

Origins of Paraphasias in Deep Dysphasia: Testing  
the Consequences of a Decay Impairment  
to an Interactive Spreading Activation  
Model of Lexical Retrieval

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This study investigates an account of atypical error patterns within the framework of an interactive spreading activation model. Martin and Saffran (1992) described a patient, NC, whose error pattern was unusual for the occurrence of higher rates of form-related than meaning-related word substitutions in naming and the production of semantic errors in repetition. They proposed that NC's error pattern could be accounted for by a pathologically rapid decay of primed nodes in the semantic–lexical–phonological network that shifts the probabilities of error outcome in lexical retrieval. In the present study, Martin and Saffran's

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account was tested and supported in a series of simulations that reproduce essential features of NC's lexical error pattern in naming and repetition. Also described here are the results of a longitudinal study of NC's naming and repetition, which revealed a shift in relative lexical error rates toward a qualitatively normal pattern. This change in error pattern was simulated by assuming that recovery reflects resolution of the rapid decay rate toward normal levels. The patient data and computational studies are discussed in terms of their significance for the understanding of aphasic impairments and their implications for models of lexical retrieval. © 1994 Academic Press, Inc.

## INTRODUCTION

Errors produced by normal speakers have historically provided the principal data base for the development of language production models (e.g., Fromkin, 1971; Garrett, 1975; Fay & Cutler, 1977; Dell & Reich, 1981; Harley, 1984; Stemberger, 1985). In addition to accounting for normal deviations from accurate processing, a model of language production should be able to accommodate error patterns that occur as a consequence of brain damage, whether these are quantitative or qualitative variants of the normal pattern. Error patterns that depart qualitatively from the normal pattern present a challenge to models developed to account for normal production. Indeed, the ability to reconcile qualitative differences between normal and pathological language performance might be viewed as a particularly stringent test of the adequacy of a language production model. The studies we report here constitute such a test, carried out on the production model developed by Dell (1986).

Martin and Saffran (1992) have described the naming and repetition performance of an aphasic patient, NC, whose error patterns depart significantly from patterns observed in normals. In naming, NC produced a higher rate of form-related word substitutions (formal paraphasias, equivalent to malapropisms in normal speech) than semantic substitutions, a pattern opposite to that observed in normal speech error corpora, where semantic errors are more frequent than form-based substitutions (e.g., Stemberger, 1985; Martin, Weisberg & Saffran, 1989). It is also rare that formal paraphasias are observed as the predominant error type in aphasics, although Blanken (1990) recently reported a disproportionately high rate of these errors in another patient, F.B.<sup>1</sup> In addition to his difficulties in naming, NC made errors in repeating words, a common manifestation of aphasia. The unusual feature of his repetition pattern was the occurrence of errors that were semantically related to the target word. The production of semantic errors in word repetition is associated with deep dysphasia, a relatively rare syndrome characterized by an inability to

<sup>1</sup> DB's formal paraphasias were unusual in that they tended to preserve the stressed vowels of target words but not their initial consonants, as is the case for malapropisms in normal speech.

repeat non-words and the production of semantic errors (along with other error types) in repetition. The term deep dysphasia is applied as an analog to deep dyslexia, an acquired reading disorder characterized by the production of semantic errors in oral reading and an inability to read non-words.

Cognitive neuropsychologists have generally tried to account for complex deficit patterns within the framework of modular information processing models by postulating multiple sites of damage within the relevant system(s) (see, for example, Shallice & Warrington, 1980, for such an account of deep dyslexia, and Howard & Franklin, 1988, for an account of deep dysphasia). For the most part, these explanations also assume a transparent relationship between the symptom (e.g., semantic error) and the impairment that gives rise to it (damage to the semantic system). Co-occurring deficits are linked not as a consequence of the functional architecture, but by virtue of anatomy, that is, by a lesion that happens to damage more than one module. As recent work has demonstrated, non-discrete models hold out the possibility of more complex relationships between deficit patterns and the deficits that underlie them. Thus, as Hinton and Shallice (1991) have shown in lesioning a connectionist network to model deep dyslexia, damage to orthographic units can give rise to semantic errors (see also Plaut & Shallice, 1991, 1992).

We have begun to explore the potential of a different type of non-discrete model, the interactive activation model of production developed by Dell (1986), to account for error patterns in aphasia (e.g., Schwartz, Saffran, Bloch, & Dell, 1994). As part of this effort, Martin and Saffran (1992) proposed an impairment to the Dell model that, they argued, would result in the error patterns observed in NC. In this paper we present two lines of evidence in support of Martin and Saffran's proposal: (1) longitudinal data consistent with predicted changes in NC's error patterns and (2) computational studies that explicitly test the consequences of the proposed "lesion" to the Dell model.

