays two different thematic roles in two clauses. Supporting this complexity metric, the mean comprehension accuracy decreased with an increasing number of the complexity factors present for the sentence type (indicated on the *x*-axis).

The data also suggest large differences in the severity of impairments. Caplan et al. performed cluster analyses based on each patient's comprehension score on each construction and statistically classified patients into five to eight subgroups per study. Table 2, which summarises the overall comprehension accuracy (averaged across the nine sentence types) for each subgroup in each study, shows that there are large performance differences among subgroups. Further demonstrating the prevalent impact of overall severity levels, the results from subsequent principal components analyses indicated that the most important determinant of the group classification was the patient's overall comprehension in the task. In all 3 studies, the first eigenvector, which accounted for approximately 60% of the total variance, was loaded equally positively (+0.28 to +0.38) on all 9 sentence types and was interpreted as "severity" or "success" factor.

Furthermore, the comprehension profiles of different subgroups revealed an interaction of syntactic complexity and degrees of severity. In addition to the overall comprehension accuracy of each subgroup, Table 2 also lists the regression coefficients (or the slopes) obtained in a regression analysis analogous to the one we reported earlier for the Naeser et al. (1987) study (excluding the subgroups that were essentially unable to perform the task at all). As before, this informal analysis examines the decrement in comprehension performance as a function of sentence complexity,

TABLE 2
The Overall Comprehension Accuracy and the Slope of the Best-Fitting Regression Lines for Each Subgroup Found in the Caplan et al. (1985) Study

	Study 1		*Study 2*		*Study 3*	
Subgroups	*Accuracy*	*Slope*	*Accuracy*	*Slope*	*Accuracy*	*Slope*
I	92.7%	−2.53	91.6%	−2.97	96.9%	−0.70
II	79.3%	−6.97	60.9%	−8.23	83.8%	−5.30
III	80.0%	−6.67	36.9%	−9.40	66.7%	−8.27
IV	54.0%	−9.20	32.0%	−9.33	45.8%	−8.53
V	50.0%	−7.93	0.0%	—	37.6%	−10.70
VI	26.4%	−8.43			32.9%	−5.80
VII	26.0%	−11.00			5.3%	—
VIII	4.2%	—				

treating the difficulty ranking of the nine sentence types (averaged across the three studies) as if it were a ratio scale (i.e. A as 1, CS as 2, etc.). In all three studies, there is a consistent tendency for subgroups with lower overall comprehension scores to have steeper negative slopes, indicating that they are more vulnerable to the effect of increasing syntactic complexity. This interaction of complexity by severity suggests that aphasic patients may have differential amounts of residual working memory resources and that poor comprehension arises on those sentences that require more resources than they have available.

In addition to group studies, the results from single case studies also corroborate the conclusion that the amount of residual working memory resources that the patient has available may be an important determinant of his/her performance on different sentence constructions. Appendix A presents the auditory comprehension accuracy of individual aphasic patients from 12 studies on 4 of the most frequently tested syntactic structures (i.e. semantically reversible active [A], passive [P], centre-embedded subject-relative [CES], and object-relative [CEO] sentences).[2] Although the 12 studies cannot be compared directly to one another, different patients show different performance levels within each study, demonstrating differential degrees of severity in their syntactic comprehension ability. The order of difficulty of different syntactic structures, however, is quite consistent from patient to patient, and only a small number of patients in the table show a slightly reverse tendency. Reflecting this complexity effect, one-tailed sign tests showed that active sentences are easier than passive sentences ($P < 0.01$) and that subject-relative sentences are easier than object-relative sentences ($P < 0.01$). Moreover, there are differential rates of performance deterioration in different patients, indicating an interaction of severity by complexity. For example, GG and JV (reported in Caplan & Hildebrandt, 1988) performed well on all the four sentence types, whereas the rest of patients (except BO) in the same study exhibited a marked decline in their performance as the structural complexity of the sentence increased.

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[2]The data were compiled from all the neuropsychological studies published since 1980 in the journals *Brain and Language* and *Cognitive Neuropsychology*, plus some additional studies that were brought to our attention (Caplan & Hildebrandt, 1988; Martin, Wetzel, Blossom-Stach, & Feher, 1989; Shankweiler, Crain, Gorrell, & Tuller, 1989; Wulfeck, 1988). The studies listed in Appendix A satisfied the following selectional criteria: (1) each individual patient's scores were reported; (2) at least two out of the four sentence constructions were tested; and (3) the language used in the testing had the canonical word order of SVO. The clinical syndrome to which the patient belonged and the symptoms he/she exhibited (such as impaired digit spans) were not included as additional criteria because sufficient information was not provided by some of the studies. Most of the patients listed in the table, however, were Broca's aphasics and demonstrated agrammatic speech.

Further support for the view that reductions in working memory resources are implicated, at least in part, in the disorders of syntactic comprehension is the finding that a patient may be able to comprehend a sentence when it contains either of two syntactic factors that leads to additional complexity, but not when it contains both. For example, a patient (KG) had no difficulty comprehending sentences that contained the empty noun phrase *PRO* (e.g. *Patrick persuaded Joe to wash*; 100% correct) and those that contained a reflexive (e.g. *Patrick said that a friend of Joe's hit himself*; 100%), but not those that contained both (e.g. *Patrick promised Joe to hit himself*; 33%) (Caplan & Hildebrandt, 1988; Hildebrandt, Caplain, & Evans, 1987). This pattern of KG's performance suggests that the patient was capable of performing all the operations related to the processing of *PRO* and reflexives, but did not have sufficient resources to carry out both operations in a single sentence.

Taken together, the data from individual patients as well as patient groups support the view that, as was the case with the normal population, working memory capacity may strongly constrain language comprehension in aphasic patients.

Summary

The comparison of normal adults' and aphasic patients' syntactic comprehension revealed similar effects of structural complexity and individual differences. These commonalities between the two populations can be explained naturally by viewing the two populations as being on the same continuum, or more specifically, on the continuum of working memory capacity. From this perspective, comprehension deterioration starts to occur when the processing of a sentence requires more working memory resources than one can afford. The larger the gap between the capacity demands and the availability capacity, the stronger the impact of capacity limitations on syntactic comprehension. Of course, it would certainly be wrong to claim that aphasic patients differ from normals *only* in terms of working memory capacity. In addition to the global reductions in working memory capacity for language, for example, they may have some disturbances in a more peripheral subsystem specialised for a set of specific processes (such as the phonological short-term memory). It may also be the case that some aphasic patients have developed some adaptive strategies to compensate for their deficits (Kolk & Heeschen, 1990). Emphasising the notion of aphasia-to-normal continuum, however, provides a new framework within which to consider a number of important issues concerning the disorders of syntactic comprehension.

A CAPACITY THEORY OF SYNTACTIC COMPREHENSION DEFICITS

In this section, we present an overview of our theory of syntactic comprehension deficits. Based on a recently developed theory of working memory constraints in normal language comprehension (Just & Carpenter, 1992), the theory specifies how reductions in working memory capacity can lead to the pattern of comprehension breakdown revealed by aphasic patients.

Unlike older proposals briefly mentioned earlier, the current theory assumes that aphasic patients who exhibit syntactic comprehension deficits still possess intact structural or procedural knowledge that is necessary to perform syntactic analysis. The same set of parsing mechanisms as in normals is thus assumed to operate during the course of language comprehension in the aphasic population. The theory postulates, however, that the disorder arises, at least in part, as a result of reductions in patients' working memory capacity for language. We propose that, whether normal or aphasic, individuals vary in working memory capacity and that, in general, aphasic patients must perform language processing with less working memory capacity than normal adults. According to the theory, one important consequence of severely reduced working memory capacity, namely a processing slowdown, makes aphasic patients' syntactic comprehension highly error-prone, particularly under strong temporal restrictions.

Central to the current theory is the definition of working memory capacity. The theory proposes that working memory capacity consists of a flexibly deployable pool of limited cognitive resources that supports the two functions of working memory, namely computation and storage. Consider, for example, the processing of the object-relative sentence given at the beginning of the paper: *The boy that the girl is chasing is tall.* To comprehend this sentence, the reader must maintain the first noun phrase *the boy* until the occurrence of the predicate *is tall*, while simultaneously parsing the embedded clause and assigning the appropriate case roles to the relevant participants. Unlike some sentence parsing models that assume a buffer of a fixed size that is structurally separate from the parsing process per se (e.g. Berwick & Weinberg, 1984; Marcus, 1980), the theory posits that such storage and computational requirements for the comprehension of the relative clause sentence are both mediated by the same supply of working memory resources. Within this framework, the constraint on working memory capacity can be defined as the maximum amount of resources available for meeting the computational and storage demands in language processing.

One important implication of this view is that the two functions of working memory compete with each other for the limited resources when the demand on the resources is high. In the current theory, this trading relation between storage and processing occurs under a resource allocation scheme that takes effect when the resource pool is about to be exceeded. Simply put, it is a mechanism that de-allocates a sufficient amount of the resources being used for the processing and storage functions in order to keep the total consumption of the resources within the maximum bound. One resource allocation scheme, for example, limits both functions proportionately, in a manner analogous to an across-the-board budget cut.[3]

This scaling-back of working memory resources has two important consequences for comprehension. First, a repeated de-allocation of the resources being used for the storage purposes induces a kind of "forgetting" by gradually reducing the amount of resources necessary to keep various intermediate and/or final products of comprehension active in working memory. If the "forgetting" is so extensive that a necessary piece of earlier information is not available in working memory when it is needed, the parsing system may not be able to compute new elements critical for the comprehension of the sentence. Even if the critical information is available at a given point in time, the product(s) of the computation may be "forgotten" by the time the end of the sentence is reached.

