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Cognitive Processes in Verbal-Number Production: Inferences From the Performance of Brain-Damaged Subjects

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This article presents a model of the cognitive processes involved in the spoken production of verbal numbers (e.g., thirteen thousand four hundred two). On the basis of single-case studies of two brain-damaged subjects with number production deficits, we argue that verbal-number production involves the generation of a syntactic frame that constitutes a plan for the production of the appropriate sequence of words. The syntactic frame specifies each to-be-retrieved word in terms of a number-lexical class (i.e., ones, teens, or tens) and a position within that class. These class/position-within-class specifications guide the retrieval of lexical representations from a production lexicon that is partitioned into functionally distinct ones, teens, and tens classes. We conclude with a brief discussion of the rationale for, and advantages of, using patterns of impaired performance as a basis for drawing inferences about normal cognition.

Traditionally, cognitive psychologists have relied almost exclusively on data from normal subjects in formulating and testing cognitive theories. However, recent years have seen a growing realization that the performance of subjects with acquired cognitive deficits also represents a rich source of information about normal cognitive processes. In essence, a pattern of impaired performance may be brought to bear on questions concerning normal cognition by asking, What must the normal cognitive system be like such that damage to the system could result in just this pattern of performance? (See e.g., Caramazza, 1984, 1986; Shallice, 1979.) This approach, which involves the detailed analysis of single cases, has proved fruitful in several areas, including reading (e.g., Beauvois & Dérouésne, 1979; Caramazza, Miceli, Silveri, & Laudanna, 1985; Patterson, 1982), sentence processing (e.g., Miceli, Mazzucchi, Menn, & Goodglass, 1983), and writing (e.g., Ellis, 1982, in press; Goodman & Caramazza, 1986; Patterson, in press).

In this article we present single-case studies of two brain-damaged subjects in support of claims about the cognitive processing of numbers. Numbers, like sentences, are sequences of symbols generated and interpreted in accord with syntactic and semantic rules. Thus, many of the issues arising in the study of sentence processing have counterparts in the realm of number comprehension and production. For example, how in number comprehension is a sequence of digits or words processed to generate an internal representation of the number as a whole? And how in number production is an internal representation transformed into the appropriate sequence of digits or words?

The cognitive processes implicated in number comprehension and production are of interest first because numbers are involved in a wide variety of everyday activities (e.g., writing a check, telling time, using the telephone, reading sports scores in a newspaper). Also, an understanding of number comprehension and production has relevance for several number-related areas of research, including research on calculation (e.g., Ashcraft & Battaglia, 1978; Ashcraft & Stazyk, 1981; Groen & Parkman, 1972), research in clinical neuropsychology on the classification, diagnosis, and treatment of number processing and calculation deficits (for reviews, see Boller & Grafman, 1983 and Levin & Spiers, 1985), and developmental research on the acquisition of number concepts, number words, and counting (e.g., Fuson, Richards, & Briars, 1982; Gelman & Gallistel, 1978; Piaget, 1965; Siegler & Robinson, 1982). In the developmental research, for example, knowledge about the endpoint of the development process is clearly important.

Finally, studies of number processing may have implications for research on language in general. As we have noted, the number systems, like languages, are symbolic systems. In contrast to natural languages, however, the number systems have circumscribed sets of basic symbols and relatively straightforward syntax. Thus, the number domain offers the opportunity to study the generation and interpretation of symbol strings within the context of naturally occurring yet relatively simple symbolic systems. Detailed analyses of the processing mechanisms for these simple systems may offer insights into the more complex language-processing mechanisms (e.g., with regard to issues of lexical representation and retrieval), although caution must of course be exercised in generalizing from numbers to language in general.

In spite of these points of interest, the cognitive mechanisms for number comprehension and production remain largely un-

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explored. Although some studies of similarity and relative magnitude judgments involving numbers have been reported (e.g., Moyer & Landauer, 1967; Shepard, Kilpatric, & Cunningham, 1975), for the most part, neither these studies nor the previously cited research on calculation, number-processing deficits, and number acquisition have focused explicitly on the cognitive processes underlying number comprehension or number production. Our specific aim in this article is to propose a cognitive model of number production. We begin by describing the general model of the cognitive number-processing system that provides the framework for our research.

Cognitive Mechanisms in Number Processing

McCloskey, Caramazza, & Basili (1985; see also Caramazza & McCloskey, in press; McCloskey & Caramazza, in press) have argued that the cognitive mechanisms for number processing comprise several functionally distinct components. At the most general level, their model distinguishes the components for number comprehension from those for number production. Within the comprehension and production components, a further distinction is drawn between components for processing Arabic numbers (i.e., numbers in digit form, such as 4,029) and components for processing verbal numbers (i.e., numbers in the form of words, such as *four thousand twenty-nine*).

The Arabic- and verbal-number comprehension components serve to convert numerical inputs into internal representations for subsequent processing (e.g., comparing two basketball scores to determine which team won, deciding whether a price is reasonable, calculating a tip at a restaurant). The number-production components translate internal representations of numbers into Arabic or verbal form for output.

The internal representations of numbers are assumed to take the form of semantic representations specifying the basic quantities in a number, and the power of ten associated with each. For example, the internal representation of the Arabic number 8,043 or the verbal number *eight thousand forty-three* might take the form {8}10EXP3, {4}10EXP1, {3}10EXP0. The digits in braces stand for semantic representations of the basic quantities in the number, and 10EXP*n* indicates the power of ten associated with each quantity. EXP signifies "exponent," so that 10EXP3, for example, stands for 10 to the third power, or thousand. (This particular notation is adopted merely to avoid confusion between semantic representations of numbers, and numbers in the form of digits or words. The important assumption is that the semantic representation specifies the basic quantities in a number, and their associated powers of ten.)

These assumptions about the general architecture of the cognitive number-processing mechanisms were motivated in part by patterns of dissociations observed in brain-damaged subjects (e.g., Caramazza & McCloskey, in press; McCloskey & Caramazza, in press; McCloskey et al., 1985). For example, dissociations of Arabic- and verbal-number processing (i.e., impairments in the processing of Arabic but not verbal numbers, and vice versa) have been reported, supporting the distinction between Arabic- and verbal-number processing components.

In this article we, focus on the verbal-number production component, with the aim of developing an explicit model of the cognitive processes implicated in spoken production of verbal numbers. According to the general model we have outlined, the verbal-number production process accepts as input a semantic representation of a number, and generates as output the sequence of words making up the verbal form of the number. Given the semantic representation {8}10EXP3, {4}10EXP1, for example, the production process would generate the sequence of words *eight thousand forty*. We assume that in the case of spoken number production, the production process generates phonological representations of number words, and that these representations serve as input to general speech production mechanisms. Thus, our goal is to specify how the verbal-number production process generates the appropriate sequence of phonological number-word representations from an input semantic representation.

Linguistic Structure of Verbal Numbers

Given this goal, it is worthwhile to consider briefly the linguistic structure of verbal numbers in the English language. (For further discussion, see Hurford, 1975, Menninger, 1969, and Power & Longuet-Higgins, 1978.) An appreciation of this structure helps to make clear the nature of the input–output mappings that a verbal-number production process must be capable of computing. Furthermore, the rich lexical and syntactic structure of verbal numbers may well be reflected in the cognitive mechanisms for verbal-number production.

In the verbal number system the words *one* through *nine*, which we will call the "ones" words, represent the basic quantities 1 through 9. In contrast, the "tens" words (i.e., *twenty, thirty, forty, . . . , ninety*) represent basic quantities times ten. Numbers including both tens and ones are represented by combining the appropriate tens word with the appropriate ones word (e.g., *thirty-six*). The single exception to this rule concerns numbers involving one ten and some ones. The verbal number system does not include a word for one ten that combines with ones words to represent one ten and some ones—there is no word like *onety* that combines with ones words to produce numbers like *onety-six*.

Instead, numbers made up of one ten and some ones are represented by a special set of words, the "teens" words. For instance, the number consisting of one ten and two ones is represented by the word *twelve*, and the number made up of one ten and six ones is represented by the word *sixteen*.

To represent numbers larger than ninety-nine, the verbal number system associates ones, teens, and tens words with "multiplier" words such as *hundred, thousand,* and *million*. The basic unit in a verbal number is the sequence, ONES–hundred–TENS–ONES (e.g., *six hundred thirty-seven*). In this unit the word *hundred* serves as a multiplier for the preceding ones word. Of course, in any given unit, some elements may not be present, as in *six hundred seven* (in which there is no tens word). Further, the sequence TENS–ONES may be replaced by TEENS, as in *six hundred seventeen*.

Whereas *hundred* acts as a multiplier for a single word, the multipliers *thousand, million, billion,* and so forth, multiply entire units. For example, in the number *six hundred thirty-seven* *thousand, thousand* multiplies the entire unit *six hundred thirty-seven.*

A complete number is represented simply by assembling the basic units, with their associated multipliers, in order of decreasing magnitude. Thus, the number 634,546,321 is represented by arranging the following units in this order: [(six) hundred thirty-four] million; [(five) hundred forty-six] thousand; [(three) hundred twenty-one]. The grouping marks show the scope of the multipliers; each multiplier applies to the expression enclosed by the set of grouping marks to its immediate left. Thus, in the millions unit, *hundred* multiplies *six,* and *million* multiplies the entire unit.

This description of the syntactic structure of verbal numbers applies to the "standard" way of representing numbers in verbal form. For numbers less than ten thousand, an alternative syntactic structure may also be used. In this alternative structure the basic unit is TENS–ONES, and *hundred* serves as a multiplier for an entire unit. Thus, for example, in *thirty-four hundred twenty-seven,* the two basic units are *thirty-four* and *twenty-seven,* and *hundred* multiplies the entire unit *thirty-four.* This article focuses on the standard verbal-number representations, although the model we will present could readily be extended to the alternative representations.

Having considered briefly the linguistic structure of the word sequences comprising verbal numbers, we may ask how these sequences of words are generated from semantic representations. The single-case studies to which we now turn were aimed at addressing this question.

Study 1: Subject HY

HY, a right-handed man, suffered a left-hemisphere cerebrovascular accident (CVA) in December, 1981, at the age of 66. He has a ninth-grade education, and owned and ran a construction company until the time of his CVA. HY reports that many aspects of his work involved dealing with numbers and that he had no difficulty with numbers prior to the CVA. HY's speech is fluent, although he has word-finding difficulties that are apparent in conversation as well as in formal testing. A brief case history, with more specific neurological and language assessment information, is presented in Appendix A.

HY was tested from April through September 1984 in weekly 2-hr sessions during which he performed a variety of number-processing tasks. This report focuses on results from a task chosen to probe the verbal-number production process. In this task, Arabic numbers ranging in size from 1 to 7 digits were presented one at a time, and HY read each number aloud (e.g., stimulus 7,452, response "seven thousand four hundred fifty-two").

During the 6-month testing period, HY read aloud almost 5000 Arabic numbers, with an error rate of approximately 14%. Examples of his errors are presented in Table 1. Nearly all of HY's incorrect responses were lexical substitution errors in which one or more incorrect number words were produced in place of the correct words. For example, in HY's response of "nine hundred six" to the stimulus 902 the incorrect word *six* was produced in place of the correct word *two.*

Table 1
Examples of HY's Errors in Reading Arabic Numbers Aloud

Stimulus	Response
5	<u>seven</u>
1	<u>five</u>
17	<u>thirteen</u>
29	<u>forty</u>-nine
317	three hundred <u>fourteen</u>
902	nine hundred <u>six</u>
5,450	five thousand four hundred <u>seventy</u>
5,718	five thousand <u>one</u> hundred <u>sixteen</u>
14,840	<u>sixteen</u> thousand eight hundred forty
30,260	thirty thousand two hundred <u>fifty</u>
940,711	nine hundred <u>twenty</u> thousand <u>five</u> hundred eleven
312,320	three hundred <u>sixteen</u> thousand three hundred twenty

Functional Locus of Impairment

In exploring the implications of HY's number-reading errors for models of normal number processing, the first step is to ask which of the cognitive processes involved in reading Arabic numbers is disrupted. Our working model of the number-processing system assumes that reading an Arabic number aloud implicates the Arabic number comprehension process, which generates a semantic representation of the number, and the verbal-number production process, which transforms the semantic representation into the appropriate sequence of phonological number-word representations.