Dell's model, as it pertains to lexical selection in production, is shown in Fig. 1. Levels of linguistic representation (semantic, lexical and phonological) are combined with a spreading activation retrieval mechanism that employs feedforward and feedback connections to carry priming activation to the target and related nodes in the lexical network. In this model, it is assumed that malapropisms are errors of lexical selection that are mediated in part by feedback from post-lexical phonological activation (e.g., Harley, 1984; Stemberger, 1985; Dell, 1986). The target lexical node has been appropriately activated by semantic processes and activates its corresponding phonemes. Feedback from these activated nodes to the lexicon reinforces activation of the target lexical node, but activates other phonologically related lexical nodes as well. Since feedback to the lexical level occurs for all phonemes of the target word, the

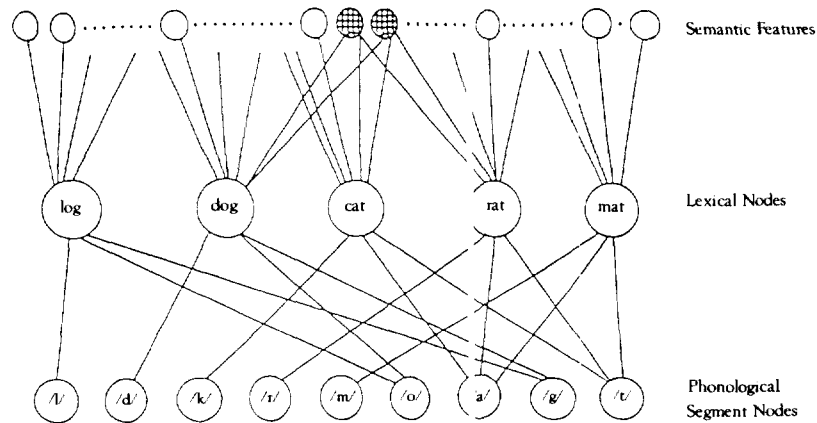


FIG. 1. Dell's model of lexical retrieval in language production. (From Dell & O'Seaghdha, 1991. Copyright 1991 by The American Psychological Association. Reprinted by permission.)

phonological similarity of malapropisms and targets need not exclusively involve initial phoneme segments. An error occurs when this feedback raises the activation of a non-target lexical node to a level higher than the target node. Several factors combine with feedback to create this situation. The competitor node may have a higher resting activation level (higher frequency) than the target and/or it may be primed in some way by the context in which the target node is activated. Contextual error sources may be internal to the planned utterance (e.g., anticipations and perseverations) (Dell, 1988) or they may be influences that intrude from outside the planned utterance (Harley, 1984). Feedback from phonemic to lexical nodes also provides a mechanism for the "lexical bias" effect, the finding that phoneme substitutions result in words at greater-than-chance levels in normal speakers (Dell, 1986). Semantic errors arise due to the priming of semantically related competitors along with the target node; this activation combines with the effects of frequency, contextual priming and noise in the system to raise the activation of the semantically related lexical node to a level higher than the target. Thus, in this model, lexical errors arise as a consequence of the normal operations of the lexical network; that they are semantically and/or phonologically related to the target word depends on spreading activation from semantic and phonological nodes which contributes to the activation levels of lexical nodes during the retrieval process. This is not to say that impairment of semantic or phonological processes would not affect the occurrence of lexical errors. To the contrary, the stability of semantic and phonological processes contributes significantly to the probability of accurate lexical selection.

As a first step in mapping aphasic disorders onto this model, we have

focused on two parameters, connection strength and decay rate, which regulate the efficiency with which activation is transmitted through the system. In conjunction with speech rate, these two variables affect the amount of activation that a targeted node receives in relation to that sent to other competing nodes in the network. The effect of connection strength on speech error patterns has been explored in several recent studies comparing computational and empirical data (Dell, 1989; Schwartz et al., 1994). Dell (1989) demonstrated that practice, a variable that presumably increases connection strength, influences not only accuracy of performance but also the pattern of error in normal adults' recitation of tongue twisters. When the system is operating at low efficiency, error rates are high, errors tend to be perseverative, and there is no significant lexical bias in sound errors. Dell (1989) notes that this "bad" pattern of error is characteristic of normals' recitation of tongue twisters before practice, adults speaking at fast rates (Dell, 1986), children's speech (Stemberger, 1989), and at least some patients with jargon aphasia, a disorder characterized by a high proportion of non-word errors (Bloch & Schwartz, 1989; Schwartz et al., 1994). In contrast, a "good" pattern of error, characterized by low error rates, anticipatory errors and an increase in lexical bias of sound errors, is observed in normal adult speech at slower speaking rates (Dell, 1986) and after practice in reciting tongue twisters (Dell, 1989).