Second, and more importantly in this paper, the de-allocation of the resources being used for computations can slow down the speed of processing because fewer resources are available to perform a particular computation. This consequence of resource limitations can make a strong impact on syntactic comprehension under severe temporal constraints, as in auditory comprehension, where the listener has no effective external means to control the presentation rate to match his/her internal processing rate. If the processing takes place much slower than the input rate, the patient may be deprived of the opportunity to perform some of the crucial computations. Even if the computations are performed, the processing necessarily becomes "shallower" than ideal, so the products of the computations may be lost more easily from working memory. From this perspective, a processing slowdown exerts a strong negative influence on the comprehension of aphasic patients by making inherently severe time constraints in auditory comprehension even more severe.

This account of syntactic comprehension failures can naturally explain why different aphasic patients are differentially affected by sentence constructions of different syntactic complexity, depending on their levels of severity. If patients have a mild deficit and possess a relatively large

[3]The relative extent to which computation or information maintenance suffers when the resource demands exceed the supply could potentially be subjected to the person's strategic control, allowing them effectively to trade off between processing and storage, depending on the nature or requirement of the task (Just & Carpenter, 1992). For a further discussion regarding this issue within the context of syntactic processing in agrammatic aphasics, see Haarmann and Kolk (1994), Kolk and Weijts (Note 2) and Vos and Kolk (Note 3).

residual working memory capacity, they are likely to be able to understand a rather complex sentence correctly, as long as the sentence imposes less working memory demands than they can accommodate. In contrast, if the patients suffer from severe deficits and have only a minimum amount of working memory resources available, they are likely to fail to comprehend even simple sentences, being unable to meet the real-time processing constraints that operate in auditory comprehension. Since different patients have different residual working memory capacities, the maximum processing demands that they can accommodate also vary concomitantly. In summary, the theory posits reductions in working memory capacity as a major source of syntactic comprehension deficits in aphasic patients and explains their comprehension problems in terms of their failures to meet the real-time processing constraints due to resource limitation.

The current theory shares the basic assumptions and mechanisms with a recent theory of working memory constraints in normal language comprehension, which is instantiated as a computer simulation model (Just & Carpenter, 1992). Later, in the General Discussion, we will describe the computational framework of this model, called CC READER, and suggest how it can be extended to encompass the current theory.

The current account of syntactic comprehension failures suggests that the comprehension performance of aphasic patients could improve if the temporal constraints are lessened. There is some evidence consistent with this prediction, although the main sources of the evidence are not necessarily directed at the syntactic level. First, a significant proportion of complaints made by aphasic patients about their everyday lives concerns their perception that other people talk "too fast" (Rolnick & Hoops, 1969; Skelly, 1975). This difficulty underlies the remarks of aphasic patients (Rosenbek, LaPointe, & Wertz, 1989, p. 154), such as "That goes in, and before I figure it out, it's gone" and "You speak in books, and I can only understand in pages," which suggest that some, if not all, patients are unable to keep up with the pace of natural speech.

In addition, several studies have demonstrated that slower speech or longer pauses facilitate syntactic and discourse comprehension in aphasic patients (e.g. Blumstein et al., 1985; Lasky, Weider, & Johnson, 1976; Nicholas & Brookshire, 1986; Pashek & Brookshire, 1982). Most relevant in the current context is the Blumstein et al. (1985) study, which examined the effects of extra processing time on syntactic comprehension by creating four types of slowed speech: (1) naturally slowed speech (110wpm); (2) speech with elongated vowels (a 70msec to 100msec elongation for each vowel); (3) speech with silent pauses between words (a 250msec pause for each word boundary); and (4) speech with silent pauses between constituent phrase boundaries (e.g. *The boy* [1sec] *who hit* [500msec] *the girl* [1sec] *chased* [500msec] *the dog*). Whereas naturally slowed speech was expected to have global effects, the other three types of speech were hypothesised to have clear effects at the level of auditory perception, word recognition, and syntactic analysis, respectively. The data suggested that, when compared to the normal speech (180wpm), only the syntactically segmented speech significantly facilitated the performance of the patients in a three-alternative sentence–picture matching task.[4] The improvement is consistent with the current theory because heavy computational demands tend to arise at the end of major constituent phrases (refer back to the reading time data from the King and Just [1991] study in Fig. 1). Relatively long pauses at such places might provide patients with the opportunity to perform computations that would not otherwise be completed within the normal time limits.[5]

Another implication of the theory concerns the possibility of degrading normal syntactic processing (e.g. Frazier & Friederici, 1991; Kilborn, 1991; Shankweiler et al., 1989). If alleviating real-time processing constraints can improve the performance of aphasic patients, then imposing much stronger temporal constraints should make normal adults perform like aphasic patients, at least in some important respects. Testing this counter-intuitive prediction will be the focus of the two experiments that we present next.

EXPERIMENT 1

The purpose of Experiment 1 is to demonstrate that normal adults show a pattern of comprehension breakdown similar to that of aphasic patients when severe time constraints are imposed by presenting stimulus sentences rapidly, thereby limiting the amount of time they can spend processing each word of the sentence. As a means of imposing strong temporal constraints, we employed the rapid serial visual presentation (RSVP) technique, in which words are presented for a brief interval, one word at a

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[4]Among different clinical syndromes, only Wernicke's aphasics (N = 5) benefited from this pause manipulation. As Blumstein et al. (1985) point out, however, this result probably reflected the near-ceiling performance by their Broca's (N = 5) and conduction aphasics (N = 5) in the control condition.

[5]We do not imply that patients' syntactic comprehension performance will necessarily benefit from releasing temporal constraints, particularly if the computational and storage demands imposed by the sentence are still far greater than the working memory capacity that they have available. For example, presenting sentences in written form and thereby making them continuously available may not have beneficial effects for all patients (even those who do not have major reading impairments). The processing of structurally complex sentences, even in written form, involves internally maintaining various partial results while performing demanding linguistic computations, which together can put a considerable burden on working memory capacity. In fact, unlimited visual presentation of structurally complex sentences does not always improve comprehension performance, when compared to either limited visual presentation or auditory presentation (e.g. Martin & Feher, 1990).

time, in the same position on a computer monitor (e.g. Forster, 1970; Juola, Ward, & McNamara, 1982; Potter, 1984).

Previous studies have demonstrated that normal adults have difficulty in processing complex sentences under strong time constraints. In general, very fast input rates may prevent a successful completion of some critical computations or a "deeper" processing of some important elements. For example, one RSVP study compared normal adults' immediate memory of sentences with a centre-embedded clause (e.g. *The lawyer she wants is busy elsewhere*) with that of sentences of the same length without any embeddings (e.g. *The wealthy child attended a private school*) (Forster & Ryder, 1971). When the sentences were presented at the rate of 62.5msec per word, recall was poorer for the centre-embedded sentences than for the one-clause sentences, mainly because the embedded relative clause was recalled less well. The words from the main clause of the centre-embedded sentences, however, were remembered as well as the words from the single-clause sentences. These results suggest that the difficulty in determining the syntactic structure of the embedded clause and assigning the correct case roles to the relevant nouns under such severe time constraints prevented readers from processing and/or storing the words from the embedded clause as well as they otherwise would have.

Using the RSVP paradigm, we presented 11 different types of sentences, including 9 sentence types used in the Caplan et al. (1985) study, to normal college-age subjects with different working memory capacities (as assessed by the Reading Span test). Sentences were presented at 2 rapid rates, either 200msec per word (called "slow") or 120msec per word (called "fast"). This speed-of-presentation manipulation and the working memory span of the subject were expected to constrain sentence processing conjointly in a way that might approximate the severity dimension of aphasic patients' comprehension. Subjects were asked to answer a yes/no question after the presentation of each sentence to assess whether they had correctly understood the case-role relationships among different participants in the sentence (e.g. *Did the actor kick the comedian?*, after the sentence *The comedian that the actor kicked ignored the pianist*).

The capacity theory of syntactic comprehension disorders makes the following predictions. First, normal adults should show similar effects of syntactic complexity as do aphasic patients. In particular, they should show a difficulty in ordering of different sentence types that closely resembles that of aphasic patients. Second, normal adults should show the effects of "severity," with a faster presentation speed and a smaller working memory capacity leading to poorer comprehension performance than with a slower speed and a larger capacity. Moreover, this "severity" dimension should interact with the syntactic complexity of the sentences, exerting greater influence as the sentence complexity increases.

Method

Reading Span Test. The Reading Span test was used to assess the reader's working memory capacity for both computation and storage during reading comprehension (Daneman & Carpenter, 1980). In this test, each subject read aloud a set of unrelated sentences (13 to 16 words in length) without pausing between them and, at the end of each set, recalled the last word of each sentence. For example, after reading the following set of two sentences, the subjects were to recall the words *abruptly* and *all*:

Due to his gross inadequacies, his position as director was terminated abruptly.
It is possible, of course, that life did not arise on the earth at all.

Sentences were presented in sets of varying size, starting from two sentences per set. Five sets of increasing set size were given in a method of limits until the subject failed to recall at least three out of five sentence sets from that particular set size. Subjects' reading span was defined as the highest set size for which they correctly recalled all of the words from at least three out of the five sets. Half credit was given if the subject was correct on two out of five sets. Low-span readers were defined as those whose reading span score was 2.5 words or less, mid-span readers either 3.0 or 3.5, and high-span readers 4.0 or more.

Subjects. The subjects were 84 students from Carnegie Mellon University who participated in the experiment either for course credit or for a $5.00 payment. All were native speakers of English and had normal or corrected-to-normal vision. There were 23 high-span, 31 mid-span, and 30 low-span readers, as indicated by performance on the Reading Span Test.

Design and Materials. The experiment involved three factors, one subject-classification and two within-subjects factors. The subject-classification factor was the subject's working memory capacity assessed by the Reading Span test (high-span vs. mid-span vs. low-span readers). The other two factors, both within-subjects, were the presentation speed and the syntactic complexity (or sentence types). The current experiment used the 2 presentation rates of 120msec per word ("fast") and 200msec per word ("slow"). This factor and the span factor were intended as two different ways to "simulate" the severity dimension of aphasic patients. The other within-subjects factor, syntactic complexity, consisted of 11 sentence types (see Table 1). The 11 types included the 9 used in the Caplan et al. (1985) study, plus 2 additional types (centre-embedded subject-relative [CES] and right-branching object-relative [RBO] sentences).