HY's number-reading errors could, then, stem from disruption of Arabic-number comprehension, verbal-number production, or both. Considering first the possibility of a comprehension impairment, HY's errors could reflect impaired encoding of individual Arabic digits (resulting from disruption of the comprehension process per se, or from some impairment of visual perception). For example, when presented with 902, HY may have misinterpreted the 2 as a 6, resulting in the generation of the semantic representation {9}10EXP2, {6}10EXP0. From this incorrect semantic representation, a properly functioning verbal-number production process may have generated the sequence of phonological representations /nine/ /hundred/ /six/, resulting in production of the spoken response "nine hundred six."

On the other hand, HY's comprehension of the Arabic stimuli may be intact, and his errors may result from disruption of the verbal-number production process. The production process, operating on a correct semantic representation, may have occasionally generated a sequence of phonological number-word representations in which one or more of the words was incorrect. For example, from the stimulus 902 an intact Arabic comprehension process may have generated the correct semantic representation {9}10EXP2, {2}10EXP0. However, a disrupted verbal-number production process may have assembled the sequence /nine/ /hundred/ /six/, which contains the incorrect phonological representation /six/ in place of the correct representation /two/.

To assess whether HY was impaired in digit comprehension, number-word production, or both, we tested him on several number-processing tasks. The results indicated intact digit comprehension and impaired number-word production, and hence suggested that HY's errors in reading aloud Arabic numbers reflect a deficit in spoken verbal-number production.

Tests of Arabic-Digit Comprehension

Magnitude comparison. In this task, a pair of Arabic numbers was presented visually and HY was asked to indicate which number was larger. In each of three testing sessions an 18-item list was presented. The list comprised nine pairs of single-digit numbers (e.g., 6 vs. 7), eight pairs of multidigit numbers (i.e., two- to six-digit numbers, such as 405,960 vs. 400,965), and one "mixed" pair (14 vs. 9). Except for the mixed pair, the two numbers in a pair had the same number of digits. HY responded rapidly and correctly to all items on each of the three presentations.

Selection of tokens. In this task a digit was presented visually, and HY was asked to select the corresponding number of tokens (plastic chips) from a pile. Across several testing sessions the digits 1 through 9 were presented eight times each. HY gave the correct response for 71 of the 72 items (99%).

Arabic–verbal matching. For this task two 81-item lists were presented visually. In the Arabic-to-verbal list each item consisted of an Arabic stimulus number and a multiple-choice list of four number words (e.g., the number 14 with the choices *nineteen, four, fourteen,* and *sixteen*). The 81 Arabic stimuli comprised three repetitions (in random order) of the 27 positive integers that are represented by single words (i.e., 1–19, 20, 30, . . . , 90). The response words in the multiple-choice lists were drawn from the corresponding 27 words. A verbal-to-Arabic list was constructed in the same way, except that each item consisted of a verbal stimulus number followed by a multiple-choice list of four Arabic numbers. On each of the two lists HY chose the correct response for 80 of the 81 items (99%).

Arithmetic verification. Addition and subtraction problems involving one- and two-digit Arabic numbers were presented visually with a correct or incorrect answer (e.g., 14 + 9 = 23, 6 + 7 = 14), and HY was asked to indicate whether the supplied answer was right or wrong. Over several testing sessions 120 problems were presented, half with correct and half with incorrect answers. HY gave the correct response for 119 of the problems (99%).

Taken together, the results for these four tasks suggest that HY's ability to comprehend Arabic digits is largely intact, and hence that his errors in reading Arabic numbers aloud do not reflect impaired comprehension of the stimulus numbers.

Tests of Spoken-Number-Word Production

Addition. Addition problems involving one- and two-digit addends were presented (e.g., 4 + 9, 17 + 18), and HY was asked to say the answer aloud, or (in separate blocks of trials) to write the answer in Arabic form. Across several testing sessions, three sets of 20 problems were each presented several times for spoken responses and several times for written responses, for a total of 220 spoken and 140 written responses. Problems were presented visually in Arabic form with the addends arranged horizontally (e.g., 25 + 10), and HY was asked to compute the entire answer in his head before writing or saying it.

HY's error rate was higher for spoken responses (8.6%) than for written responses (2.1%). A sign test comparing the error rate for spoken versus written responses to each of the 60 problems revealed that this difference was reliable, $z = 1.98, p < .05$. We assume that the spoken- and written-response tasks involve the same cognitive processes (i.e., encoding of the problem, calculation of the sum) except in the response production stage, where the spoken response task involves spoken verbal-number production, and the written response task involves Arabic-number production. Given this assumption, a difference between tasks in error rate can be attributed only to the difference in response production processes. The significantly higher error rate for spoken than for written responses thus points to an impairment in spoken verbal-number production. (The small number of errors for written Arabic responses in this task, and the tasks described below, may reflect a mild impairment in production of Arabic numbers.)

The incorrect spoken responses were interpretable as lexical substitution errors stemming from a deficit in spoken production of number words, and many could not readily be construed as the result of errors in performing a calculation. For example, HY's response "twenty-four" to the problem 80 + 4 is unlikely to be an error in computing the sum of 80 and 4, but may be interpreted as resulting from the substitution of "twenty" for "eighty" during production of the spoken response.

Reading written verbal numbers aloud. Individual number words (e.g., *thirty*) were presented visually, and HY was asked to read the number aloud or to write it in Arabic form (i.e., 30). Across several testing sessions, a 28-item list comprising the ones, teens, and tens words, and zero, was presented 11 times for spoken responses and 11 times for written responses.

When reading number words aloud, HY made the same sorts of errors as in reading Arabic numbers (e.g., *three* read as "five," *ninety* read as "seventy"). Furthermore, his error rate was higher for spoken responses (8.1%) than for written responses to the same words (2.6%). The difference in error rate was reliable by sign test, $z = 2.02, p < .05$, again suggesting a deficit in spoken-number-word production.

General knowledge questions. General knowledge questions with numerical answers (e.g., How many states are there in the United States?) were presented aurally, and HY was asked to give a spoken or written (Arabic) response. Twelve different questions were presented, all but one of which (How many days are there in a year?) required production of a one- or two-word response. Across several testing sessions, each question was presented four times for a spoken response and four times for a written response, except for the number-of-days-in-a-year question, which was presented six times for a spoken response and five times for a written response. For the spoken responses, HY made seven errors (14%). For example, he said "twenty-three" in response to "What day of December is Christmas?" For the written responses HY made two errors (4.1%). Although the spoken–written difference is not statistically reliable, the pattern is the same as in the transcoding and addition tasks. Further, the results for the number-of-days-in-a-year question, the only item that required production of several number words, strongly suggest a deficit in the production of spoken number words. HY correctly produced "365" on all five of the occasions on which a written response was requested, indicating that he understood the question and knew the answer. Nevertheless, four of his six spoken responses were incorrect (i.e., "three hundred forty-two," "three hundred sixty-three," "three hundred sixty-seven," and "three hundred fifty-four").

A final indication that HY is impaired in spoken-number-word production is the informal observation that on tasks that did not require spoken responses he often said aloud an incorrect response while writing or otherwise indicating the correct response. For example, when asked to write the answer to the question, How many eggs are there in a dozen?, HY said "sixteen" while writing 12; and when presented with the multiplication problem 2×5, HY said "eight times five" but wrote the correct answer 10.

The combination of excellent performance on tests of digit comprehension and impaired performance on tests of spoken-number-word production suggests that HY's errors in reading Arabic numbers aloud resulted not from a deficit in Arabic-number comprehension, but rather from an impairment of spoken-verbal-number production. As we discuss in a later section, the data from the Arabic-number-reading task itself provide further support for this conclusion.

It is also worth noting here that the results for the spoken-number production tasks support an assumption that is implicit both in our use of these tasks to identify the source of HY's number-reading errors, and in our use of the Arabic-number-reading task to study verbal-number production mechanisms. Specifically, the finding that HY made the same sorts of errors in responding orally to addition problems, reading number words aloud, and answering numerical knowledge questions as in the Arabic-number-reading task supports our assumption of a general verbal-number production process that is used not only in reading Arabic numbers aloud, but also in other situations requiring spoken production of verbal numbers.

Given the conclusion that HY is impaired in spoken-verbal-number production, we may ask what his performance can tell us about the cognitive mechanisms implicated in the production process. To answer this question, we must look more closely at the Arabic-number-reading task.

The Arabic-Number-Reading Task

Method

Several lists of Arabic numbers were each presented several times to be read aloud. The stimulus numbers were printed one per line in large type, centered on the line. A masking sheet was used during testing to ensure that only one stimulus was visible at a time. The task was untimed, and HY was under no pressure to respond quickly.

The stimulus lists differed primarily in the orders of magnitude included—for example, some lists contained only one- and two-digit numbers, whereas others included one- through six-digit numbers. For most lists, the digits making up a stimulus number were chosen at random, with certain constraints. Some lists were constructed so that each of the digits 0 through 9 occurred equally often; other lists were generated so that each of the ones, teens, and tens words occurred equally often in the correct verbal responses to the Arabic stimuli. Lists varied in length from 28 to 200 items. For most lists two random orders of the stimulus numbers were generated, and on each presentation of a list the pages making up the list were arranged in a different random order. The list context in which a number appeared (i.e., the nature of the other numbers in the list) had no discernible effect on HY's performance. Hence, in the following discussion we present results collapsed across stimulus lists.

Table 2
HY's Percentage of Incorrect Responses in the Arabic-Number-Reading Task as a Function of the Number of Digits in the Stimulus

Number of digits	Total presented	% Error
1	772	3.5
2	1,286	6.5
3	1,561	13.5
4	702	26.2
5	427	28.3
6	223	30.5
7	18	5.6

Results

Over the 6-month testing period, HY read a total of 4,989 Arabic numbers aloud, with an error rate of 13.9%. Table 2 presents HY's error rate as a function of the number of digits in the stimulus. The low error rate for seven-digit numbers probably reflects the fact that the seven-digit stimuli (but not the stimuli of lower orders of magnitude) had 0s in all but the leftmost position (e.g., 5,000,000), so that production of only two words (e.g., *five million*) was required.

Of the 694 total incorrect responses, 654 (94.2%) were lexical substitution errors, in which one or more incorrect number words were produced in place of the correct words (e.g., stimulus 29, response "forty-nine"). The remaining 40 incorrect responses (e.g., stimulus 503,300, response "fifty thousand three hundred thirteen") involved other types of errors instead of or in addition to lexical substitutions. The following discussion focuses on the lexical substitution errors; the other errors are listed in Appendix B.

Lexical substitution errors occurred for numbers of all magnitudes, and at each of the positions in a number (see Table 1 for examples). The probability of error did not vary systematically with position in the number (e.g., hundreds position vs. thousands position). However, the likelihood of producing any individual word incorrectly increased slightly with the number of digits in the stimulus number. For example, the probability of producing a particular word incorrectly was 5.0% for two-digit stimuli, and 7.9% for six-digit stimuli.

In examining the lexical substitution errors, we first asked whether these errors represented responses to a digit present somewhere in the stimulus number. That is, when HY said "fifty" instead of the correct word "seventy," did he do so because the digit 5 appeared elsewhere in the stimulus? The answer was clearly no. Words (e.g., *fifty*) corresponding to a particular digit (e.g., 5) were no more likely to occur as errors when

	zero	one	two	three	four	five	six	seven	eight	nine	ten	eleven	twelve	thirteen	fourteen	fifteen	sixteen	seventeen	eighteen	nineteen	twenty	thirty	forty	fifty	sixty	seventy	eighty	ninety
zero	64																											
one		615	15		1	5		2	3	2	1																	
two		10	649	1	7	1	14	1	2	1	1																	
three			14	618	2	27	8	10	3	1		1										2						
four		1	1	2	653	3	7	7	8	3																		
five		1	2	4	9	646	3	17	6	5	1					2												
six			8	3	7	4	649	1	17	1															1			
seven		7	1	1	12	10	2	624		13																5		
eight		1	3	2	8	9	17	7	607	2																		
nine			1		2	2	4	12	1	615	2																	
ten		1	1					1			181				2		1			1	1							
eleven										1	1	158		1	1	1		2										
twelve							1				1		154	1	4	1	30		1		1							
thirteen												2		172		1	3	7										
fourteen													1		164		2	3	1	1								
fifteen											4	2		1	1	129	3	8										
sixteen													1				151	1	2									
seventeen												1		1	4	1		135	2	2								
eighteen													1				11	1	137	2								
nineteen											1	1			1		4	5	2	150								1
twenty			1				2				1		1								263	4	4	3	9		3	
thirty						1		1	1					2							2	277		8	3	3	3	
forty					3										3						7	2	277	1		5	2	2
fifty						1					4					1					3	6	4	266	5	7		
sixty																	1				7	1	1	2	277		3	
seventy								4										1					7	4	2	263	2	1
eighty																			1		3	1	6	1	10	4	247	3
ninety										1											1		1	5	2	10	3	269

Figure 1. Word confusion matrix for subject HY. (Rows represent the correct words and columns represent the words produced by HY.)

the digit was present in the stimulus than when the digit was not present. For example, words corresponding to the digit 5 comprised 11.4% of the lexical substitution errors for stimuli that contained a 5, and 12.5% of the errors for stimuli that did not contain a 5.