Although a reduction in connection strength in Dell's interactive model can account for certain error patterns in aphasia (Schwartz et al., 1994), it is unlikely that this manipulation would generate the high rate of formal paraphasias that was a prominent feature of NC's naming performance. According to the model, these errors result from the activation of phoneme nodes that feed back to competitors in the lexical network; for this feedback to occur, the target node must receive adequate priming. Reducing connection strength throughout the network might reduce the probability of selecting the target. However, it should not increase the probability of selecting a phonologically related node because the spread of activation to the phonological nodes in the network would be reduced as well (Martin & Saffran, 1992).

Martin and Saffran (1992) reasoned that two conditions would have to be satisfied in order to generate an increase in formal paraphasias within the Dell model. First, connection strength would have to be sufficient to allow priming at levels of representation that supply feedback to phonologically related lexical competitors. Second, when feedback reached the lexical nodes, the relative activation levels of the target node and of competitors activated by feedback would have to be altered to reduce the advantage normally enjoyed by the target. They argued that these conditions could be satisfied by a manipulation that allowed activation to spread normally through the network but, at the same time, reduced the target's advantage related to phonological competitors. This, they

suggested, could be accomplished by increasing the rate of decay of activation at all levels of the network. They argued, further, that a pathologically rapid decay rate could account for NC's unusual error pattern not only in naming but also in repetition. Martin and Saffran (1992) proposed that the distinctive features of NC's error pattern, formal paraphasias in naming and semantic errors in repetition, could be explained by a pathologically rapid decay of primed nodes in the semantic-lexical-phonological network. Support for this hypothesis is provided by longitudinal studies and simulations described below.

The case for the decay rate hypothesis will be developed in two parts. First, we present a summary of NC's clinical profile (described in detail in Martin & Saffran, 1992) and an analysis of his errors in naming and in repetition. Second, in a series of computational studies, we demonstrate that NC's qualitatively abnormal lexical error pattern in both naming and repetition can be accounted for by a quantitative change in the decay rate parameter that shifts the relative activation levels of nodes in the lexical network. In addition, we show that this "lesion" is consistent with changes in NC's lexical error pattern that occurred over time as he recovered from his language impairment.

#### PART I. NC: CASE DESCRIPTION AND ANALYSIS OF LANGUAGE PERFORMANCE SUBJECT

NC, a 28-year-old male, suffered a left middle cerebral artery aneurysm in November, 1989 at the age of 26. A post-operative CT scan revealed a periventricular hyperdense area. A more recent CT scan (March, 1991) showed a well-defined region of low attenuation in the left temporoparietal region. This left him with severe deficits in auditory comprehension, repetition, and naming. NC was originally classified as a Wernicke's aphasic and also demonstrated characteristics of word deafness. Spontaneous speech was fluent, but contained numerous errors including formal, semantic, and phonological paraphasias as well as neologisms (mostly target-related).

##### Summary of Background Investigation

A detailed report of background studies of NC may be found in Martin and Saffran (1992). Below, we present a summary of that investigation.

##### *Phoneme Discrimination*

NC's ability to discriminate phonemes was tested in a minimal pair judgment paradigm that required him to decide if auditorily presented pairs of words or nonwords were the same or different. The test was run under three conditions varying the delay between presentation of each

item in the pair: no delay, unfilled 5-sec delay and a filled 5-sec delay. In the last condition, the examiner and the subject counted from 1 to 5 at a rate of approximately one count per second. While NC performed perfectly under the no delay condition, his performance declined in the unfilled (.80 correct) and filled (.65 correct) delay conditions, indicating rapid decay of the information that supports discrimination of phonemes.

### *Lexical Decision*

While lexical decision with written words was nearly perfect, auditory lexical decision was very impaired. In judging the lexicality of 79 words and 79 nonwords, NC reliably rejected nonwords (only one error), but his recognition of real words was influenced by imageability (High: .59 vs. Low: .25) ( $\chi^2(1) = 6.83, p < .01$ ), although not by frequency (High: .45 vs. Low: .36) ( $\chi^2(1) = .354, p > .70$ ).