Two versions of stimulus sentences were constructed for the purpose of counterbalancing. Each version contained 88 semantically reversible sentences, with 8 sentences for each sentence type. The sentences were generated from a set of eight nouns and eight verbs (slightly more complex ones than those used in the Caplan et al. study), each appearing the same number of times within the same sentence type and playing different thematic roles equally often. For the dative (D) and dative passive (DP) sentences, four verbs (i.e., *send*, *take*, *bring*, and *present*), rather than eight verbs, were used repeatedly because only a few dative verbs were available that allowed both of the two possible dative constructions (i.e. with and without the proposition *to*, such as *send the banker the doctor* and *send the banker to the doctor*). Different sets of nouns and verbs were used for the two versions, except for the four dative verbs that appeared in both versions.

The yes/no comprehension questions were always simple active sentences in the interrogative form (e.g. *Did the doctor kick the banker?*), regardless of the sentence types. Within each sentence type, the correct answer was "yes" for half of the sentences and "no" for the other half. For the relative-clause sentences and the conjoined sentences, the questions interrogated each of the two clauses equally frequently.

Procedure. Each subject read a total of 176 sentences in 2 blocks. The presentation speed (120msec per word or 200msec per word) was kept constant within each block. The order of administering the two versions of the stimulus sentences and the two presentation speeds was counterbalanced across subjects for each reading span group. Prior to the 88 experimental trials in each block, 11 practice trials (1 for each sentence type) were given in order to familiarise subjects with the presentation speed used in that block.

Stimulus sentences were presented on an IBM-PC monitor with the RSVP technique. The display, at first, contained an asterisk at the centre. When a subject hit the "start" button on a response box, a sentence flashed rapidly one word at a time where the asterisk had previously been located, with the centre of each word corresponding to the location of the asterisk. Immediately after the last word of the sentence, a row of percent signs appeared for 200msec, serving as a visual mask. Two seconds after the presentation of the mask, a yes/no comprehension question was presented on the monitor, all words visible at once. After reading the statement, subjects indicated their answer by pressing either the "yes" or the "no" button. Subjects were instructed to make their judgments as accurately as possible, with no emphasis on their response time. The stimulus sentences were presented in a random order for each subject.

Results and Discussion

A central thesis of the theory tested in Experiment 1 was that normal adults' processing under severe temporal restrictions would show some of the characteristics of aphasic patients' performance. Supporting this hypothesis, the results from Experiment 1 (presented in Fig. 4) parallel the pattern of performance that we argued is typical among aphasic patients.

First, the syntactic complexity of the sentence had a significant effect on comprehension performance, $F(10, 810) = 52.69$, $MSe = 1.11$, $P < 0.01$. As Fig. 4 indicates, the ordering of difficulty of 11 sentence types (averaged across subjects) was almost identical to the ordering found in the Caplan et al. (1985) aphasia study (see Fig. 3). Consistent with the complexity metric presented in Table 2, the result of a single-df contrast indicated that the number of relevant complexity factors had a highly significant impact on subjects' comprehension performance, with sentence types associated with more complexity factors being comprehended less accurately, $F(1, 810) = 303.82$, $MSe = 1.11$, $P < 0.01$. The complexity metric accounted for approximately 50% of the variance associated with the complexity factor in the omnibus 3-way ANOVA (289.63 out of

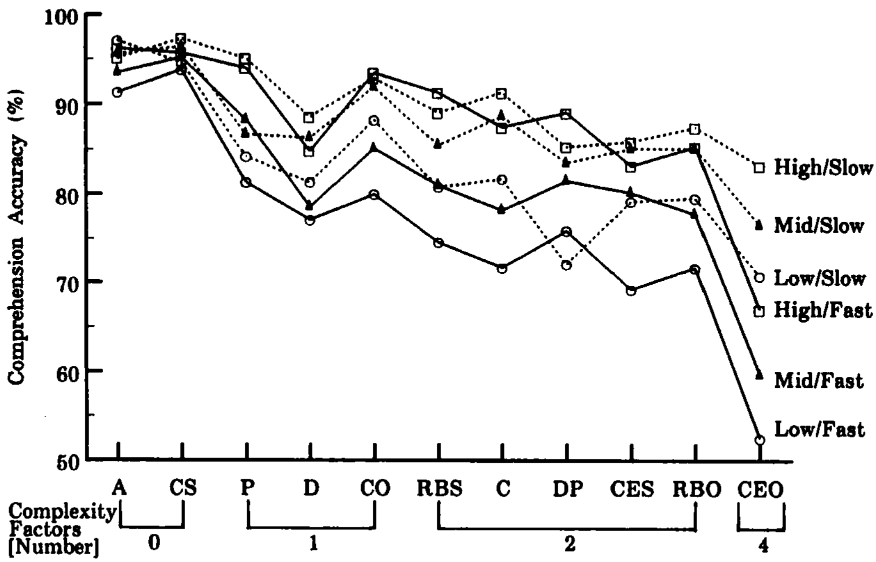


FIG. 4 Syntactic comprehension performance of normal college-age adults with different working memory capacities under 2 rapid presentation rates (labelled "slow" and "fast") for 11 sentence types, 9 from Caplan et al. (1985) plus Centre-Embedded Subject-Relative (CES) and Right-Branching Object-Relative (RBO) sentences. As the complexity level of the sentence increases, the "severity" level, which is approximated conjointly by the working memory span of the subject and the presentation speed, exerts increasingly stronger detrimental effects on comprehension accuracy.

586.74). Note that the most complex sentence type, the centre-embedded object-relative (CEO) sentence, was comprehended at chance level when the presentation rate was fast (120msec per word), which is consistent with a number of studies with aphasic patients (Caramazza & Zurif, 1976; Grodzinsky, 1989; Sherman & Schweickert, 1989; Wulfeck, 1988).

Second, the two factors (i.e. reading span and presentation speed) that were intended to approximate the severity level of aphasic patients each had a significant impact on the comprehension accuracy. Higher-span readers were generally more accurate than lower-span readers in answering questions, with the overall comprehension accuracy being 89.0%, 84.6%, and 79.5% for high-span, mid-span, and low-span readers, respectively, $F(2, 81) = 12.19$, $MSe = 7.07$, $P < 0.01$. Similarly, subjects performed better in the slow condition (86.6%) than in the fast condition (81.5%), $F(1, 81) = 37.52$, $MSe = 1.71$, $P < 0.01$.

Importantly, the "severity" factors interacted with the syntactic complexity of the sentences, with the more "severe" groups exhibiting disproportionately more difficulty with the more complex sentences. The "severity" continuum is represented in Fig. 4 by the six conditions resulting from the combination of the two levels of the speed factor (fast vs. slow) and the three levels of the reading span classification factor (high-span vs. mid-span vs. low-span). Note that, just like the seven regression lines for the different subgroups with different degrees of severity presented in Fig. 2 (Naeser et al., 1987), the six curves representing different "severity" levels in Fig. 4 diverge as the syntactic complexity of the sentences increases.

Several statistical results support this "severity" by complexity interaction among normal adults. First, the demanding sentence constructions were particularly difficult to comprehend when the presentation speed was fast, resulting in a significant Speed × Complexity interaction, $F(10, 810) = 6.66$, $MSe = 0.94$, $P < 0.01$. Similarly, more complex sentences caused more severe comprehension difficulty for those with smaller working memory capacities, $F(20, 810) = 1.58$, $MSe = 1.11$, $P < 0.06$. This Span × Complexity interaction emerged even more clearly when only the two extreme span groups (low-span and high-span readers) were contrasted, $F(10, 510) = 2.71$, $MSe = 1.13$, $P < 0.01$. Thus, consistent with our prediction, the "severity" dimension, operationalised in this experiment as the reader's working memory capacity and the presentation speed, interacts with the syntactic complexity of the sentences.

Moreover, the faster presentation speed had a greater impact on the syntactic comprehension performance of readers with smaller working memory capacities, $F(2, 81) = 2.86$, $MSe = 1.71$, $P < 0.07$ (with all three groups included), and $F(1, 51) = 4.15$, $MSe = 2.15$, $P < 0.05$ (with only high-span and low-span readers included). Further analyses indicated that this Span × Speed interaction arose because, whereas low-span readers and mid-span readers comprehended the sentences significantly better at the slower presentation rate ($F[1, 29] = 43.79$, $MSe = 1.55$, $P < 0.01$, and $F[1, 30] = 36.03$, $MSe = 0.97$, $P < 0.01$, respectively), there was no such simple effect of Speed for high-span readers, $F(1, 22) = 1.13$, $MSe = 2.95$, $P > 0.10$. However, because reading span and presentation speed interacted with the syntactic complexity factor in a qualitatively similar manner, the three-way interaction (Span × Speed × Complexity) did not approach statistical significance ($F < 1$).

In summary, this aphasic-like pattern of data elicited from *normal* adults supports the hypothesis that severe temporal restrictions in the face of reduced resources may also be a major cause of syntactic comprehension failures of aphasic patients.

EXPERIMENT 2

An important implication of the results from Experiment 1 is that such general deficits as reductions in working memory capacity for language may account for a significant proportion of syntactic comprehension impairments that many aphasic patients exhibit. It has often been pointed out, however, that some patients show a pattern of comprehension performance that deviates from what such a general-deficit account alone would predict. According to one view, such deviant patterns of performance suggest that the patient may have a comprehension impairment specific to that particular sentence type or the entailed linguistic operation (e.g. Caplan & Hildebrandt, 1988). In Experiment 2, we critically evaluate this specific impairment hypothesis by assessing the extent to which normal adults, who are supposed to have no such specific impairments, show similar "deviant" comprehension profiles under strong temporal constraints. More specifically, the current experiment attempts to replicate several aspects of the results from the Caplan et al. (1985) study described earlier, particularly those aspects of the data that were interpreted as suggesting the existence of specific syntactic impairments.