More interesting results emerged from an analysis exploring the relation between the incorrect words produced by HY and the corresponding correct words. In this analysis, HY's responses were compared word by word with the correct responses. Consider, for example, HY's response to the stimulus 374:

> HY's response: "five hundred seventy-four";
> Correct response: "three hundred seventy-four."

A word-by-word comparison for this response reveals that in place of the correct word "three," HY said "five." The remaining words (i.e., *hundred, seventy, four*) were produced correctly.

The 40 incorrect responses that were not simple lexical substitution errors (e.g., stimulus 808, response "eighty-eight") were excluded from this analysis, because a word-by-word comparison is not meaningful for these responses. Thus, the analysis included 4,949 of the 4,989 total responses (99.2%), and 654 of the 694 erroneous responses (94.2%).

Figure 1 presents a confusion matrix constructed from the word-by-word comparisons. The rows represent the correct response words, and the columns represent the words produced by HY. For example, the row for the word "two" indicates that when the correct response word was "two," HY never said "zero," but said "one" 10 times, "two" 649 times, "three" once, and so forth. The matrix presents results for the ones, teens, and tens words, and zero; results for the multiplier words (e.g., *hundred, thousand*) will be discussed later.

A total of 10,130 response words are tabulated in the confusion matrix; 720 of these words (7.1%) are errors (e.g., "five" produced in place of "three" for the stimulus 374). Note that the unit of analysis is now the individual word and not the entire response to a stimulus number. Thus, whereas HY gave an incorrect response to 13.9% of the 4,989 stimulus numbers, only 7.1% of the 10,130 words he produced were incorrect. Similarly, whereas 694 of the incorrect responses to stimuli were lexical substitution errors, these 694 errors included 720 incorrect words (i.e., some responses included two or more substitutions of an incorrect word for a correct word).

Inspection of the confusion matrix reveals a striking pattern: HY's errors are not evenly distributed across the possible incorrect response words. Rather, the errors fall into three distinct clusters: a ones cluster, a teens cluster, and a tens cluster. When the correct word was a ones word (i.e., between one and nine), 367 of the 384 incorrect words produced by HY (96%) were also ones words. Thus, for example, when the correct word was "six," HY sometimes said "two" or "three" or "eight," but not "twelve" or "fifty." When the correct word was a teens word (i.e., between ten and nineteen), 132 of HY's 138 errors (96%) were also teens words. For example, when the correct word was "thirteen," HY sometimes said "sixteen" or "seventeen," but not "four" or "twenty." Finally, when the correct word was a tens word (i.e., *twenty, thirty, forty, . . . , ninety*), 166 of HY's 196 errors (85%) were also from the tens set. For example, when the correct word was "sixty," HY sometimes said "twenty" or "eighty," but not "nine" or "seventeen."

Within each of the three error clusters, the incorrect words showed little or no tendency to be close in magnitude to the corresponding correct words. For example, when the correct word was four, HY was no more likely to say "five" than "eight" or "nine."

The pattern in HY's errors is apparent in the examples shown in Table 1. For instance, HY produced "five thousand one hundred sixteen," in response to the stimulus 5,718, thereby substituting "one" for "seven," and "sixteen" for "eighteen."

What must we assume about the normal verbal-number production process to account for this pattern of performance? In the following sections we present a model of spoken-verbal-number production, and argue that the clustering of HY's errors, as well as other aspects of his performance, provide support for the model's major assumptions.

Table 3
Number-Lexical Classes in the Phonological Production Lexicon

Ones	Teens	Tens
—	ten	—
one	eleven	—
two	twelve	twenty
three	thirteen	thirty
four	fourteen	forty
five	fifteen	fifty
six	sixteen	sixty
seven	seventeen	seventy
eight	eighteen	eighty
nine	nineteen	ninety

A Model of Spoken-Verbal-Number Production

The model we present constitutes a modification and extension of ideas discussed by McCloskey et al. (1985), Caramazza and McCloskey (in press), and McCloskey and Caramazza (in press). The major assumptions of the model concern the representations of number words in the phonological production lexicon (i.e., the store of phonological word representations used in the production of spoken language), and the processes that determine from an input semantic representation which particular words should be retrieved from the production lexicon.

The Phonological Production Lexicon

We assume that within the phonological production lexicon, the representations of the basic number words (i.e., one, two, . . . , eighty, ninety) are partitioned into three functionally distinct classes, as shown in Table 3. The ones class contains phonological representations of the words *one* through *nine*, the teens class contains phonological representations of the words *ten* through *nineteen*, and the tens class contains phonological representations of the words *twenty, thirty*, and so forth, up to *ninety*. Retrieval of a phonological representation (e.g., /fifty/) thus involves addressing the appropriate lexical class (e.g., tens), and the appropriate position within the class.

We further assume that the production lexicon includes, distinct from the representations of the basic number words, a multiplier class containing phonological representations of the multiplier words *hundred, thousand, million*, and so forth.

The Production Process

We hypothesize that the spoken-verbal-number production process is a three-stage procedure that culminates in the retrieval of the appropriate phonological representations from the lexicon. When the verbal-number production system receives a semantic representation of a number, the largest power of ten in the number is identified, and on this basis a "syntactic frame" is generated. Consider, for example, the semantic representation {4}10EXP3, {6}10EXP2, {3}10EXP1, corresponding to the Arabic stimulus number 4,630. From this input, the following frame would be generated:

[ONES:___] MLT:T [[ONES:___] MLT:H TENS:___ ONES:___]
"10EXP3" "10EXP2" "10EXP1" "10EXP0".

This frame specifies, among other things, that for numbers in which 10EXP3 is the largest power of ten, the generalized verbal form is a ones word, followed by the multiplier *thousand*, followed by a ones word, and so forth.

After the syntactic frame is generated, each basic quantity in the input semantic representation is assigned to the appropriate slot in the frame. This filling of the frame is guided by the syntactic category labels beneath each slot. For example, the label under the leftmost slot specifies that this slot should be filled with the quantity associated with 10EXP3 (i.e., {4}). Thus, for 4,630 the filled frame takes the following form:

[ONES:{4}] MLT:T [[ONES:{6}] MLT:H TENS:{3} ONES:___]
"10EXP3" "10EXP2" "10EXP1" "10EXP0".

The filled syntactic frame represents a plan for production of the sequence of words comprising the verbal form of the number. (See, e.g., Garrett, 1980, for a discussion of planning structures in sentence production.) The particular phonological number-word representations to be retrieved from the production lexicon are specified in a manner reflecting the organization of these representations in the lexicon. For each filled slot the class label (e.g., ONES) indicates the number-lexical class, and the quantity representation (e.g., {4}) identifies the position within class. Thus, for example, the leftmost slot specifies retrieval of the phonological representation /four/. An empty slot (such as the "10EXP0" slot in the frame shown above) indicates that no phonological representation should be retrieved.

Multiplier words are specified in terms of the multiplier class (abbreviated MLT in our depictions of syntactic frames) and the particular item within that class. In the frame shown above, the MLT:T and MLT:H represent instructions for retrieval of the phonological representations /thousand/ and /hundred/, respectively.

The final step in the production process is thus the retrieval of the phonological representations specified by the filled syntactic frame. In the present example, the retrieval process would yield the sequence /four/ /thousand/ /six/ /hundred/ /thirty/.

The lexical retrieval stage proceeds as described, unless a {1} is encountered in a tens-class slot. In this event, a special "teens" procedure is invoked. This procedure does not retrieve a phonological representation from the tens class, but instead proceeds to the next slot and pairs the quantity value in that slot with the class label TEENS, in order to address a phonological representation in the teens class. For example, for the filled frame shown below the teens procedure would generate TEENS: {3}, so that the lexical retrieval stage would yield the sequence /six/ /hundred/ /thirteen/.

[[ONES:{6}] MLT:H TENS:{1} ONES:{3}]
"10EXP2" "10EXP1" "10EXP0"

If the slot that specifies the position within the teens class is empty (as it would be for 610), then the teens procedure generates the specification TEENS:{0}, leading to the retrieval of /ten/.

Finally, one additional assumption about multipliers and empty slots is needed. The *brackets* in the syntactic frame indicate the slots to which the multipliers apply. If all slots within the scope of a multiplier are empty, then the multiplier word is omitted. Consider, for example, the filled frame for the number 4,023:

[ONES:{4}] MLT:T [[ONES:___] MLT:H TENS:{2} ONES:{3}]
"10EXP3" "10EXP2" "10EXP1" "10EXP0".

The multiplier hundred applies only to the ones slot to its immediate left. Because this slot is empty, the phonological form /hundred/ is not retrieved. Thus, the retrieval process yields the sequence /four/ /thousand/ /twenty/ /three/. Similarly, multipliers that apply to entire units (e.g., *thousand, million*) are omitted when all slots in the unit are empty. For example, in the case of the number 3,000,789, all of the slots within the scope of the multiplier *thousand* would be empty, and consequently /thousand/ would not be retrieved.

The verbal-number production process posited by the model will generate the correct verbal form of any positive integer. Furthermore, the cognitive processes assumed by the model closely reflect the linguistic structure of verbal numbers (see pp. 308–309). The distinction drawn on linguistic grounds among ones, teens, and tens words, and multipliers is captured in the partitioning of the number-word representations in the production lexicon, and in the number production processes that exploit this partitioning. The model also reflects the characterization of the teens words as an exception to a general rule (i.e., the rule that combinations of some tens and some ones are represented by conjoining a tens word with a ones word), in that the teens words are treated as a special case in the number production process. Finally, the linguistic analysis of verbal numbers into units of the form (ONES–hundred–TENS–ONES) is reflected in the assumption that the syntactic frames are divided into these units for purposes of determining whether a multiplier word that applies to an entire unit should be produced or omitted.

Application of the Model to HY's Performance

In the following sections we present our assumptions about the nature of the damage to HY's verbal-number production system, and show that given these assumptions, the proposed model offers a straightforward explanation for the major phenomena evident in HY's number-reading performance.

The Nature of HY's Deficit

We assume that most components of HY's verbal-number production system are intact. He is, we assert, largely unimpaired in generating the syntactic frame and in filling the frame with the appropriate quantity representations (e.g., {4}). Furthermore, in using the syntactic frame to assemble the appropriate phonological number word representations, HY appropriately skips empty slots, omits multipliers when all slots to which they apply are empty, and invokes the teens procedure when a {1} is encountered in a tens slot.

HY's impairment is, we assume, at the level of retrieving phonological number-word representations from the production lexicon—the lexical retrieval process occasionally retrieves a representation other than that correctly specified in the syntactic frame. More specifically, we assume that given a specification of a basic number word (e.g., TENS:{4}), HY's ability is largely intact in using the class label (e.g., tens) to access the specified number-lexical class, but is impaired in using the quantity representation (e.g., {4}) to access the specified position within the class. Thus, for example, given the specification TENS:{4}, the disrupted lexical retrieval process might retrieve /twenty/ or /ninety/, but not /six/ or /eighteen/.

HY's Number-Reading Performance

Clustering of errors. A lexical retrieval process that is intact in addressing number-lexical classes (e.g., tens) but impaired in accessing positions within a class (e.g., the position for the quantity {5}) should lead to lexical substitution errors in which the incorrect words are from the same number-lexical class as the corresponding correct words. This is just what the confusion matrix in Figure 1 shows—HY substituted ones words for ones words, teens words for teens words, and tens words for tens words. Thus, the proposed model provides a straightforward interpretation for the finding that HY's lexical substitution errors fell into well-defined ones, teens, and tens clusters.