Earlier, our discussion of the Caplan et al. study focused on several systematic aspects of the data that are consistent with the capacity-reduction view of syntactic comprehension deficits. It is important to note, however, that the data reflect more than just such general trends; indeed, the comprehension profiles of different patient subgroups do not show a strict monotonic decrease in accuracy with increasing complexity of the sentence type. Figure 5 shows the comprehension profiles of the six subgroups obtained in Caplan et al.'s Study 1 (excluding the one subgroup who virtually could not perform the task). Note that, although approximately 60% of the total variance was attributable to the first principal component that appeared to tap the overall accuracy or the severity level, different sub-

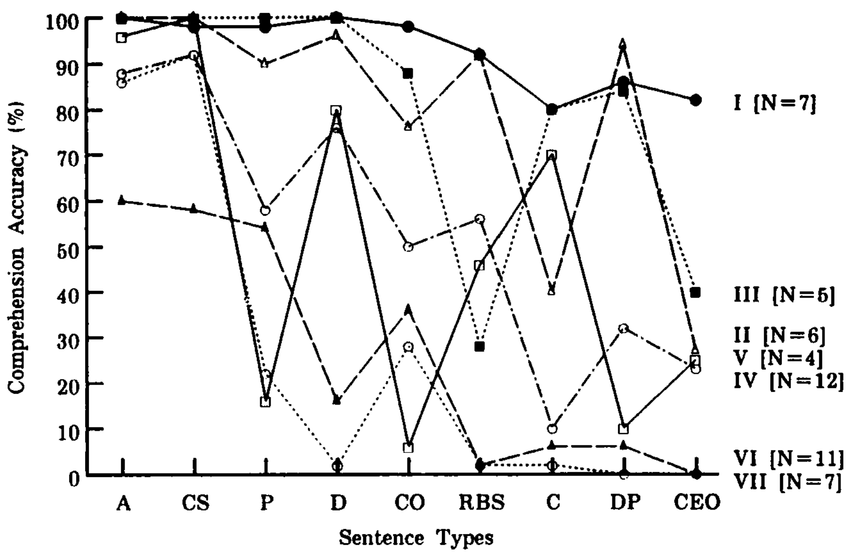


FIG. 5 Comprehension performance of statistically formed subgroups of patients for nine different syntactic constructions in Study 1 reported in Caplan et al. (1985). Although the comprehension accuracy generally decreases with increasing structural complexity, different subgroups exhibit different "strengths" and "weaknesses" on different sentence types, reflected by differential "ups and downs" in the curves. These idiosyncratic comprehension profiles deviate from the pattern of performance that would be predicted from syntactic complexity and the patient's severity level alone. Studies 2 and 3 of Caplan et al. also report similar results. The graph is based on the data reported in Caplan, Baker, and Dehaut, 1985; Table 4, p. 135.

groups had different "strengths" and "weaknesses," as indicated by the differential patterns of ups and downs in the graph. Those different comprehension profiles revealed by different subgroups were reflected in the later eigenvectors (second and third) of the principal components analysis, which conjointly accounted for roughly 20% of the total variance in each of the 3 studies. Unlike the first "severity" vector, these subsequent vectors were loaded differentially on different sentence types, suggesting that the comprehension performance on some specific sentence types could also play a role in differentiating the patients into separate groups. These results naturally led to the conclusion (Caplan & Hildebrandt, 1988, p. 143) that "to the extent that patient subgroups [were] determined by performances on particular sentence types, these subgroups include[d] patients with specific impairments affecting the processing of certain syntactic structures and the assignment of certain semantic values more than other structures and values."

In the current experiment, we attempted to approximate the Caplan et al. (1985) study as closely as possible, using the RSVP paradigm. The test of comprehension employed in the current experiment also resembled the object-manipulation task used in the Caplan et al. study. Because the current theory assumes that there are no selective impairments of particular sentence types or linguistic operations, normal adults are expected to show differential abilities to comprehend different sentence types in a manner comparable to aphasic patients. If, however, normal adults do not show any strong indication of differential profiles of comprehension performance, then, contrary to the current theory, at least some aphasic patients may have specific impairments in particular sentence types or linguistic operations.

Method

Subjects. The subjects were 36 students from Carnegie Mellon University who participated in the experiment either for course credit or for a $5.00 payment. They were all native speakers of English and had normal or corrected-to-normal vision. In this experiment, we restricted the range of subjects by including only low-span and mid-span readers (14 and 22 readers, respectively), who were likely to make more comprehension errors and thus were more suitable for the main purpose of the experiment than were high-span readers. None of the subjects had participated in Experiment 1.

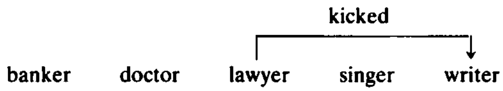
Materials and Procedure. Each subject read a total of 55 sentences in the experimental session. As in the Caplan et al. study, there were five sentences for each sentence type. The sentences were constructed in the same way as in Experiment 1, except that only five nouns and five verbs were used in the current experiment. For the dative (D) and dative passive (DP) sentences, only four verbs (the same dative verbs as the previous experiment) were used (for the same reason as before).

Each subject was given a booklet in which to indicate their interpretation of the sentences. On each page of the booklet, the names of the five possible participants (i.e. *banker*, *doctor*, *lawyer*, *singer*, and *writer*) were printed for each trial. The subjects were asked to indicate the interrelationship among the participants by drawing a diagram containing one or two arrows. Table 3 shows examples of how to draw diagrams. If the sentence is either *The lawyer kicked the writer* or *The writer was kicked by the lawyer*, for example, the correct diagram should look like (a) in the table, with the arrow being drawn from *lawyer* to *writer*. It was emphasised that subjects always start drawing an arrow from the actor (or agent) to the recipient (or patient) of the described action and to label it with the name of the appropriate action. For two-verb sentences, two arrows were required to be drawn, as in diagram (b), indicating the agent and patient roles for each verb. Two arrows were required to be drawn in the case of

TABLE 3
Examples of How to Draw a Diagram for Experiment 2

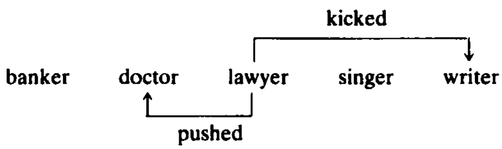
Sentences with a Single Two-Place Verb

(A) The lawyer kicked the writer
(P) The writer was kicked by the lawyer
(CS) It was the lawyer that kicked the writer
(CO) It was the writer that the lawyer kicked

(a) 

Sentences with Two Verbs

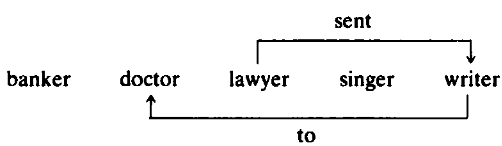
(CES) The lawyer that kicked the writer pushed the doctor
(C) The lawyer kicked the writer and pushed the doctor

(b) 

(Diagrams should be drawn in an analogous way for the CEO, RBS, and RBO sentences)

Dative/Dative Passive Sentences

(D) The lawyer sent the writer to the doctor
(DP) The writer was sent to the doctor by the lawyer

(c) 

dative (D) and dative passive (DP) sentences also, but one of them was to be labelled as *to*, as in diagram (c), which illustrates that the *lawyer* sent the *writer* (the arrow labelled as *sent*) and that the *writer* went *TO* the *doctor* (the arrow labelled as *to*).

The stimulus sentences were presented to subjects in the same way as in Experiment 1, except that only 1 presentation rate was used (160msec per word). Prior to the 55 experimental trials, 11 practice trials (1 for each sentence type) were given in order to familiarise subjects with the task. When subjects drew diagrams in ways other than the ones specified during the practice trials, the experimenter explained how they were supposed to draw the diagram until they completely understood it. Subjects were instructed to draw the diagram as accurately as possible and, again, no emphasis was put on their response time. All the subjects read the 55 sentences in the same order, but the sentences were presented in a random order, with the constraint that sentences of the same syntactic structures could not appear in succession.

Data Scoring and Data Analysis. A diagram was scored as correct if it accurately depicted the thematic roles of different nouns used in the sentence, namely if all the arrows in the diagram were drawn from the correct agent noun to the correct patient noun (in the case of dative-verb sentences, one of the two arrows had to be drawn from the correct patient noun to the correct goal noun). For dative-verb and two-verb sentences, subjects drew the arrows appropriately but mislabelled or forgot to label one of the arrows on approximately 5% of the trials. Because the assignment of thematic roles was the primary criterion for scoring in the Caplan et al. (1985) study, a diagram with a mislabelled or unlabelled arrow was scored as correct, as long as the other arrow was appropriately labelled and the diagram depicted all the thematic roles correctly.

In order to classify subjects into subgroups, a cluster analysis was performed, based on each subject's scores on the 11 sentence types. We used the same clustering technique as did Caplan et al., called Ward's method, which is a hierarchical clustering method designed to minimise the within-cluster variance (Ward, 1963). Because the CLUSTAN program (Wishart, 1978) used by Caplan et al. was not available to us, the CLUSTER program in the SAS package was used instead for the analysis, with the raw, untransformed data as input. We also ran a principal components analysis, using the BMDP 4R program. Again, the analysis was based on each subject's scores on different sentence types, but the data were initially standardised by dividing each score by the sample standard deviation for that sentence type (a default option of BMDP 4R).

Results and Discussion

Despite the fact that the current experiment employed a different presentation speed, a different task, and subjects with a more restricted range of working memory capacity, it replicated some of the basic findings of Experiment 1. First, as Fig. 6 shows, there was a strong effect of syntactic complexity, $F(10, 340) = 29.49$, $MSe = 0.93$, $P < 0.01$. Second, the effect of working memory capacity (or "severity") was also present, with mid-span readers performing better overall than low-span readers (77.9% vs. 68.0%), $F(1, 34) = 3.95$, $MSe = 5.81$, $P < 0.06$. Furthermore, low-span readers showed disproportionately more difficulty with complex sentence types than did mid-span readers, reflected in a marginally significant Span $\times$ Complexity interaction, $F(10, 340) = 1.80$, $MSe = 0.93$, $P < 0.06$.

The main focus of the experiment, however, is whether different subjects show different comprehension profiles analogous to the differing

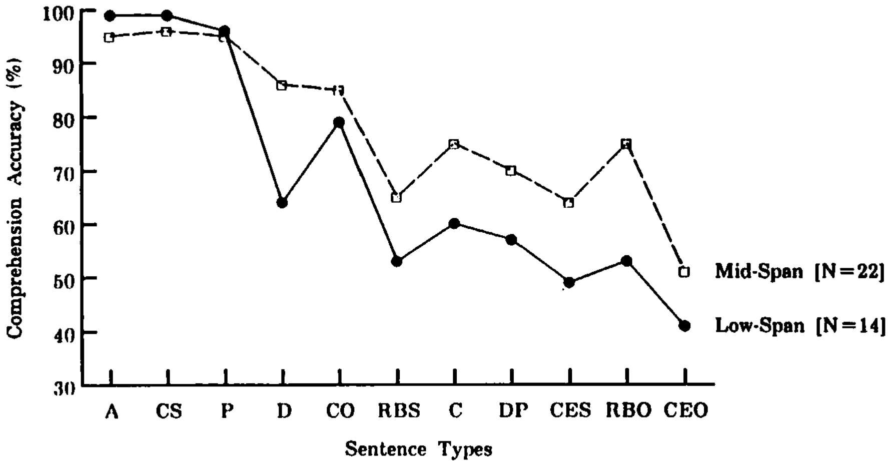


FIG. 6 Mean comprehension performance of normal college-age adults with different working memory capacities for 11 sentence types presented under RSVP (160msec per word) in Experiment 2. As in Experiment 1, the working memory capacity of the reader manifests increasingly stronger detrimental effects on comprehension accuracy, affecting low-span readers to a greater extent than mid-span readers.

profiles among aphasic patients in the Caplan et al. study. Figure 7 summarises the results of the cluster analysis, which generated 6 subgroups at about the 40% level of the total variance (i.e. the total error sum of squares for this clustering is about 40% of the total variance). A comparison with the data from aphasic patients (Fig. 5) suggests two important parallels. First, as was the case with the Caplan et al. study, the subgroup with the best overall performance (i.e. Subgroup I) comprehended all the sentence types relatively well, showing only a slight decrease in their comprehension accuracy with increasing syntactic complexity. Second, the curves for the rest of the subgroups were much less smooth, going up and down abruptly such that a particular construction is comprehended much better by one group than another. Among aphasics, such a dissociation has often been interpreted as evidence of a specific impairment, but Fig. 7 suggests that it can also be found with nonaphasic individuals.

A principal components analysis also replicated one of the most important findings of the Caplan et al. study, namely the vector that seems to correspond to the "severity" factor. Table 4 presents the factor loadings of the three eigenvectors obtained in the analysis of the present data, with the percentage of total variation accounted for by each of the three vectors. The analysis excluded the three simplest sentence types (active [A], cleft-subject [CS], and passive [P] sentences) that were comprehended by most subjects without any errors and, thus, were not illuminating as to the nature

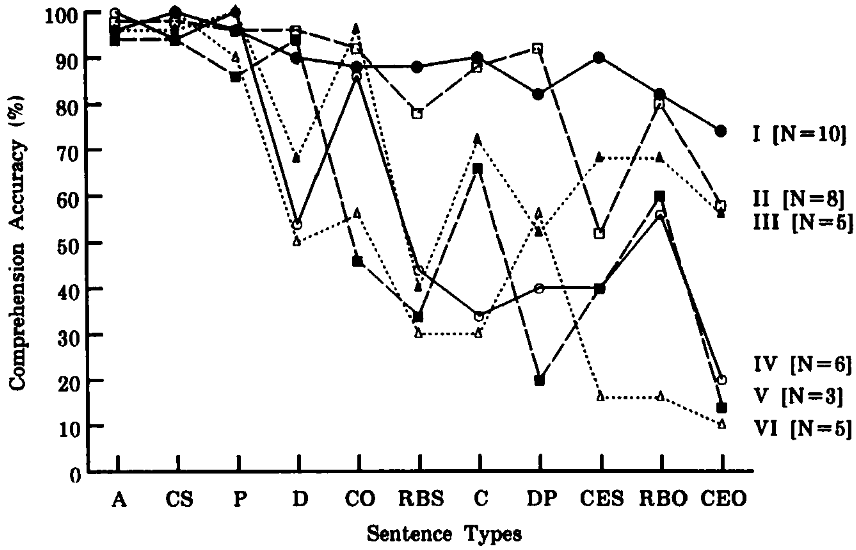


FIG. 7 Comprehension performance of statistically formed subgroups of normal adults for 11 sentence types in Experiment 2. As is the case with aphasic patients, different subgroups of normal adults show different comprehension profiles, which are suggestive of "double dissociations" on some sentence types among some subgroups. A comparison with Fig. 5 indicates, however, that the idiosyncratic patterns of the comprehension profiles are not as marked among normal adults as aphasic patients.

of the determinants of subject classification. Just as the first "severity" eigenvector in each of the 3 Caplan et al. studies accounted for approximately 60% of the total variance and was loaded equally positively (+0.29 to +0.38) on all sentence types, so the first eigenvector obtained in the current experiment accounted for 54.8% of the total variance, with the contribution from the 8 sentence types being relatively equal (+0.27 to +0.40). This result suggests that the overall level of comprehension performance in the task was a major determinant of group classification

TABLE 4
The Results of Principal Components Analysis in Experiment 2
(Excluding A, CS, and P Sentences)

Eigen-vectors	Total Variance	*Factor Loading by Sentence Type*							
		D	*CO*	*RBS*	*C*	*DP*	*CES*	*RBO*	*CEO*
1st	54.8%	0.33	0.27	0.35	0.39	0.32	0.37	0.37	0.40
2nd	11.5%	0.29	−0.65	0.30	0.02	0.48	−0.40	−0.04	−0.06
3rd	8.0%	−0.13	0.63	0.00	−0.22	0.61	−0.37	−0.09	−0.15

for normal adults, too. Both the second and third vectors in the current analysis (like those reported by Caplan et al.) appear to be related to those aspects of comprehension profiles that are specific to particular subgroups of subjects. However, as was the case with the Caplan et al. study, there is no obvious linguistic or psychological construct that precisely characterises what each of these principal components really means.

The types of errors that the normal subjects made in the current experiment were also similar to the ones made by aphasic patients. The types of errors were coded according to the same notation system as Caplan et al. As the examples in Table 5 illustrate, the notation consisted of labelling each noun in a sentence in terms of its linear position, and assigning "slots" for the arguments around each verb of the sentence in the order of agent, patient, and goal. Table 6 summarises the incorrect responses most frequently made on three of the five two-verb sentences that were also used in the Caplan et al. study. We present the error data from two-verb sentences only, because normal adults made relatively few errors for the other sentence types. According to the coding scheme described earlier, there are 35 different possible error responses to any 2-verb sentences, but the table lists only those error responses that constituted more than 10% of all the error responses excluding lexical errors[6] and incomplete responses. The data from Caplan et al.'s (1985) Study 2 (reported in Caplan & Hildebrandt, 1988) are also provided for the sake of comparison. Since different subgroups did not show any clear systematic differences in the error types in either of the two populations, all the subgroups are aggregated in the table for each population.

A comparison of normal adults' error types with those of aphasic patients reveals that the types of errors made by the two populations are quite similar. In the case of right-branching subject-relative (RBS) sentences, both populations had only one dominant error type, namely the 12;13 response (correct response: 12;23). As for centre-embedded object-relative (CEO) sentences, three of the four major error responses made by normal adults were also the most frequent errors in the aphasic population (i.e. 12;13, 12;23, and 21;23), the remaining common error from normals being the reversal of the two clauses (i.e. 13;21) (correct response:

[6]Unlike the Caplan et al. study, the current study produced a considerable number of lexical errors, in which subjects replaced one or more nouns that occurred in the sentence with the one(s) that did not actually appear when they drew the diagram. On average, approximately 17% of the total (both correct and incorrect) responses to 2-verb sentences included such lexical errors. This could be due to a methodological difference between the two studies. It seems that the object-manipulation task in the Caplan et al. study was such that patients could not pick up the animal dolls that were irrelevant to the sentence in question. In contrast, in the diagram-drawing task employed in the current experiment, the entire set of nouns was always present on the answer sheet, which enabled subjects to incorporate into the diagram a noun that was not mentioned in the sentence.

TABLE 5
The Coding Scheme Used for the Error Analysis

Right-Branching Subject-Relative (RBS) Sentences

The doctor^{1} kicked the banker^{2} that phoned the lawyer^{3}.

*Correct response: 12;23 (Nouns 1 and 2 are, respectively, the agent and the patient of the first verb; Nouns 2 and 3 are, respectively, the agent and the patient of the second verb)

Centre-Embedded Object-Relative (CEO) Sentences

The doctor^{1} that the banker^{2} kicked phoned the lawyer^{3}.

*Correct response: 21;13 (Nouns 2 and 1 are, respectively, the agent and the patient of the first verb; Nouns 1 and 3 are, respectively, the agent and the patient of the second verb)

Conjoined (C) Sentences

The doctor^{1} kicked the banker^{2} and phoned the lawyer^{3}.

*Correct response: 12;13 (Nouns 1 and 2 are, respectively, the agent and the patient of the first verb; Nouns 1 and 3 are, respectively, the agent and the patient of the second verb)

21;13). In the case of conjoined (C) sentences, the four major error types made by normal adults included the two most common error responses from aphasic patients (i.e. 12;23 and 21;23), although the reversal of the two clauses (the 13;12 response) was, again, frequent among normal adults (correct response: 12;13). Note that most of the common error responses for both normals and aphasics would have been correct for some other sentence types, suggesting that neither population was responding randomly when comprehension failed.