The critical feature of this interpretation is the assumption that verbal-number production involves a level of representation at which to-be-retrieved number words are represented in terms of number-lexical class and position within class (e.g., TENS:{3}). This assumption allows us to specify a deficit that would result in the observed pattern of errors (i.e., a deficit in using the position-within-class part of the class/position representations to address phonological representations in the production lexicon).

The error pattern is not merely consistent with the assumption of a class/position-within-class level of representation; in the absence of this assumption the pattern cannot readily be explained. This point may be made clear by considering the apparently simpler interpretation in which HY's errors are attributed to a deficit in encoding the digits in the Arabic stimulus numbers. The encoding deficit account exemplifies a class of potential interpretations in which HY's errors are attributed to disruption at a level of representation involving individual digit or quantity representations not associated with number-lexical class specifications. Thus, the arguments we offer against the encoding deficit hypothesis apply, for the most part, to the class as a whole.

Suppose that when the stimulus 46 was presented, HY encoded the 6 as a 2. The result would be the production of *two* in place of *six,* regardless of how the number production process worked. Similarly, encoding of the 4 as a 7 would lead to substitution of *seventy* for *forty.* In this way, the encoding deficit hypothesis can (for the most part) account for the substitution of ones words for ones words, and tens words for tens words.

The hypothesis cannot, however, explain the results for the teens words. When the correct word in the verbal form of a stimulus number was from the teens class, HY almost always produced a teens word (although not always the correct word; see Figure 1). This result forces an encoding deficit hypothesis to make untenable assumptions about accuracy in the encoding of the digit 1. HY's data include 654 instances in which a 1 in a stimulus number corresponded to the word *one* in the correct verbal form of the number (e.g., 61; 1253; 125,832). HY produced an incorrect ones word (e.g., "sixty-two" in response to 61) for 31 of these instances, or 4.7%. According to the encoding deficit hypothesis, this result implies that a 1 corresponding to the word *one* in the verbal form of a number was encoded incorrectly (e.g., as a 2) 4.7% of the time. (Note that in this analysis, and in fact in all analyses bearing on alternative interpretations of our results, we consider not only the responses tabulated in the confusion matrix shown in Figure 1, but also the responses that were excluded from the word-by-word analysis because the correct response and HY's response included a different number of words.)

The data also include 166 instances in which the digit pair 11 corresponded to the word *eleven* in the correct verbal form of a stimulus number (e.g., 11,527, but not 112). For eight of these instances (4.8%) HY produced an incorrect response (e.g., "thirteen") that, according to the encoding deficit argument, reflected an error in encoding the rightmost *1* in the pair. Pooled, these data include all 1s except those in the tens and ten thousands positions in a stimulus number (i.e., all 1s except those occupying the first position in a teens digit pair), and suggest that these 1s were encoded incorrectly about 4.8% of the time.

An encoding deficit hypothesis provides no basis for expecting a 1 in the tens or ten thousands positions of a number to be encoded more accurately than a 1 in another position. Thus, we would expect a 1 in the tens or ten thousands position (e.g., 215, 318,432) to be encoded incorrectly about 4.8% of the time. If such a *1* is misinterpreted, the result *will* be the production of a tens word and/or a ones word in place of the correct teens word (e.g., *forty-five* produced in place of 15). Hence, on the encoding deficit hypothesis HY should have produced non-teens words in place of about 4.8% of the correct teens words.

In fact, however, HY produced non-teens word(s) in only 10 of the 1,677 instances in which the correct word was a teens word (0.6%). Further, only 6 of these 10 errors could be attributed to an error in encoding the 1 in the tens or ten thousands position. Thus, according to the encoding deficit argument, a 1 in the tens or ten thousands position of a number was encoded incorrectly only 0.4% of the time. The difference in error rate between 1s in the tens or ten thousands position (0.4%) and 1s in other positions (4.8%) is highly reliable, $\chi^2(1, N = 2,497) = 58.67, p < .001$.[1]

This result for 1s cannot be attributed to generally higher accuracy for the tens and ten thousands positions than for other

[1] Note that this use of chi-square does not violate the independence-of-observations assumption, even though all observations are from a single subject. We are using the chi-square test as a basis for conclusions not about processing of 1s in a population of individuals, but rather about HY's ability to process 1s. Thus, what is relevant for our use of chi-square is that the individual data points represent independent observations of HY's ability to process 1s in particular positions of a number. This same point applies to the chi-square tests reported subsequently.

positions in a number. For digits other than 1, accuracy for the tens and ten thousands positions (M = 94.5%) was no higher than for the other positions (94.2%). The higher accuracy for the tens and ten thousands positions occurred, then, only for 1s.

Clearly, it is difficult to maintain that 1s in the tens or ten thousands position of a number were encoded incorrectly less than 0.5% of the time, whereas 1s in other positions were misencoded nearly 5% of the time, especially given that only the digit 1 showed this pattern. Thus, the encoding deficit argument cannot account for the teens results.

In contrast, the model we have proposed provides a straightforward explanation of the results. In our model the quantity representations in a filled syntactic frame are used to address particular positions within number-lexical classes in the phonological production lexicon. For example, a {3} in a tens-class slot is used to retrieve /thirty/ from the tens class, whereas a {3} in a ones-class slot is used to retrieve /three/ from the ones class, or /thirteen/ from the teens class (if the preceding slot is a tens-class slot filled with a {1}). However, a {1} in a tens-class slot has a special status. A {1} in a tens slot (corresponding to a 1 in the tens or ten thousands position of a number, as in 2<u>1</u>7, or <u>1</u>5,283) is not used to address a particular phonological representation within a number-lexical class, but instead specifies that the teens procedure should be invoked. This procedure does not perform a lexical retrieval for the tens slot, but uses the quantity representation in the next slot to address a position in the teens class.

We have assumed that HY is impaired only in retrieving number-word representations from the phonological production lexicon. We assume that he fills the syntactic frame with the correct quantity representations and appropriately invokes the teens procedure when encountering a {1} in a tens slot. Thus, we expect HY to be very accurate in producing teens responses to teens stimuli (which requires a correct quantity representation {1} in the appropriate tens slot, and the appropriate use of this representation to invoke the teens procedure). However, we expect HY to make within-class errors in attempting to retrieve the phonological representations /one/ and /eleven/ (which requires the use of a {1} in a ones slot to address a representation in the production lexicon). As we have seen, the data show just this pattern.

Class errors. In 55 of HY's 720 lexical substitution errors the incorrect word was from a different number-lexical class (i.e., ones, teens, or tens) than the corresponding correct word (see Figure 1). Examination of these "out-of-class" errors provides further support for the proposed model. Thirty-two of the 55 errors (58.2%) were "class errors," in which the number-lexical class was incorrect but the position within class was correct. For example, in response to the stimulus 606, HY said, "six hundred <u>sixty</u>." Other examples of class errors are presented in Table 4.

The class errors cannot be interpreted by assuming that out-of-class errors were randomly scattered over the out-of-class regions of the ONES/TEENS/TENS confusion matrix, and by chance occasionally fell into cells we have designated class-error cells. Only 50 of the 484 out-of-class cells in the confusion matrix (10.3%) correspond to class errors. By chance, then, we would expect about 5 or 6 of the 55 out-of-class errors to fall into the class-error cells. The actual number of class errors (32) is reliably different from the number expected by chance, $\chi^2(1, N = 55) = 139.39, p < .001$.

Table 4
Examples of Class Errors Made by HY in the Arabic-Number-Reading Task

Stimulus	Response
20	<u>twelve</u>
10,019	ten thousand <u>ninety</u>
5	<u>fifteen</u>
7,007	seven thousand <u>seventy</u>
40	<u>four</u>
30,105	<u>thirteen</u> thousand one hundred five

Our model interprets the class errors by assuming that the lexical retrieval process occasionally accessed the wrong number-lexical class but the right position within the class. For example, the substitution of *eighteen* for *eighty* may have occurred when the retrieval process, given the specification TENS: {8}, accessed the position corresponding to the quantity {8} in the teens class instead of the tens class. Thus, the class errors represent further evidence in favor of the claim that verbal-number production involves a level of representation at which to-be-retrieved number words are specified in terms of number-lexical class, and position within class.[2]

The class errors also suggest more specifically that the within-class "address system" (i.e., the means by which a position within class is specified) is the same for all three number-lexical classes. Our model assumes that for each of the three classes, positions within class are addressed on the basis of quantity representations. For example, in ONES:{4}, TEENS:{4}, and TENS:{4}, the quantity representation {4} is used to address a position within the ones, teens, or tens class, respectively. The occur-

[2] Within the framework of our model, class errors are interpreted as errors in retrieving whole-word representations from the phonological production lexicon. Another possibility is that the production lexicon stores morphologically decomposed representations, so that retrieval of a number word involves assembling a base morpheme (e.g., /six/) with a suffix (e.g., /-ty/), with some special provision being made for irregular words such as *twelve*. From this perspective, the class errors could be interpreted as errors in selecting the appropriate suffix (or the appropriate irregular form). For example, the substitution of "sixteen" for "sixty" could be interpreted as the result of assembling the correct base /six/ with the incorrect suffix /-teen/. In the General Discussion we argue against a morphological decomposition hypothesis. However, even if we were to adopt the morphological decomposition hypothesis, our interpretation of the class errors in terms of a class/position-within-class level of representation would not be affected. The morphological decomposition hypothesis presumably would require that to-be-retrieved number words be specified in a form essentially equivalent to our class/position-within-class representations. That is, the base morpheme (e.g., /six/) would be specified in a form equivalent to a position-within-class representation (that is, by a quantity representation such as {6}), and the suffix (e.g., /-ty/) would be specified by a representation equivalent to a number-lexical class representation (e.g., tens).

rence of class errors suggests, consistent with this assumption, that even when the wrong class is accessed (e.g., the ones class for the specification TENS:{4}), the within-class part of the specification can be used to address a position within this incorrect class.

If a class/position-within-class level of representation is not assumed, the class errors are difficult to explain. One might suggest that the class errors actually resulted from transpositions of adjacent digits. For example, the response "forty thousand five hundred seventy" to the stimulus 40,507 could be interpreted by assuming that HY transposed the last two digits. Although this interpretation seems plausible, it ultimately proves inadequate.

Fourteen of the 32 class errors could conceivably be simple transpositions. However, the other 18 class errors pose insurmountable difficulties for a transposition interpretation. For six of the errors (e.g., stimulus 5, response "fifteen") no transposition interpretation can be offered. Furthermore, to interpret the remaining 12 errors, the transposition hypothesis must assume both a transposition and a 0-to-1 or 1-to-0 substitution. For example, to interpret the response of "fifteen" to the stimulus 50, both a transposition and a substitution of 1 for 0 must be assumed. On the transposition interpretation, the joint occurrence of a transposition and a 0/1 error is presumably accidental; there is no basis for assuming that a transposition leads to a 0/1 error, or vice versa. Clearly, then, the interpretation can be maintained only if transpositions unaccompanied by 0/1 errors, and 0/1 errors unaccompanied by transpositions, occurred sufficiently often to warrant the assumption that the two errors happened by chance to occur together on 12 occasions. This is not, however, the case.

The stimuli presented to HY included 2,633 pairs of digits for which the joint occurrence of a transposition and a 0/1 substitution error would have resulted in a response falling into the class-error category. The responses to these digit pairs include only 10 responses interpretable as transpositions without 0/1 errors, and only 3 responses interpretable as 0/1 errors without transpositions. Obviously, it cannot be maintained that two very rare and independent events occurred more often together (12 times) than either occurred alone. (On an assumption of strict independence, the rates at which the two errors occurred separately yield an expected joint occurrence frequency of 1 in 232,000 digit pairs.)

Other potential interpretations of the class errors (e.g., a digit-encoding deficit interpretation) encounter problems of comparable severity. Hence, the class errors point strongly to a level of representation at which to-be-retrieved number words are represented in terms of class and position within class.

Table 5 summarizes the information in the word-confusion matrix (Figure 1), presenting the number of correct response words, within-class errors, class errors, and other errors (i.e., responses that were neither within-class nor class errors) as a function of the lexical class of the correct word. It is apparent from the table that the vast majority of HY's lexical substitution errors (i.e., 697 of 720, or 97%) were either within-class errors, interpretable as the result of accessing the wrong position within the correct number-lexical class, or class errors, interpretable as the outcome of accessing the correct position within the wrong class.

The digit 0. The results for the digit 0 provide an opportunity to evaluate additional predictions of the proposed model. We have assumed that semantic representations of numbers do not include representations of the quantity {0}. Thus, for example, we assume that 6,040 is represented as {6}10EXP3, {4}10EXP1, and not as {6}10EXP3, {0}10EXP2, {4}10EXP1, {0}10EXP0.

This assumption is not arbitrary. The need for the digit 0 in the Arabic number system arises from the Arabic system's use of position to indicate the power of ten associated with each quantity in a number. For example, a 6 represents 6 tens if it is in the second position from the right, and 6 thousands if it is in the fourth position. To maintain the appropriate placement of digits, all positions corresponding to powers of ten smaller than the largest power in the number must be filled, even if some of these powers of ten are not represented in the number. For example, the number six hundred four cannot be written as 64; the tens position must be filled, even though there are no tens in the number. The digit 0 serves this place-holding function.

In representational schemes that do not use position to indicate the power of ten associated with a quantity, there is no need for a place-holding element. The semantic representations we have postulated do not use a positional system; each quantity representation is explicitly associated with a representation of the appropriate power of ten. Hence, there is no motivation for including {0}s in the semantic representations.

In our model, then, no representations of the quantity {0} are inserted into slots in syntactic frames. Slots corresponding to a 0 in a stimulus number remain empty and are skipped dur-

Table 5
Distribution of HY's Response Words as a Function of the Class of the Correct Word

Class of correct word	Correct: Number	Correct: %	Within-class error: Number	Within-class error: %	Class error: Number	Class error: %	Other error: Number	Other error: %
Ones	5,676	93.7	367	6.1	10	0.2	7	0.1
Teens	1,531	91.6	132	7.9	2	0.1	6	0.4
Tens	2,139	91.6	166	7.1	20	0.9	10	0.4
Total	9,410	92.9	665	6.6	32	0.3	23	0.2

ing the lexical retrieval stage. Consider, for example, the syntactic frame corresponding to the stimulus 20:

[TENS:{2} ONES:___]
"10EXP1" "10EXP0".

The tens-class element would be used to retrieve /twenty/ from the production lexicon. However, no lexical retrieval would be carried out for the ones-class element, because the quantity slot is empty.

We have assumed that HY is unimpaired in filling the syntactic frame with the appropriate quantity representations, and in skipping empty slots. Hence, we would not expect him to make zero-to-nonzero errors, such as stimulus 20, response "twenty-six." Further, we would not expect HY to make nonzero-to-zero errors, such as stimulus 39, response "thirty." Given a specification such as ONES:{9}, HY might retrieve the wrong phonological representation from the production lexicon (e.g., /four/ rather than /nine/), but he should not simply fail to retrieve a word.

There is, however, an exception to these predictions. Consider the syntactic frame corresponding to the stimulus 610:

[[ONES:{6}] MLT:H TENS:{1} ONES:___]
"10EXP2" "10EXP1" "10EXP0".

For this frame the teens procedure will be invoked when TENS: {1} is encountered. This procedure, finding the empty ones-class slot, will generate the specification TEENS:{0}, leading in the normal course of events to the retrieval of /ten/ from the phonological production lexicon. In HY, however, the disrupted lexical retrieval process may retrieve another teens word in place of /ten/, resulting in errors such as stimulus 610, response "six hundred thirteen." Further, the representation /ten/ may be retrieved erroneously in place of another teens word, leading to errors such as stimulus 417, response "four hundred ten." Thus, our model predicts two interesting dissociations: errors having the appearance of zero-to-nonzero substitutions, and nonzero-to-zero substitutions, should occur more often for the second digit in a teens digit pair (e.g., 210, 13,456), than for digits in other positions.

In contrast, a digit-encoding deficit hypothesis provides no basis for expecting that zero/nonzero errors should be more likely for some positions in a number than for others. On this hypothesis, zero-to-nonzero errors such as stimulus 20, response "twenty-six," or stimulus 305, response "three hundred sixty-five," should be as likely as errors like stimulus 10, response "sixteen." Similarly, nonzero-to-zero errors like stimulus 35, response "thirty," or stimulus 752, response "seven hundred two" should be as likely as errors such as stimulus 15, response "ten."

Examination of the data reveals both of the dissociations expected on the basis of our model. Considering first the zero-to-nonzero errors, the stimuli presented to HY included 189 0s in the second position in the teens digit pair 10. For 4 of these 0s (2.1%) HY produced another teens word in place of *ten* (e.g., "two hundred fourteen" produced in response to 210). The stimuli also included 2,495 0s in positions other than the second position in the teens pair 10. For 7 of these 0s (0.3%), HY made errors interpretable as zero-to-nonzero substitutions (e.g., stimulus 70,330, response "seventy-three thousand three hundred"). (Class errors—for example, stimulus 40, response "fourteen"—were not included in these tallies of zero-to-nonzero errors, or in the nonzero-to-zero tallies reported subsequently, because as discussed in the preceding section, the class errors are not interpretable as zero/nonzero substitutions.) As expected from our model, the likelihood of a zero-to-nonzero error was reliably higher for 0s in the teens pair 10 than for 0s in other positions, $\chi^2(1, N = 2{,}684) = 14.81, p < .001$. It should be noted, however, that this chi-square test and the test reported in the next paragraph, must be interpreted with caution because of the low expected frequencies for errors (see, e.g., Hays, 1973, pp. 735–736).

Turning next to nonzero-to-zero errors, the stimuli included 1,478 teens digit pairs in which the second digit was nonzero. For 7 of these pairs (0.5%) HY produced the word "ten" in place of the correct teens word (e.g., stimulus 715, response "seven hundred ten"). The stimuli also included 10,094 nonzero digits in positions other than the second position in a teens pair. For 5 of these digits (0.05%) HY made an error interpretable as a nonzero-to-zero substitution (e.g., stimulus 812, response "eight hundred six"). (Note that the error probabilities in this analysis are lower than in other analyses because we are counting only errors that took a particular form.) As expected from our model, the probability of a nonzero-to-zero error was reliably higher for the second digit in a teens pair than for a digit in another position, $\chi^2(1, N = 11{,}572) = 22.35, p < .001$.

The word zero. In discussing verbal-number production, we have not yet considered the word *zero*. How, then, is zero represented in the number production lexicon, and what is the process by which the response "zero" is generated when the stimulus 0 is presented? One might imagine that /zero/ is included as the first entry in the ones class of the number production lexicon. However, there are compelling arguments against this position. Zero is different from the ones words—it does not combine with tens words to represent a number made up of some tens and no ones; nor is it multiplied by the multiplier words. The Arabic number 20 does not take the verbal form twenty-zero, and 4,024 is not represented verbally as four thousand zero hundred twenty-four. The word zero is used only to represent the quantity *none*, and as the name for the digit 0. These considerations suggest that /zero/ should be considered distinct from the ones, teens, and tens words in the number production lexicon.

HY's data are consistent with this position. If /zero/ were included in the ones class, then we would expect other ones words to occur as substitution errors when the stimulus 0 was presented. Further, we would expect zero to occur as an error in place of other ones words. In fact, however, the word *zero* was empirically distinct from the other number words. The stimulus number 0 was presented 64 times, and HY correctly responded "zero" on all 64 occasions. Even more impressive is the finding that zero never occurred as an error in place of another number word. In contrast, all of the ones, teens, and tens words occurred as errors at least 4 times, and usually much more often.

How, though, is the response "zero" produced when the stimulus 0 is presented? We assume that when the Arabic number 0 is presented, the Arabic number comprehension system gen-

Table 6
Examples of HY's Multiplier Errors

Stimulus	Response
800	eight thousand
242	two thousand forty-two
1,010	one hundred ten
19,012	nineteen hundred sixteen
56,124	fifty-six hundred one hundred twenty-four
2,000	two million

erates the semantic representation {0}. As discussed above, the semantic representations generated by the number comprehension system do not contain {0}s corresponding to place-holding 0s in a nonzero Arabic number; {0} is generated only as the semantic representation of the *number* 0. Note also that {0} is a representation of the quantity *none,* and not a representation of the digit 0.

We assume that the verbal-number production process treats {0} as a special case. Specifically, we assume that when the production process receives the representation {0}, a special procedure is invoked that bypasses the generation and filling of a syntactic frame, and simply retrieves the phonological representation /zero/ from the number production lexicon. These assumptions are consistent both with the special role of the word zero in the verbal-number system, and with the finding that HY made no errors in which *zero* was substituted for another number word, or vice versa.

Multiplier words. We have assumed that the phonological production lexicon includes, distinct from the ones, teens, and tens words, and /zero/, a multiplier class containing the phonological representations of the multiplier words *hundred, thousand, million,* and so forth. Consistent with the assumption that the multipliers are functionally distinct from the other number words, none of HY's errors can be interpreted as a substitution of a multiplier word for a nonmultiplier, or vice versa. For example, HY never said something like "two hundred thousand" in response to 206, or "twenty-seven" in response to 20,000.

Occasionally, however, HY apparently retrieved an incorrect multiplier word in place of the correct word. Although HY produced the correct multiplier word over 99% of the time, he made 26 errors that are interpretable as substitutions of one multiplier for another. For example, HY said "two thousand forty-two" in response to 242; "nine hundred twelve" in response to 9,012; and "two million" in response to 2,000. Other examples of multiplier errors are presented in Table 6, and a multiplier confusion matrix is presented in Table 7.

Given our assumption that retrieval of a phonological representation of a multiplier word involves accessing the multiplier class and the appropriate item within this class, HY's multiplier errors may be interpreted as the result of accessing the wrong item within the class. This interpretation must be considered tentative, however. In most of the multiplier errors HY's response was of a different order of magnitude than the correct response (e.g., stimulus 9,012, response "nine hundred twelve"). HY also made several other "wrong-order-of-magnitude" responses that are not interpretable as substitutions of one multiplier word for another (e.g., stimulus 901,091, response "ninety thousand one hundred ninety-one"). It is conceivable that whatever processing error led to these latter responses was also responsible for at least some of the responses we have interpreted as multiplier substitutions.

However, 6 of the 26 multiplier errors cannot readily be explained in this way, and are most straightforwardly interpreted as multiplier substitutions (e.g., stimulus 56,124, response "fifty-six hundred one hundred twenty-four"). Thus, although any conclusions about the multiplier words must be tentative, the data provide some support for the assumption that HY occasionally retrieved the wrong item from a multiplier class, and so substituted one multiplier word for another.

In the next section we describe briefly a second case study involving a subject whose pattern of lexical substitution errors in the Arabic-number-reading task complements that of HY, and provides further support for the proposed model of verbal-number production.

Study 2: Subject JG

JG, a right-handed woman, sustained a closed-head injury in September 1983 at the age of 22. JG is a high school graduate and works as a hair stylist. She and members of her family report that she had no difficulty with numbers prior to her accident. JG's spoken language comprehension and production are essentially normal, although she evidences impairments in spelling, and in reading aloud words and nonwords (e.g., boke). A brief case history, with more specific neurological and language assessment information, is presented in Appendix C.

In weekly testing sessions from August 1984 through May 1985, JG read aloud 2,745 Arabic numbers ranging in size from one to nine digits, with an error rate of 5.8%. Many of her errors involved substitutions, deletions, or transpositions of multiplier words (e.g., *hundred, thousand, million*). These multiplier errors, which have implications for issues concerning the representation and generation of syntactic frames, will be considered in a separate report. Here we focus on JG's lexical substitution errors for ones, teens, and tens words.