TABLE 6
The Percentage of Occurrence of Frequent Error Responses to RBS, CEO, and C Sentences in Experiment 2 and in the Caplan et al. (1985) Study

Right-Branching Subject-Relative (RBS) Correct Response 12;23			*Centre-Embedded Object-Relative (CEO) Correct Response 21;13*			*Conjoined (C) Correct Response 12;13*		
Error Type	*Expt. 2*	*Caplan et al.*	*Error Type*	*Expt. 2*	*Caplan et al.*	*Error Type*	*Expt. 2*	*Caplan et al.*
1) 12;13	35.5%	46.2%	1) 12;13	23.9%	22.8%	1) 12;23	22.6%	53.8%
2) 13;32	16.1%	6.2%	2) 12;23	17.4%	33.7%	2) 21;23	22.6%	11.5%
			3) 13;21	13.0%	0.0%	3) 13;12	22.6%	5.8%
			4) 21;23	10.9%	13.0%	4) 12;32	16.1%	3.8%

Furthermore, the distribution of incorrect responses over the 35 possible error types was remarkably similar in the 2 populations, although normal adults generally made a smaller number of errors than did aphasic patients (see Appendix B, which presents a complete summary of the distribution of incorrect responses). For all 3 2-verb sentences, the percentage of occurrence of a certain error type in the normal population correlated highly with the frequency of the same error type in the aphasic population, $r(33) = +0.90$ (RBS sentences), $+0.83$ (CEO sentences), and $+0.67$ (C sentences), respectively, all $P < 0.01$.[7]

In summary, Experiment 2 "simulated" several important aspects of the Caplan et al. (1985) aphasia study strikingly well, including the way subjects were statistically clustered into subgroups, the nature of the determinants of subject classification as revealed by the principal components analysis, and the patterns of error responses. Although there is no straightforward way to characterise the comprehension profile of each subgroup (except Subgroup I) in the current study (as well as in the Caplan et al. study), the data nonetheless suggest that even normal adults can and do show different comprehension profiles that deviate from the pattern expected from the syntactic complexity of the sentences and the "severity" level of the individual alone. The presence of such idiosyncratic comprehension profiles among normal adults, who supposedly have intact structural and procedural knowledge necessary to perform syntactic analysis, suggests that a selective loss of knowledge at the level of sentence type or linguistic operation may not necessarily be implicated in similar deviant profiles found in aphasic patients.

What, then, would give rise to such different comprehension profiles among aphasic patients (as well as normal adults)? At this point, it is impossible to specify the sources precisely. Without any systematic data from both normals and aphasics on the stability of each individual's comprehension profile across different testing sessions, the "deviant" patterns of data could simply be due to stochastic noise inherently present in a cognitive system (Haarmann & Kolk, 1991; McClelland, 1993). To the extent that the patterns are found to be stable, however, alternative interpretations need to be considered. For example, individuals may vary in terms of the efficiency with which they execute different processes or operations (Carr, Brown, Vavrus, & Evans, 1990; Frederiksen, 1982), and these "strengthens" and "weaknesses" inherent within individuals might manifest themselves in a somewhat exaggerated manner under some kind

[7]This regression analysis is unjustified from a statistical point of view, because it involves an interrelationship between two random variables, rather than a prediction of the dependent variable from the values of an independent, regressor variable (Isaac, 1970). This informal linear regression analysis, nonetheless, provides a good summary of the degree to which the error distribution of normal adults corresponds to that of aphasic patients.

of mental strain (such as a stroke or a rapid presentation of sentences). Alternatively, the emergence of "deviant" profiles could be due to the utilisation of different adaptive strategies favoured by different individuals, whether aphasic or normal (e.g. Caplan & Hildebrandt, 1988; Friederici & Graetz, 1987). A related account concerns individual differences in the use of various linguistic cues (such as morphological agreement, word order, and the animacy of nouns) in interpreting sentences. A series of studies conducted within the framework of the competition model (MacWhinney & Bates, 1989) has shown that there are considerable individual differences in the kinds of cues preferred by aphasic patients (Bates, Friederici, & Wulfeck, 1987) and also by normal adults (Bates et al., 1982; Harrington, 1987), and such variation could contribute to between-subjects differences in comprehension profiles.

Future research is necessary to specify the nature of the factors leading to differential comprehension profiles among aphasics and normals and to determine whether they are the same for the two populations. Nonetheless, the current results suggest that there is less need to postulate specific impairments in particular sentence types or linguistic operations in order to account for deviant comprehension profiles found among aphasic patients.

GENERAL DISCUSSION

The results from the two "simulation" experiments support the central thesis of the theory that the disorders of syntactic comprehension arise, at least in part, from reductions in effective working memory capacity for language. According to the theory, a capacity reduction leads to a slowing down of computational processes at the time of high demands and makes it harder for patients to complete all the necessary computations under the operation of strong temporal restrictions. We tested the sufficiency of this account by imposing strong temporal demands on normal adults using the RSVP technique. Consistent with the theory, speeded presentation of sentences produced, among normal adults, patterns of comprehension breakdown that were, in some important respects, both quantitatively and qualitatively similar to those shown by aphasic patients.

It is important to acknowledge, however, that there are some notable differences as well. First, whereas there are some aphasic patients who have difficulty comprehending relatively simple sentences, most normal adults can comprehend them well, even under the operation of strong temporal constraints. Particularly important in this context is the comprehension of passive sentences, for which a considerable proportion of aphasic patients exhibit poor performance (see, for example, Fig. 5). This difference may be due, in part, to the homogeneity of normal adults as a whole. When compared to most aphasic patients, even low-span readers may have a large enough resource pool that allows them to accommodate the processing of relatively simple sentences (but not complex ones) under RSVP. In addition, the difference may also be attributable to the observation that many aphasic patients have additional impairments such as an impaired phonological short-term memory system. Although a severely restricted digit or word span (two or three items) does not necessarily correlate with sentence comprehension performance (e.g. Caplan & Waters, 1990; Martin, 1987), there is some evidence suggesting that the system might serve as a general-purpose backup resource that can be used when the first-path analysis fails (e.g. McCarthy & Warrington, 1987; Saffran & Marin, 1975; Shallice & Warrington, 1970). The intact ability to use this peripheral storage system may have helped normal adults attain almost perfect comprehension performance for relatively short and simple sentences like passive sentences. A second, related difference is that, although both normal adults and aphasic patients reveal deviant comprehension profiles, normal adults show somewhat smaller amounts of deviance than do aphasic patients (compare Figs. 5 and 7). This difference might again be due to less variability associated with normal adults as a group or, alternatively, due to an increased "noise" level among aphasic patients (Haarmann & Kolk, 1991; Stemberger, 1984).

Despite such differences, various points of similarities between the two populations revealed in the current study suggest that the RSVP technique could potentially serve as a useful methodology to explore further the nature of syntactic comprehension deficits in aphasic patients. Indeed, informal remarks from a number of participants in the current study (e.g. "I saw all the words, but they were gone before I figured out what they really meant") were strikingly similar to aphasic patients' frequent complaints about speaking rates cited earlier (Rosenbek et al., 1989), suggesting that some aspects of the phenomenological experience of normal adults in RSVP reading may indeed resemble those of aphasic patients in auditory comprehension.

The capacity theory presented in this paper is not alone in assuming that aphasic patients still possess the structural and procedural knowledge necessary for parsing. A central thesis of the theory, namely that syntactic comprehension impairments in aphasic patients reflect performance deficits, as opposed to competence deficits, is shared by a number of other recent theories and proposals (e.g. Bates et al., 1987; Frazier & Friederici, 1991; Kilborn, 1991; Kolk & van Grunsven, 1985). One particularly compatible class of accounts posits that the deficits reflect reduced efficiency of computational processes, such as a slower processing speed and/or a more rapid decay of old information (e.g., Friederici, 1988; Friederici & Kilborn, 1989; Gigley, 1983; Haarmann & Kolk, 1991). Despite the differences in their intuitive appeal as explanations for syntactic comprehension disorders, the capacity-based and efficiency-based explanations are not mutually exclusive, and one explanation can easily be related to the other. The two major manifestations of reduced efficiency, namely a slower processing speed and faster decay of old information (Haarmann & Kolk, 1991), correspond directly to the two consequences of the over-budget demand on working memory capacity in the current theory. Alternatively, just as less efficient cars consume more gasoline over the same distance, a less efficient system may consume more working memory resources to perform the same computation, producing virtually the same effect as having less working memory capacity. At this point, it is difficult to distinguish empirically whether capacity or efficiency, or some combination of the two, provides the more satisfactory account of comprehension deficits.

The current theory also shares some of the tenets of several earlier models of aphasia. One such tenet concerns the notion of an aphasia-to-normal continuum, a perspective that has been emphasised repeatedly since the beginning of aphasia research (e.g. Freud, 1891; McNeil, 1988; Schuell, Jenkins, & Jimenez-Pabon, 1964). Capacity-based explanations also have some resemblance to the so-called global models of aphasia (e.g. Goldstein, 1948; Schuell et al., 1964), in the sense that they all postulate a disturbance of a single functional capacity to account for the target phenomena. For example, in a large-scale factor analytic study with more than 150 aphasic patients, Schuell and her associates found a single factor that loaded highly on more than two-thirds of various language-related tests and accounted for 41% of the common factor variance (Schuell, Jenkins, & Carroll, 1962). They proposed that, despite apparently diverse arrays of symptoms, one facet of impairment was common to all aphasic patients and characterised the common facet of impairment, varying in severity from patient to patient, as affecting the symbolic processing involved in language (Schuell et al., 1964). Although the current theory posits a different unitary construct (working memory resources) to account for a more circumscribed set of phenomena (syntactic comprehension disorders) than in Schuell's theory, it is nonetheless similar to these earlier theories of aphasia in its proposal of a common thread that may underlie many different manifestations of impairments exhibited by aphasic patients.

One challenge to a capacity-based approach, then, concerns the variety of empirical demonstrations that brain damage can affect some aspects of language processing more than others. Why does such selectivity arise from such a general deficit as the reduction in working memory capacity for language?

One possibility is that there can be selective impairments to one or more peripheral systems that could co-occur with reductions in working memory resources. In their factor analytic study, for example, Schuell et al. (1962) found not just a single common factor but also several lesser factors that could be characterised as impairments to peripheral systems (such as speech output deficits). In addition, there is a possibility of impairment to other systems, such as the visuo-spatial processing system, that may interact with the language system (as in reading), but can otherwise be impaired independently. Thus, impairments to peripheral systems and/or separate processing systems, in conjunction with differing amounts of reduction in working memory resources, could give rise to diverse patterns of relative sparing and impairment among aphasic patients in language-related tasks. A capacity-based approach, then, is not necessarily incompatible with the notions of double dissociations and modular organisations of cognitive functions that play an important role in neuropsychological research.

At the level of syntactic comprehension discussed in this paper, however, there may be no need to postulate a selective impairment in the comprehension of particular sentence types or in the execution of specific linguistic operations. Although the possibility of such an impairment still cannot be ruled out, the two experiments reported in this article provide alternative interpretations to such a micro-level construal of selectivity. Experiment 1 showed that the processing of certain constructions may be more impaired because they are more demanding; some reduction in working memory resources would thus be expected to show effects with those constructions, in the sense that the "weakest link" is the most vulnerable. In addition, the results from Experiment 2 suggest that *non*aphasic individuals could have an idiosyncratic processing profile that would manifest itself only under particularly demanding situations. A stroke may exaggerate this pre-morbid profile, producing various patterns of selective sparing and impairment. Consequently, a micro-level dissociation that a patient may reveal in a syntactic comprehension task does not necessarily imply a selective impairment, particularly if the same dissociation can be induced among normal adults by putting them in capacity-demanding situations.

There are also several other arguments for being more cautious about inferring selective impairments at the level of particular sentence types and linguistic operations. First, some of the dissociations at such a micro-level could be a statistical artifact, occurring entirely by chance. A computer simulation study of syntactic comprehension, for example, demonstrated that stochastic noise will occasionally produce a comprehension profile that deviates considerably from an averaged pattern (Haarmann & Kolk, 1991). Similarly, a Monte Carlo simulation study of speech production (Bates, Appelbaum, & Allard, 1991) showed that at least some of the dissociations that had been observed along a variety of micro-level linguistic dimensions in the free speech samples of 20 agrammatic patients (Miceli, Silveri, Romani, & Caramazza, 1989) could have arisen by chance, rather than constituting different functional deficits among different patients.

Second, the selectivity could be a reflection of adaptive strategies that the patient may employ, rather than (or in addition to) a direct reflection of his or her primary deficit (e.g. Kolk & Heeschen, 1990). This is a potential alternative explanation, for example, for a double dissociation between the processing of pronouns (e.g. *him*) and of reflexives (e.g. *himself*) (Caplan & Hildebrandt, 1988), which may arise, in one view, from separable parsing mechanisms for the comprehension of pronouns and reflexives. The dominant errors that the patients made in an object-manipulation task, however, indicate that the patient who was impaired on pronouns (CV) tended to treat them as if they were reflexives, whereas the patient who was impaired on reflexives (AB) tended to interpret them as pronouns. It is thus possible that these two patients employed different compensatory strategies, one assimilating the responses one way and the other assimilating the other way.

Moreover, at least some of the suggested dissociations have not been demonstrated in tasks of comparable difficulty, which can leave open the possibility of alternative interpretations. For example, one such dissociation concerns the relatively spared ability of agrammatic patients to make grammaticality judgments versus their impaired ability to comprehend semantically reversible sentences (e.g. Berndt, Salasoo, Mitchum, & Blumstein, 1988; Linebarger et al., 1983), which has often been taken as evidence for a selective impairment in the ability to map syntactic structures onto thematic relations. A difficulty with this dissociation is that there are many differences between the two tasks, such as the task demands (i.e. yes–no response in grammaticality judgments vs. sentence–picture matching in comprehension) and the nature of the processing requirements (i.e. semantic processing is optional in grammaticality judgments), that may make grammaticality judgments significantly easier than comprehension. Supporting this view, the dissociation in the opposite direction has not yet been reported, to the best of our knowledge. Also, a recent study (Cupples & Inglis, 1993) reports that a patient's comprehension performance can vary greatly, depending on the nature of the task demand, raising the possibility that the dissociation may be eliminated or at least decreased in magnitude if less demanding tasks than sentence–picture matching are used to assess the patient's comprehension performance.

In summary, most of the evidence for specific impairments postulated at the level of specific sentence types or linguistic operations seems to be equivocal, suggesting that a more careful assessment of the dissociations in question may be necessary before postulating such highly specific impairments.

In the current study, we "simulated" several aspects of comprehension performance of aphasic patients with normal adults. Another way to simulate cognitive impairments and make the underlying mechanisms more explicit is via computer modelling (e.g. Gigley, 1983; Haarmann & Kolk, 1991). Although the current theory concerning *aphasic* performance has not yet been instantiated as a computational model, an implemented model of sentence parsing in normals, called CC READER (Just & Carpenter, 1992), provides a base system that can be generalised to account for syntactic comprehension failures in aphasic patients.

CC READER (the CC stands for Capacity Constrained) parses a limited number of sentence constructions from left to right, building syntactic and semantic representations as fully as possible as it goes. As is the case with conventional production systems, the procedural knowledge in CC READER consists of a set of units called productions, each of which is a condition–action contingency that specifies what symbolic manipulation should be made when a given information condition arises in working memory. The execution of the manipulation can change the contents of working memory, thereby enabling another production to operate (or fire). Unlike conventional production systems, however, CC READER incorporates several mechanisms that are often found in activation-based parallel connectionist models (e.g. Cottrell, 1989; St. John & McClelland, 1990; Waltz & Pollack, 1985). In CC READER, for example, activation is a commodity that fuels the two functions of working memory, namely processing and storage. All the processing in CC READER takes place through repeated firings of productions that propagate activation from source elements to target elements re-iteratively over successive cycles, until the latter elements reach some pre-determined threshold. The storage of information is accomplished simply by keeping the activation levels of previously activated elements above threshold.

In CC READER, the constraint on capacity is defined as the maximum amount of activation that the system has available conjointly for propagation and maintenance. However, the demands for activation that the two functions make sometimes exceed the activation quota. In that case, CC READER proportionately de-allocates a sufficient amount of activation being used for propagation and maintenance purposes, effectively imposing a budget cut. This scaling-back of activation can slow down processing by increasing the number of cycles required for an element to reach threshold. It can also produce "forgetting" of intermediate comprehension results by repeatedly decrementing the activation levels of older elements. The total amount of activation available for propagation and maintenance thus determines the speed and accuracy of processing when the demand on activation is higher than the supply.

This capacity constraining mechanism in CC READER can simulate a wide range of phenomena, including the reading-time profiles of readers in the King and Just (1991) study described earlier (see Just & Carpenter, 1992, for details). The model implements individual differences in working memory capacity (high-span vs. low-span readers) by varying the maximum amount of activation available to the system. Just like normal adult readers, the model spends disproportionately more time (cycles) processing the two verbs of centre-embedded object-relative sentences when the activation maximum is set low (to simulate low-span readers) than when it is set high (to simulate high-span readers). The high–low capacity difference emerges because, in the case of the lower activation quota, the activation pool is depleted by the time the two demanding verbs are encountered, producing a scaling-back of the supply of activation, which in turn results in slower, more forgetting-prone comprehension.

Within this computational framework, the current proposal is that the aphasic system is yet more severely limited than the normal low-span system in the maximum amount of activation available for propagation and maintenance purposes, despite intact structural and procedural knowledge represented in production rules. Due to this severely reduced activation quota, the aphasic system is likely to consume its quota sooner. As a result, a scaling-back of activation takes place much more frequently than in the normal system and causes abnormal slowing-down of computational processes as well as "forgetting" of potentially critical information. The precision of this detailed computational model of on-line sentence processing constitutes a major advantage of the current theory, providing good accounts and clear predictions of aphasic patients' performance (e.g. Haarmann, Note 1; Haarmann & Kolk, 1994).

Conclusion

The capacity theory outlined in this paper shifts the scientific schema within which the disorders of syntactic comprehension have been studied to focus on the dynamics of language comprehension that operate under real-time constraints. As pointed out at the onset of the paper, some of the earlier theories identified a loss of structural or procedural knowledge as a primary cause of the comprehension deficits (e.g. Berndt & Caramazza, 1980; Caramazza & Zurif, 1976; Grodzinsky, 1986). From this perspective, a comprehension failure is a natural consequence of the brain damage that should occur in an all-or-none manner, depending on whether the sentence requires the utilisation of the missing piece(s) of knowledge, virtually irrespective of such factors as the degrees of severity, syntactic complexity, and the speed of presentation. In contrast to this rather static view, the current theory emphasises the dynamic nature of sentence processing, by paying close attention to the capacity and temporal constraints that need to be satisfied on-line during the course of comprehension. This new focus does not just provide the basis for our account of syntactic comprehension failures in aphasic patients, but also serves to bring the studies of brain-damaged patients, both theoretically and empirically, into closer alignment with those of normal adults. Although a single factor, such as reductions in working memory capacity, is certainly not adequate to account for every single aspect of syntactic comprehension deficits, the current approach, together with other compatible approaches, may allow us to understand better the nature of syntactic comprehension deficits in aphasic patients.