An analysis comparing JG's responses word by word with the correct responses was carried out in the manner described for HY (p. 312). Twelve responses were excluded from the analysis because JG's response contained a different number of words than the correct response; these responses are listed in Appen-

Table 7
Multiplier Word Confusion Matrix for HY in the Arabic-Number-Reading Task

Correct multiplier word	Multiplier word produced by HY		
	hundred	thousand	million
hundred	2,683	18	0
thousand	7	1,311	1
million	0	0	17

	zero	one	two	three	four	five	six	seven	eight	nine	ten	eleven	twelve	thirteen	fourteen	fifteen	sixteen	seventeen	eighteen	nineteen	twenty	thirty	forty	fifty	sixty	seventy	eighty	ninety
zero	15	1																										
one		619		1						2																		
two		1	488	2																	2							
three			1	488			2																					
four					512										1								1					
five			1			474		2																1				
six			2				509																		2			
seven								496		1																2		
eight								2	491	2																	1	
nine							1			505										5								3
ten											143			1														
eleven		1										151	1															
twelve													149			1					2							
thirteen				1										149														
fourteen					3							1	2		142								1					
fifteen																147	1	1						1				
sixteen							1										149	1										
seventeen								1						1		1		156										
eighteen																			150	1							1	
nineteen										1		1	1					1		145								
twenty			5																		202							
thirty														1								217						
forty					7										1								184					
fifty						2										2								194		2		
sixty																	2								173	1		
seventy								4										1								173		
eighty									1										1								195	
ninety										1												1						193

Figure 2. Word confusion matrix for subject JG. (Rows represent the correct words and columns represent the words produced by JG.)

dix D. Figure 2 presents the confusion matrix resulting from the analysis, and Table 8 summarizes the information in the matrix.

The most notable feature of JG's performance is the predominance of class errors (e.g., stimulus 312, response "three hundred twenty"; see Table 9 for other examples). Whereas only 4% of HY's lexical substitutions were class errors, 60% of JG's substitutions fell into the class error category. Also notable is that all of JG's lexical substitutions for ones, teens, and tens words were either class errors or within-class errors (e.g., stimulus 908, response "nine hundred seven"); she made no errors in which both the class and the position within class were incorrect. Finally, it is clear from the confusion matrix and from Table 8 that JG's error rate was very low—lexical substitution errors occurred for only 98 of the 7,692 ones, teens, and tens words produced by JG (1.3%).

Table 8
Distribution of JG's Response Words as a Function of the Class of the Correct Word

Class of correct word	Type of response: Correct		Within-class error		Class error		Other error
	Number	%	Number	%	Number	%	
Ones	4,582	99.2	20	0.4	18	0.4	0
Teens	1,481	98.1	15	1.0	13	0.9	0
Tens	1,531	98.0	4	0.2	28	1.8	0
Total	7,594	98.7	39	0.5	59	0.8	0

Within-Class Errors

JG's within-class errors (e.g., stimulus 501, response "five hundred three) are consistent with the assumption that in retrieving phonological number-word representations from the production lexicon, JG occasionally accessed the correct number-lexical class but the wrong position within class. However, the possibility that the within-class errors resulted from occasional digit encoding errors cannot be excluded entirely. JG made within-class errors so rarely that even a very low rate of digit encoding errors would be sufficient to account for the within-class lexical substitutions. Although JG showed excellent performance on several tests of Arabic-digit comprehension, the comprehension results cannot rule out the possibility that encoding errors occurred at such a rate. Further, the error pattern within the Arabic-number-reading task does not discriminate clearly between digit encoding and lexical retrieval interpretations of the within-class errors. Hence, JG's within-class errors do not provide a basis for conclusions about the verbal-number production process and will not be considered further.

Class Errors

In contrast, JG's class errors strongly support the claim that verbal-number production involves a level of representation at which to-be-retrieved number words are specified in terms of class and position within class (e.g., TENS:{5}). The errors may be interpreted by assuming that the lexical retrieval process, given a class/position-within-class specification of a to-be-retrieved number word (e.g., TEENS:{4}), occasionally accessed the wrong number-lexical class in the phonological production lexicon (e.g., the tens class), but the correct position within the class (e.g., the position for {4}), resulting in errors such as "forty" produced in response to 14.

The class errors are not merely consistent with the assumption of class/position-within-class representations; in the absence of this assumption the errors cannot readily be explained. The class errors clearly cannot be attributed to errors in encoding the digits in the Arabic stimulus numbers. First, 9 of the 59 class errors (e.g., stimulus 916, response "nineteen hundred sixteen"; stimulus 20,417, response "twenty thousand fourteen hundred sixteen") cannot be interpreted in terms of digit-encoding errors. Furthermore, even those errors that have the potential to fall within the scope of an encoding error interpretation cannot be adequately explained. Forty-one of the errors would require the assumption of encoding errors for two adjacent digits. For example, to interpret the response of "forty" to the stimulus 14 in terms of digit-encoding errors, one must assume that the 1 was encoded as a 4, and the 4 was encoded as a 0.

The simplest form of a multiple encoding error argument—one that assumes that the two presumed encoding errors are unrelated—is completely untenable. In the 41 class errors that require the assumption of encoding errors for two adjacent digits, the two errors are *complementary.* That is, the quantity that is "lost" from one position in the number reappears at the adjacent position. For example, in the response of "eighteen thousand six hundred seventeen" to the stimulus 18,670, the 7 lost from the tens position (in the presumed encoding of 7 as 1) reappears in the ones position (in the presumed encoding of 0 as 7). Given the assumption that the two presumed encoding errors are unrelated, the complementarity can be explained only as a chance occurrence. In other words, it must be assumed that the quantity lost from one position occasionally happened merely by chance to be the same as the incorrect quantity appearing as the result of an encoding error at the adjacent position. This assumption can be maintained only if JG often made responses interpretable as resulting from two adjacent encoding errors that did *not* happen to be complementary (e.g., stimulus 18670, response "eighteen thousand six hundred fifteen," which might be interpreted as the result of encoding the 7 as a 1, and the 0 as a 5). In fact, however, JG made only one such

Table 9
Examples of Class Errors Made by JG in the Arabic-Number-Reading Task

Stimulus	Response
916	nineteen hundred sixteen
60,905	sixty thousand nine hundred fifty
13,014	three thousand fourteen
912	nine hundred twenty
50,300	five thousand three hundred
20,417	twenty thousand fourteen hundred seventeen
17,311	seventeen thousand three hundred one
620	six hundred two

response. Hence, the complementarity evident in the class errors must be considered systematic and not accidental.

To account for the systematic complementarity, it might be suggested that JG's class errors resulted from digit transpositions (e.g., transposition of 2 and 0 to yield the response "one hundred twenty" from the stimulus 102). However, a transposition interpretation also proves inadequate. First, 18 of the 59 class errors (e.g., stimulus 14,890, response "four thousand eight hundred ninety) cannot be interpreted in terms of digit transpositions. Of the remaining 41 errors, only 28 can be interpreted as simple transpositions (e.g., stimulus 102, response "one hundred twenty"). To explain the other 13 errors (e.g., stimulus 60,980, response "sixteen thousand nine hundred eighty"), the transposition argument must assume not only a transposition, but also a 0-to-1 or 1-to-0 substitution. However, as was the case for HY, transpositions alone and 0/1 substitutions alone were far too infrequent to permit the claim that these two unrelated error types occurred together 13 times.

The stimuli presented to JG included 2,577 pairs of digits for which the joint occurrence of a transposition and a 0/1 error would have resulted in a class error. For these digit pairs JG made only 20 responses interpretable as transpositions without 0/1 errors, and only 9 responses interpretable as 0/1 errors without transpositions. Clearly, it cannot be maintained that transpositions and 0/1 errors, two rare and unrelated events, occurred more often together (13 times) than 0/1 errors alone, and nearly as often as transposition errors alone. (On an assumption of strict independence, the rates at which the two errors occurred separately yield an expected joint occurrence frequency of 1 in 36,630 digit pairs.)

Consider finally the possibility that JG's class errors do not reflect a partitioning of the number words into ones, teens, and tens classes in the phonological production lexicon, but instead stem from a tendency in lexical retrieval to access a word that is phonologically similar to the intended word. On this interpretation, JG's lexical substitutions sometimes took the form of class errors simply because the corresponding ones, teens, and tens words (e.g., *four, fourteen, forty*) tend to be phonologically similar.

However, JG's error pattern does not conform to that expected on the basis of the phonological error interpretation. In several of JG's class errors the correct and incorrect words were low in phonological similarity. For example, JG substituted *one* for *eleven, two* for *twenty, three* for *thirteen, fifty* for *five,* and so forth. Yet JG failed to make substitution errors involving words of equal or greater phonological similarity (e.g., *eleven* and *seven, one* and *ten*), when such substitutions would not result in class errors. The words *two, ten,* and *twenty* illustrate the point clearly. JG made seven class errors in which *two* and *twenty* were substituted for one another. However, *ten* and *twenty,* which are more similar phonologically, were never produced in place of one another.

Furthermore, for corresponding ones, teens, and tens words (e.g., *seven, seventeen, seventy*) the phonological similarity of the teens word (e.g., *seventeen*) and the tens word (e.g., *seventy*) is uniformly higher than the similarity of either of these words to the ones word (e.g., *seven*). Thus, on the phonological error interpretation one would expect that substitutions for teens words (e.g., *seventeen*) would more often be tens words (e.g., *seventy*) than ones words (e.g., *seven*). Similarly, substitutions for tens words should more often be teens words than ones words. However, it is evident from Figure 2 that the pattern is just the opposite. Finally, it is worth noting that JG's within-class errors (e.g., stimulus 501, response "five hundred three") clearly are not phonologically based.

In contrast to the digit-encoding, transposition, and phonological-error arguments, our model straightforwardly explains the class errors in terms of a level of representation at which to-be-retrieved number words are specified in terms of number-lexical class, and position within class (e.g., TEENS:{7}). Thus, JG's results converge with the data from HY in support of the model we have proposed.

General Discussion

In this article we have presented data from two brain-damaged subjects in support of a model of spoken verbal-number production. According to the proposed model, the verbal-number production process accepts as input a semantic representation of a to-be-produced number, and on the basis of this input generates a syntactic frame that constitutes a plan for the production of the appropriate sequence of words. The syntactic frame, filled with quantity values from the semantic representation, specifies each to-be-produced word in terms of number-lexical class and position within class (e.g., TENS:{3}). The class/position-within-class specifications guide the retrieval of the appropriate phonological number-word representations from a production lexicon in which the number words are partitioned into functionally distinct ones, teens, and tens classes.

The patterns evident in the number-reading errors made by subjects HY and JG support the major assumptions of the model. In particular, the assumption that number-word representations in the phonological lexicon are partitioned into ones, teens, and tens classes, and the corresponding assumption that to-be-retrieved words are specified in terms of class and position within class are supported by the finding that in nearly all of HY's lexical substitution errors the incorrect word preserved the class (i.e., ones, teens, or tens) of the correct word. Further support is provided by the finding that in all of JG's out-of-class errors the incorrect word (e.g., *sixty*) preserved the position within class of the correct word (e.g., *six*).

Our assumptions about the partitioning of the number-word representations in the production lexicon are also consistent, at least on a general level, with discussions of number words in previous research. For example, the importance of the ones/teens/tens distinction is assumed at least implicitly in developmental work on counting (e.g., Fuson et al., 1982; Miller, 1985; Siegler & Robinson, 1982). Furthermore, Deloche and Seron (1982a, 1982b, 1984; Seron & Deloche, 1983, 1984) have invoked the concept of number-lexical classes ("stacks" in their terminology) in classifying the errors made by groups of aphasic subjects on various number-processing tasks. It must be acknowledged, however, that Deloche and Seron's assertions about the stack structure of number words may not have been intended as claims about cognitive number-processing mechanisms, but rather as descriptions of the verbal-number system considered as a formal symbolic system. (See, e.g., Seron & Deloche, 1984, p. 233: "Thus, there is evidence that stack notions are relevant to neuropsycholinguistics, but this does not mean that the mental lexicon is organized according to such structures.")

The model we have proposed raises a variety of issues to which the performance of HY and JG does not speak directly. In the following discussion we touch upon several of these issues. We then point out some of the broader implications of our results, and finally, we comment briefly on the use of data from brain-damaged subjects in developing and evaluating cognitive theories.