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APPENDIX A

Individual Patients' Comprehension Accuracy on Four Different Syntactic Structures (Compiled from 12 Published Studies)

		Sentence Types				
Study	*Patient*	*A*	*P*	*CES*	*CEO*	*Patient Type*
Berndt, Salasoo,	VS	75	58	na	na	agrammatic
Mitchum, & Blumstein	FM	67	58	na	na	agrammatic
(1988)	JS	67	50	na	na	non-agrammatic
	JD	100	83	na	na	non-agrammatic
	HY	92	92	na	na	anomic
	VO	92	83	na	na	anomic

Study	Patient	*Sentence Types* A	P	CES	CEO	Patient Type
Caplan & Hildebrandt (1988)[a]	GG	100	100	92	100	anomic?
	JV	100	100	92	92	paragrammatic?
	BO	100	76	92	75	anomic[b]
	KG	100	100	83	25	agrammatic[c]
	RL	100	67	50	20	conduction[d]
	GS	100	75	83	25	?
	SP	100	50	50	20	agrammatic[e]
	CV	100	58	17	0	?
	AB	100	42	72	17	?
Druks & Marshall (1991)[f]	AB	100	88	na	na	agrammatic
	CD	100	94	na	na	agrammatic
	EF	100	44	na	na	agrammatic
	GH	81	31	na	na	agrammatic
Grodzinsky (1989)	ER	na	na	80	60	agrammatic
	LD	na	na	80	50	agrammatic
	RD	na	na	80	20	agrammatic
	EM	na	na	90	70	agrammatic
Kolk & van Grunsven (1985)[g]	BA	85	60	na	na	agrammatic
	DIJ	100	100	na	na	agrammatic
	HE	90	75	na	na	agrammatic
	KOE	100	95	na	na	agrammatic
	LA	95	85	na	na	agrammatic
	OO	95	95	na	na	agrammatic
	PO	75	75	na	na	agrammatic
	POE	100	100	na	na	agrammatic
	ROE	35	40	na	na	agrammatic
	ROO	90	45	na	na	agrammatic
	ZO	90	85	na	na	agrammatic
Martin (1987)	AK	50	63	50	50	agrammatic
	GL	50	63	na	na	agrammatic
	JS	88	25	79	58	agrammatic
	RD	94	81	na	na	non-fluent
	MM	88	88	100	79	non-fluent
	RS	100	88	100	92	non-fluent
	AB	88	100	100	72	fluent
	JC	81	94	na	na	fluent
	WS	66	59	na	na	fluent[h]
	WZ	88	100	96	88	fluent
	EA	na	na	96	33	conduction[i]

Study	Patient	Sentence Types A	P	CES	CEO	Patient Type
Martin & Feher (1990; Auditory condition)	NB	na	na	92	58	non-fluent[j]
	AP	na	na	83	33	fluent[j]
	AB	na	na	92	42	fluent
	MW	na	na	92	92	fluent
	BH	na	na	67	42	fluent
Martin, Wetzel, Blossom-Stach, & Feher (1989; sets 1–3)[k]	NB	93	91	na	na	non-fluent
	AP	63	45	na	na	fluent
	RW	95	68	na	na	?
Schwartz, Saffran, & Marin (1980; Expt. 1)	BL	71	29	na	na	agrammatic
	HR	96	42	na	na	agrammatic
	JR	67	71	na	na	agrammatic
	VS	92	58	na	na	agrammatic
	HT	50	54	na	na	agrammatic
Shankweiler, Crain, Gorrell, & Tuller (1989)[l]	PJ	98	98	na	na	agrammatic
	ME	98	98	na	na	agrammatic
	LS	67	52	na	na	agrammatic
	AK	79	42	na	na	agrammatic
	ED	71	29	na	na	agrammatic
Sherman & Schweickert (1989)	EM	100	100	na	63	agrammatic
	LD	88	63	na	44	agrammatic
	FC	75	88	na	53	agrammatic
	DN	75	75	na	64	agrammatic
	RD	100	75	na	31	agrammatic
Wulfeck (1988)	S1	100	na	na	25	agrammatic
	S2	75	na	na	0	agrammatic
	S3	75	na	na	50	agrammatic
	S4	50	na	na	75	agrammatic
	S5	75	na	na	25	agrammatic
	S6	25	na	na	50	agrammatic
	S7	100	na	na	25	agrammatic
	S8	50	na	na	50	agrammatic
	S9	50	na	na	25	agrammatic
	S10	100	na	na	75	agrammatic

[a]This study used the object-manipulation task. All other studies utilised the sentence-picture matching task.

[b]Also reported in Waters, Caplan, & Hildebrandt (1991).

[c]Also reported in Hildebrandt, Caplan, & Evans (1987).

[d]Also reported in Caplan, Vanier, & Baker (1986).

[e]Also reported in Caplan & Futter (1986).

[f]The four patients in this study were all Hebrew-speaking. The entry for the passive sentences is based on the mean comprehension accuracy of passives with and without "traces."

[g]The 11 patients in this study were all Dutch-speaking.

[h]Also reported in Martin & Blossom-Stach (1986).

[i]Also reported in Friedrich, Martin, & Kemper (1985).

[j]NB and AP's performance on A and P sentences is reported in Martin et al. (1989).

[k]The data from patient JS were not included because this patient's performance on the four sentence types is reported in Martin (1987). Patients NB and AP's performance on CES and CEO sentences is reported in Martin & Feher (1990).

[l]The data from patient VS were not included because this patient's performance on the two sentence types is reported in Schwartz et al. (1980).

APPENDIX B

The Distribution of Incorrect Responses to Two-Verb Sentences in Experiment 2 (Data from Caplan et al.'s Study 2 in Parentheses)

	Centre-Embedded		*Right-Branching*		
Response	*Subject-Relative (CES) %*	*Object-Relative (CEO) %*	*Subject-Relative (RBS) %*	*Object-Relative (RBO) %*	*Conjoined (C) %*
12;12	0.0 (na)	0.0 (0.0)	0.0 (3.1)	0.0 (na)	0.0 (3.8)
12;13	Correct	23.9 (22.8)	35.5 (46.2)	0.0 (na)	Correct
12;21	0.0 (na)	0.0 (0.0)	0.0 (3.1)	0.0 (na)	3.2 (0.0)
12;23	35.9 (na)	17.4 (33.7)	Correct	25.9 (na)	22.6 (53.8)
12;31	15.4 (na)	4.3 (2.0)	3.2 (3.1)	7.4 (na)	3.2 (1.9)
12;32	0.0 (na)	2.2 (1.0)	9.7 (9.2)	Correct	16.1 (3.8)
13;12	25.6 (na)	8.7 (5.0)	3.2 (7.7)	0.0 (na)	22.6 (5.8)
13;13	2.6 (na)	2.2 (0.0)	0.0 (0.0)	0.0 (na)	0.0 (0.0)
13;21	0.0 (na)	13.0 (0.0)	0.0 (1.5)	0.0 (na)	0.0 (1.9)
13;23	2.6 (na)	0.0 (1.0)	0.0 (3.1)	14.8 (na)	0.0 (1.9)
13;31	0.0 (na)	0.0 (0.0)	0.0 (0.0)	0.0 (na)	0.0 (0.0)
13;32	5.1 (na)	0.0 (2.0)	16.1 (6.2)	0.0 (na)	0.0 (0.0)
21;12	0.0 (na)	0.0 (0.0)	0.0 (0.0)	0.0 (na)	0.0 (0.0)
21;13	0.0 (na)	Correct	9.7 (4.6)	0.0 (na)	3.2 (5.8)
21;21	0.0 (na)	0.0 (1.0)	0.0 (0.0)	0.0 (na)	0.0 (0.0)
21;23	7.7 (na)	10.9 (13.0)	6.5 (1.5)	3.7 (na)	22.6 (11.5)
21;31	0.0 (na)	4.3 (5.0)	0.0 (1.5)	25.9 (na)	3.2 (1.9)
21;32	0.0 (na)	0.0 (1.0)	0.0 (0.0)	3.7 (na)	0.0 (0.0)
23;12	0.0 (na)	2.2 (0.0)	9.7 (0.0)	3.7 (na)	3.2 (0.0)
23;13	2.6 (na)	0.0 (2.0)	0.0 (0.0)	7.4 (na)	0.0 (0.0)
23;21	0.0 (na)	0.0 (1.0)	0.0 (0.0)	0.0 (na)	0.0 (1.9)
23;23	0.0 (na)	2.2 (0.0)	0.0 (0.0)	0.0 (na)	0.0 (0.0)

(Continued)

	Centre-Embedded		*Right-Branching*		
Response	*Subject-Relative (CES) %*	*Object-Relative (CEO) %*	*Subject-Relative (RBS) %*	*Object-Relative (RBO) %*	*Conjoined (C) %*
23;31	0.0 (na)	2.2 (0.0)	0.0 (0.0)	0.0 (na)	0.0 (0.0)
23;32	0.0 (na)	0.0 (0.0)	0.0 (0.0)	0.0 (na)	0.0 (0.0)
31;12	2.6 (na)	2.2 (5.0)	3.2 (3.1)	0.0 (na)	0.0 (0.0)
31;13	0.0 (na)	0.0 (0.0)	0.0 (0.0)	0.0 (na)	0.0 (0.0)
31;21	0.0 (na)	2.2 (1.0)	3.2 (3.1)	3.7 (na)	0.0 (0.0)
31;23	0.0 (na)	0.0 (1.0)	0.0 (0.0)	0.0 (na)	0.0 (1.9)
31;31	0.0 (na)	0.0 (0.0)	0.0 (0.0)	0.0 (na)	0.0 (0.0)
31;32	0.0 (na)	0.0 (0.0)	0.0 (0.0)	0.0 (na)	0.0 (1.9)
32;12	0.0 (na)	2.2 (0.0)	0.0 (0.0)	0.0 (na)	0.0 (0.0)
32;13	0.0 (na)	0.0 (0.0)	0.0 (0.0)	0.0 (na)	0.0 (0.0)
32;21	0.0 (na)	0.0 (2.0)	0.0 (1.5)	3.7 (na)	0.0 (0.0)
32;23	0.0 (na)	0.0 (0.0)	0.0 (0.0)	0.0 (na)	0.0 (0.0)
32;31	0.0 (na)	0.0 (1.0)	0.0 (1.5)	0.0 (na)	0.0 (1.9)
32;32	0.0 (na)	0.0 (1.0)	0.0 (0.0)	0.0 (na)	0.0 (0.0)
Total number of errors[a]	39 (na)	46 (101)	31 (65)	27 (na)	31 (52)

[a]Lexical errors and incomplete responses are excluded from the analysis.