Issues in Number Processing

Lexical Representations in the Production Lexicon

One major issue concerns the form of the number-word representations in the phonological production lexicon. We have assumed that the production lexicon stores number word representations in whole-word units (e.g., /sixty/, /nineteen/). Another possibility is that the phonological representations are stored in morphologically decomposed form, so that retrieval of a number word involves assembling a base (e.g., /six/) with the appropriate suffix (e.g., /-ty/), with some special provision being made for irregular words such as *twelve.*

The data from subjects HY and JG do not discriminate clearly between these alternatives. However, results we have obtained from AT, another brain-damaged subject who is impaired in retrieval of phonological number-word representations from the production lexicon, are more informative. In the Arabic-number-reading task, AT exhibited a pattern of lexical substitution errors that is difficult to reconcile with the morphological decomposition hypothesis. For example, she was only 59% correct in producing the word *sixteen.* All of her errors were within-class substitutions, with "fourteen" and "seventeen" clearly predominating. The morphological decomposition hypothesis would interpret this result to mean that AT is impaired in accessing the phonological representation of the base morpheme /six/, often retrieving /four/ or /seven/ instead. Thus, the hypothesis predicts that AT should show the same pattern of errors for the words *six* and *sixty,* because production of these words also requires retrieval of the base /six/. That is, AT should show poor performance for *six* and *sixty* and should frequently substitute *four* or *seven* for *six,* and *forty* or *seventy* for *sixty.* In fact, however, AT was 94% correct in production of the word *six,* and 98% correct for *sixty.* Furthermore, the pattern of substitution errors for *six* and for *sixty* was very different than for *sixteen.* For example, whereas *fourteen* and *seventeen* were by far the most common substitutions for *sixteen,* the word most commonly substituted for *six* was *eight* (22 times); *four* and *seven* were substituted far less frequently (1 time and 8 times, respectively). These results strongly suggest that phonological number-word representations are retrieved from the production lexicon in whole-word units (so that retrieval of /sixteen/ could be disrupted independent of retrieval of /six/ or /sixty/).

Syntactic Frames

A related set of issues concerns the representation and generation of syntactic frames. Is a complete syntactic frame prestored for each order of magnitude (e.g., a frame for numbers in the hundreds, a separate frame for numbers in the thousands, and so forth), so that frame generation involves simply retrieving the frame for the appropriate order of magnitude? Or does the frame generation process exploit the fact that verbal numbers are made up of one or more units of the form [(ONES) hundred TENS ONES] MULTIPLIER (see pp. 308–309), such that the frame shown below is used for numbers of all orders of magnitude?

[(ONES:____) MULT:H TENS:____ ONES:____] MULT:____

On this view, reading aloud the number 327,519,420 would involve using the frame first to produce the millions unit of the number (i.e., *three hundred twenty-seven million*), then to produce the thousands unit (i.e., *five hundred nineteen thousand*), and finally to produce the ones unit (i.e., *four hundred twenty*). Furthermore, the same frame would be used in reading numbers such as 423,610, or 543. Data concerning multiplier errors made by JG and another brain-damaged subject (JS) suggest that the actual state of affairs may be somewhere between these two extreme alternatives.

Written- Versus Spoken-Verbal-Number Production

We have focused in this article on spoken production of verbal numbers. However, it seems likely that many of the processes we have discussed are also implicated in written verbal-number production. The filled syntactic frame specifies the sequence of to-be-produced number words in an abstract form that is not tied to either the spoken or written production mode. Thus, we might expect that the processes of generating and filling the syntactic frame would be shared by spoken and written verbal-number production. In this view, the production processes for the two modes of response diverge only at the lexical retrieval stage, such that number-word representations are retrieved from a phonological production lexicon in the case of spoken production, and from a graphemic production lexicon in the case of written production. The pattern of performance evidenced by subject JS in spoken and written verbal-number production supports these assumptions (Sokol & McCloskey, 1986). Specifically, JS makes the same sorts of "syntactic" errors in both spoken- and written-verbal-number production, suggesting that processing of the syntactic frame is common to spoken and written production. However, JS makes lexical retrieval errors in spoken- but not in written-verbal-number production, supporting the assumption that retrieval of phonological representations from a phonological production lexicon (impaired in JS) should be distinguished from retrieval of graphemic representations from a graphemic production lexicon (intact in JS).

Reading Written Verbal Numbers Aloud

Our assumptions about the functional architecture of the cognitive number-processing system suggest that reading aloud a number always involves first the generation of a semantic representation and then the conversion of the semantic representation into the appropriate sequence of phonological number-word representations. However, at least for reading individual number words (e.g., *seventy*), the generation of a semantic representation may not always be necessary; studies of reading suggest that there are other means by which a word may be read aloud. It is generally assumed that nonwords (e.g., *jope*), and words that have not previously been encountered and therefore are not represented in the phonological production lexicon, are read aloud through the application of grapheme-to-phoneme conversion rules (e.g., Coltheart, 1978, 1981; Morton, 1980, 1982; but see Glushko, 1979, 1981; Marcel, 1980). Thus, pronunciations of written number words presumably could be generated through grapheme–phoneme conversion. However, several English number words (e.g., *two, eight*) have orthographically irregular spellings; that is, the pronunciation cannot reliably be deduced from the orthography. Thus, grapheme–phoneme conversion presumably would not suffice to generate correct pronunciations for these words.

However, irregular (as well as regular) number words might be read aloud through direct nonsemantic access to stored phonological representations. Recent evidence suggests that phonological representations in the production lexicon may be activated directly from an orthographic representation of a stimulus word, without the mediation of a semantic representation (Bub, Cancelliere, & Kertesz, 1986; Schwartz, Saffran, & Marin, 1980). For example, Schwartz et al. describe a brain-damaged subject (WLP) who performed well in reading aloud orthographically regular and irregular words while apparently having little or no understanding of their meaning. Thus, we might expect at some point to encounter a brain-damaged subject who was impaired in accessing semantic representations of written number words, but could nevertheless read the words aloud.

Numbers in Other Languages

The syntax and lexical structure of verbal numbers vary considerably across languages (see, e.g., Hurford, 1975; Menninger, 1969). For example, a set of teens words is not a universal feature of verbal number systems. The model we have proposed concerns production of English verbal numbers, and some aspects of the model reflect specific characteristics of the English verbal-number system. However, the basic principles embodied in the model (e.g., number production involves an abstract planning level, the organization of the number word lexicon and the lexical retrieval process reflect important distinctions at the planning level) are likely to be more general. Consider, for example, the Japanese number system, which includes neither teens words nor tens words. The basic number words in Japanese comprise the set one (*ichi*) through nine (*ku*). The word for ten (*ju*) acts as a multiplier, so that, for example, 30 is represented as three-ten (*san-ju*). More generally, numbers are represented by associating the word for each basic quantity in the number with a multiplier specifying the power of ten. Thus, 35,020 is represented as three-tenthousand five-thousand two-ten (*san-man go-sen ni-ju*). Clearly, many of the specific assumptions of our model do not apply to Japanese. Nevertheless, our general conceptualization of verbal-number production leads to clear predictions about the structure of the Japanese number lexicon, the production process, and the types of error patterns that may result from disruption of the system. For example, we would expect the number words in the production lexicon of Japanese speakers to be organized into two classes, a class of basic number words containing the words for the quantities one through nine, and a multiplier class containing *ju* (ten), *hyaku* (hundred), *sen* (thousand), *man* (ten thousand), and so forth. Further, we would expect this lexical organization to be reflected in deficits in retrieval of number-word representations from the lexicon. For example, a deficit in retrieval of multiplier words might result in errors such as *go-ju* (five-ten) produced in place of *go-hyaku* (five-hundred) or vice versa. In contrast, we would not expect an English-speaking subject with a multiplier retrieval deficit to make this sort of error, because *ten* is not a multiplier in English. It is interesting to note in this context that Miller (1985) has argued that the counting errors made by Chinese and American children differ in ways that reflect differences in the linguistic structure of the Chinese and English verbal-number systems.

Relation Between Number- and Language-Processing Mechanisms

Do the cognitive number-processing mechanisms constitute a cognitive system that is entirely distinct from a language-processing system? Or is number processing instead carried out wholly or in part by general language-processing mechanisms? Patterns of performance in brain-damaged subjects conceivably could shed light on this issue. For example, given a subject with an impairment of some cognitive process involved in number production (e.g., syntactic-frame generation or lexical retrieval), one could ask whether the subject evidences the language-processing impairments that would be expected if the disrupted process were also implicated in language processing (see also Deloche & Seron, 1982b, for research concerning number-processing deficits in subjects with various sorts of language impairments).

Carrying out such a program of research might appear on the surface to be a straightforward matter. However, the surface simplicity conceals substantial complexity at both theoretical and empirical levels. As an example, consider the hypothesis that the phonological number-production lexicon and the processes acting upon it (e.g., lexical retrieval) are completely distinct from the general language-production lexicon and its associated processes. Even at a theoretical level, it is not entirely clear how this hypothesis would differ from the (presumably) weaker claim that the number words constitute a functional class in a general production lexicon, such that retrieval of a number word involves specifying the class "number," the appropriate subclasses (e.g., cardinal, tens), and ultimately the specific item within a subclass.

Furthermore, it is unclear what sorts of evidence would distinguish a separate-lexicon hypothesis from one in which the number words are viewed as a class in a general production lexicon. Suppose, for example, that we observed one or more brain-damaged subjects who exhibited severe lexical retrieval deficits in verbal number production, but not in the production of other sorts of words. This hypothetical dissociation would presumably be consistent with a separate-lexicon hypothesis, but could also be interpreted in terms of a category-specific disruption of a general lexicon.

The point is not that issues concerning relations between number- and language-processing mechanisms are meaningless or intractable, but merely that these issues are more complex and difficult than they may at first appear. We have chosen to concentrate initially on developing an explicit model of the cognitive processes involved in verbal-number production. With this model as a basis for formulating specific hypotheses, we hope in future research to explore relations between number- and language-production mechanisms.

Broader Implications

Thus far, we focused specifically on number processing. However, our findings also bear on several broader issues.

The Lexicon and Lexical Retrieval

In our verbal-number production model, the planning of the to-be-produced word sequence is carried out in terms of classes of words: ones words, teens words, tens words, multiplier words. The error patterns of subjects HY and JG strongly suggest that these lexical class distinctions are reflected in the organization of the number-word representations in the production lexicon, and in the processes that retrieve these representations.

It is not a foregone conclusion that this principle applies to language in general. At the least, however, our results suggest the hypothesis that lexical class distinctions relevant to language comprehension and production processes are reflected in the structure of the lexicon and in lexical access procedures. Recent evidence suggests that this may indeed be the case, both for the distinction between open- and closed-class words (see Caramazza & Berndt, 1985, for a review), and also for distinctions within the set of open-class words (e.g., the distinction between nouns and verbs; see Miceli, Silveri, Villa, & Caramazza, 1984).

Language Production Processes

The model we have proposed represents a specific embodiment of the general claim (e.g., Garrett, 1980) that language production involves a progression through several levels of representation, each of which is required to support a particular type of computation (e.g., the planning of the syntactic form of an utterance, the selection of particular lexical items). Although once again caution must be exercised in generalizing from numbers to language in general, our results can reasonably be taken as support for this claim. It would certainly be surprising if multiple levels of representation were required in the production of verbal numbers, which have a relatively straightforward lexical and syntactic structure, but not in the production of sentences, which are vastly more complex.

This is not to say that the representations and processes implicated in number production are identical to those involved in sentence production. The specific levels of representation and the computations carried out at each level will depend upon the nature of the items that are being processed. For example, numbers and sentences differ in an interesting way: a semantic content is expressed solely through major lexical items and word order in the case of numbers, whereas for sentences inflectional morphemes and free-standing grammatical markers are also required. A comparison of our number production model with the Garrett (1980) model of sentence production suggests that this difference may be reflected in production processes. Whereas the number production model assumes that a phonological representation of a to-be-produced word sequence is generated solely by retrieving the phonological forms of major lexical items specified at an abstract level of representation, the sentence production model assumes an additional class of computations to retrieve and insert grammatical morphemes not represented at the abstract level. In spite of this interesting difference, both models reflect the general claim that the production process requires a series of representational levels to support the necessary computations.

Specificity of Acquired Cognitive Deficits

Finally, our results underscore a point that is becoming increasingly apparent in cognitive research with brain-damaged subjects: The cognitive impairments resulting from brain damage may be exquisitely specific. Deficits may be specific not only to particular major components of a cognitive system, but in fact to particular subprocesses within these components (although this is of course not always the case). An important implication of this specificity is that analyses of impaired performance may serve not only to define the major components of a cognitive system, but also to explore in considerable detail the internal structure of these components.

Cognitive Research With Brain-Damaged Subjects

It is important to emphasize that the research strategy we have illustrated in this article involves the use of brain-damaged subjects to address issues in cognitive psychology. The aim is to draw conclusions about normal cognition, and not about the functions of particular brain areas or about the nature of the cognitive deficits underlying particular clinical syndromes. (However, the research does yield a characterization of each individual subject's impairment in terms of disruption to particular cognitive processes, because this characterization is needed to link the subject's performance to claims about normal cognition.)

Furthermore, as in traditional cognitive research with normal subjects, the conclusions about normal cognition are drawn on the basis of the subject's performance on cognitive tasks, not on the basis of neurophysiological or neuroanatomical data (e.g., lesion localization data). For example, the loci of the brain lesions in subjects HY and JG played no role in our use of their number-reading performance to make inferences about verbal-number production (although these localization data conceivably could contribute to an understanding of the neural substrata of the impaired cognitive processes).

As we have attempted to illustrate in this article, patterns of impaired performance may be used to inform the development of a model of a cognitive system by asking for each performance pattern, What must the cognitive system be like such that damage to the system could result in just this pattern of performance? Similarly, given a pre-existing model, a pattern of performance is brought to bear on the model by asking, Can the postulated cognitive system be damaged in such a way as to produce the observed performance pattern? If the answer is yes, the subject's performance constitutes support for the model. If, however, damage that would lead to the observed pattern of performance cannot be specified, then the performance pattern represents evidence against the model.

In using data from brain-damaged subjects to develop and test cognitive models, the appropriate methodology is that of the single-case study. Brain damage may disrupt a cognitive system in a variety of different ways, and thus may lead to a variety of different patterns of impaired performance. Consequently, differences in performance among brain-damaged subjects cannot be dismissed as noise, and averaging data across subjects is usually not justified. In fact, the research strategy is powerful in large measure because it capitalizes on the heterogeneity of cognitive deficits, by requiring that a model of a normal cognitive system be capable of accounting for each of the many diverse patterns of impairment that may result from damage to the system.

It is important to point out that the use of a single-case-study methodology does not mean that a different model is developed for each subject. To the contrary, the same model of the normal system must be used in interpreting the data from each subject; only the assumptions about what components of the system are damaged can vary across subjects. Thus, the aim is to bring data from many different subjects to bear on a single model of the normal system, by specifying damage to the system that would result in the particular pattern observed for each individual subject.

The analysis of patterns of impaired performance exhibited by brain-damaged subjects represents an important methodological tool for cognitive psychology. We hope therefore to see a more widespread application of the methodology, and the integration of research involving brain-damaged subjects with more traditional research involving normal subjects.

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(*Appendix follows on next page*)

Appendix A

Subject HY: Case History and Language Assessment

Case History

HY, a right-handed male, suffered a left cerebrovascular accident in December 1981 at the age of 66. Computed tomography (CT) scans performed in December 1981 and January 1982 revealed an intracerebral hemorrhage of the left temporal and parietal lobes, obliteration of the left lateral ventricle, and intraventricular bleeding with minimal midline shift to the right. No information pertaining to the patient's speech-language skills or orientation at hospital admission are documented in the medical reports released to the experimenters.

HY is a ninth-grade graduate and reportedly left school as a result of having to work during the Depression. Prior to his stroke, he had started and co-managed his own construction company. HY and other members of his immediate family report that his reading, writing, and number processing skills were excellent prior to his stroke.

Language Assessment

A brief description of each test discussed in this section is provided in Appendix E.

Boston Diagnostic Aphasia Examination (Goodglass and Kaplan, 1972)

HY was given a 4 on the aphasia severity rating scale (i.e., "some obvious loss of fluency in speech or facility in comprehension, without significant limitation on ideas expressed or form of expression"). His spontaneous speech is fluent with normal intonation contours and he occasionally produces literal and verbal paraphasias and has some mild word-finding difficulty. HY exhibited a rich vocabulary and used a variety of syntactic constructions. Repetition of words and high-probability phrases was perfect, but repetition of low-probability phrases was moderately impaired. Responsive naming and visual confrontation naming were moderately impaired, eliciting semantic errors and circumlocutory responses. HY scored 3 on the "Animal-naming (Fluency in controlled association)" subtest. Auditory comprehension was relatively intact. HY exhibited a moderate-to-severe deficit for reading comprehension of sentences (5/8 prorated) and because of his frustration, the task was discontinued after item 7. Oral reading of words (10/13 correct) and sentences (1/10) was moderately and severely impaired, respectively. HY also had much difficulty for tasks in the written language expression section of the battery. He produced errors for copy transcoding and for all other spelling subtests.

Boston Naming Test (BNT; Goodglass and Kaplan, 1983)

HY scored 10 of 60 on this test. On the BNT norms, normal adults in HY's age range average 55.82 (SD = 2.63). He responded excellently to phonemic cuing (45 of 50 correct) but not to stimulus (semantic) cuing (0 of 50 correct). HY failed to respond well to phonemic or stimulus cuing for only two out of the last 11 items on the test.

Peabody Picture Vocabulary Test—Revised, Form M (PPVT; Dunn and Dunn, 1981)

HY scored 154 of 175. On the PPVT norms, this score falls into the 40th percentile rank for normal adults within his age range. Fourteen of the 21 errors were produced for stimuli in the most difficult section of the test (items 146–175).

Appendix B

Responses Excluded From Word-by-Word Analysis for Subject HY

Stimulus	Response	Stimulus	Response
503,300	fifty-seven hundred thirty	70,300	seventy-three thousand three hundred
505,015	fifty thousand five hundred seventeen	430,091	forty-three thousand seventy-one
6,700	six hundred seventy	306,200	seventy thousand six hundred ten
306,200	six thousand five hundred sixty	400,400	forty thousand nine hundred
50,037	seven hundred thousand thirty-seven	845	eight hundred fourteen
50,702	five thousand seventy-two	400	forty
806	eighty-two	400	forty
2,100	twelve thousand	19,017	one thousand nine hundred one
70,046	seventy thousand two hundred sixty	430,091	four thousand sixty ninety-one
8,015	one thousand one hundred eight	809,100	sixty thousand one hundred and nine thousand
411	four hundred seventy-seven	10,000	ten hundred thousand
1,100	one thousand ten	95,066	ninety-five thousand ninety-nine hundred
1,090	one thousand nine hundred	505,015	thirty thousand three hundred fifteen
825	eight hundred fifteen	680,014	five thousand seven hundred fourteen
8,524	eight thousand five hundred fourteen	307,073	thirty thousand four hundred forty-one
512	seventy-two	901,091	ninety thousand one hundred ninety one
50,037	five hundred thousand forty-seven	7,000,000	seven hundred million
10,019	ten thousand seventy-nine	404	forty-four
3,261	three thousand two hundred sixteen	808	eighty-eight
503,300	fifty thousand three hundred thirteen	809,301	eighty-nine thousand three hundred one

Appendix C

Subject JG: Case History and Language Assessment

Case History

JG, a right-handed female, sustained a closed-head injury as a result of a fall in September 1983 at the age of 22. A family member found her lying unconscious within a half hour of the accident. At the time of admission to the hospital, JG was described as being somewhat confused and agitated. Her spontaneous speech and language production skills were intact, she responded appropriately to multiple-order commands, and answered complex questions accurately. However, JG did show some difficulty in confrontation naming, perseverating on some responses and exhibiting mild word finding problems on others. Neurological examination, performed within 24 hr of admission, revealed that JG had sustained lambdoid suture and basal skull fractures, and she suffered a grand mal posttraumatic seizure during evaluation. Computed tomography (CT) scan revealed a small intracerebral hematoma in the left temporoposterior region. Surgery was not indicated. Motor functioning and cranial nerve examination were intact. At the time of discharge from the hospital 1 week after admission, JG's naming abilities had greatly improved. A second CT scan, performed in November, 1983, revealed an area of edema compatible with porencephaly in the left temporoparietal area adjacent to the occipital and temporal horns.

JG is a high school graduate. She has been employed as a hair stylist for six years. JG and the other members of her immediate family report that her reading, writing, and number-processing skills were intact prior to her accident.

Language Assessment

A brief description of each test discussed in this section is provided in Appendix E.

Boston Diagnostic Aphasia Examination (Goodglass and Kaplan, 1972)

JG was given a (5) on the aphasia severity rating scale (i.e., "Minimal discernible speech handicaps; patient may have subjective difficulties that are not apparent to listener"). Her spontaneous speech is fluent with normal intonational contours, articulation, and word usage. Grammatical complexity and vocabulary were judged to be within normal limits for JG's age and education level. Repetition of single words and phrases was performed perfectly. Responsive naming and visual confrontation naming were performed perfectly and JG scored 16 on the 'Animal-naming (Fluency in controlled association)' subtest. Auditory comprehension, in terms of word discrimination, body-part identification, commands, and complex ideational material were all performed quickly and accurately. Reading comprehension of words and sentences was intact and oral reading of single words was perfect; however, JG exhibited a few errors in performing oral sentence reading (i.e., she produced a visually similar nonword response and a function word substitution). The most difficult section of the battery for JG was the written language expression section. Even though copy transcoding was intact, oral and written spelling of single words and sentences was impaired. For a more detailed discussion of JG's writing deficit, see Goodman and Caramazza (in press).

Boston Naming Test (BNT; Goodglass and Kaplan, 1983)

JG scored 36 of 60 on this test. On the BNT norms, normal adults in JG's age range average 55.86 (SD = 2.86). She responded well to phonemic cuing (16 of 24 correct) but not to stimulus (semantic) cuing (1 of 25 correct). JG did not respond well to phonemic or stimulus cuing for six of the last eight items on the test, possibly a reflection of her lack of knowledge of these words premorbidly.

Peabody Picture Vocabulary Test—Revised, Form M (PPVT; Dunn and Dunn, 1981)

JG scored 144 of 175 correct. On the PPVT norms, this score falls into the 28th percentile rank for normal adults within her age range. The majority of errors (22 of 31) were produced for stimuli in the most difficult section of the test (items 146–175). As was the case for results of the BNT, this finding may simply reflect the fact that JG never had these particular words in her vocabulary prior to her accident.

Appendix D

Responses Excluded From Word-by-Word Analysis for Subject JG

Stimulus	Response
580,016	five hundred eighty thousand one hundred sixteen
314	thirteen one hundred four
460,980	four hundred sixty thousand ninety-eight
13,014	thirteen thousand four hundred
305,450	three hundred five thousand forty-five hundred
460,980	forty-six thousand nine hundred eighty
125	one hundred twelve
2,000,000	two hundred thousand
1	one hundred
31,470	thirty-one hundred seventy
13	three hundred
87,016	eighty-seven thousand one hundred sixteen

Appendix E

Descriptions of Language Tests Administered to HY and JG

Boston Diagnostic Aphasia Examination (BDAE; Goodglass and Kaplan, 1972)

The BDAE assesses language performance for five major areas: conversational and expository speech, auditory comprehension, oral expression, understanding written language, and writing. The major purposes of the test are "(1) diagnosis of presence and type of aphasic syndrome, leading to inferences concerning cerebral localization; (2) measurement of the level of performance over a wide range, for both initial determination and detection of change over time; (3) comprehensive assessment of the assets and liabilities of the patient in all language areas as a guide to therapy" (Goodglass & Kaplan, 1972, p. 1).

Boston Naming Test (BNT; Goodglass and Kaplan, 1983)

The BNT consists of 60 pictures of objects for which the subject must verbally provide the name. If the subject is unable spontaneously to generate the target name for a stimulus, the experimenter is to first provide a specified semantic cue, and in the event that this does not facilitate naming, to then provide a phonemic cue. The test is organized such that there is an increasing level of complexity in that pictures appearing later in the test are associated with less frequently occurring names.

Peabody Picture Vocabulary Test—Revised, Form M (PPVT; Dunn and Dunn, 1981)

The PPVT is a vocabulary test of single-word comprehension. The subject is aurally presented with 175 words, one word at a time, and asked to point to the picture, from among an array of four, that best matches the word. As is the case for the BNT, the PPVT is organized such that the target pictures appearing later in the test are associated with more difficult vocabulary words.

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