### *Auditory Comprehension*

The auditory comprehension subtests of the Boston Diagnostic Aphasia Examination (BDAE) (Goodglass & Kaplan, 1972) were administered over the first few months following the onset of his aphasia. NC's scores on these subtests placed him in the following percentile ranks (For aphasics): word discrimination, 55; body part identification, 80; following commands, 10; and complex ideational material, 30. Although auditory and written comprehension were impaired, the latter appeared less so, and NC frequently asked to see the written form of spoken words he could not understand.

On other tests of auditory word comprehension, NC performed relatively poorly. On the Peabody Picture Vocabulary Test (Form L), for example, his performance was well below the first percentile for his age group. On the auditory word-picture matching subtest of the Philadelphia Comprehension Battery (Saffran, Schwartz, Linebarger, Martin & Bochetto, 1988), he showed significant tendencies to select distractors semantically or phonologically related to the targets.

### *Short-Term Memory Span*

NC's performance on auditory span tasks was severely impaired. Repetition even of single items was poor (digits, .65 correct; words, .60 correct). Using a pointing response, he made many errors with single digits (.35 correct) and although better with single words (.90 correct) his performance dropped off rapidly with two word lists (.53 correct). Performance with visually presented digit strings was much better (two digits, .95 correct; three digits, .80 correct).

### *Summary of Background Investigation*

NC demonstrates severe impairments in auditory input processing and short-term memory. Although his performance with visual materials is generally below normal, he tends to perform much worse with auditory presentation. NC's ability to discriminate phonemes is intact, but his ability to recognize phoneme strings as words is dependent on a meaning-related parameter, imageability. Sensitivity to imageability has been observed in other patients with deep dysphasia (e.g., Howard & Franklin, 1988).

### Naming

As was noted, NC's production was fluent but paraphasic. Both lexical and nonlexical errors were observed in all production tasks. In confrontation naming the accuracy of his performance was shown to be sensitive to both frequency and syllable length of the target (Martin & Saffran, 1992). The most striking feature of NC's naming errors was the large percentage of formal paraphasias. Despite their lexical form, it has been suggested that formal paraphasias may be phonological errors that by chance resemble real words (e.g., Butterworth, 1979; Buckingham, 1980; Ellis, Miller & Sin, 1983). The analyses described below demonstrate that NC's formal paraphasias are, in fact, lexically generated.

### *Selecting and Classifying the Corpus of Errors*

The corpus of errors used in the analyses that follow was obtained from NC's responses to pictures on three naming tests. Although NC frequently made multiple attempts, the corpus consists only of first attempts at naming the target pictures. NC was very talkative during these sessions and sometimes made comments about a pictured object before attempting to give its name. Thus, his first utterance did not always represent his first attempt to name the picture. It could be argued that these verbalizations influence the eventual response, but it did not seem judicious to assume NC's first utterance was necessarily a first effort to produce the name. We therefore used subjective criteria to identify the subject's first attempt to name the target. These judgments were based on the context in which the utterance occurred and clues from intonation and starter phrases (e.g., "It's a . . ."). If NC made no attempt to name the picture, but talked about it appropriately, the response was labeled a semantic description.

To classify the errors, we used a scheme similar to that used in Martin & Saffran (1992), but with a few modifications. Two categories were further refined (Appendix A): (1) semantically related descriptions that were not direct attempts to name the target (formerly classified as semantic paraphasias) were placed in a separate category and (2) neologisms



were subdivided into target-related and abstruse neologisms (although NC's neologisms were primarily target-related). Our criteria for classification of an error as a formal paraphasia were fairly liberal: the error had to be a word and had to have at least one consonant or stressed vowel in common with the target. Following Butterworth (1979), we adopted a broad standard to avoid making a priori assumptions about the nature of the processes that give rise to these errors (see Schwartz et al., 1994, for further discussion of this issue).

### *Distribution of Errors*

For the analyses which follow, we used naming responses from three naming tests (one with targets varied for frequency and syllable length ( $n = 48$ ),<sup>2</sup> the Boston Naming Test ( $n = 60$ ) (Kaplan, Goodglass, & Weintraub, 1976), and the Low Frequency Naming Test (Saffran, 1981) ( $n = 64$ ) for a total of 172 responses. NC correctly named .27 of these items and the errors he produced were distributed as follows: semantic paraphasias, .03; semantic descriptions, .08; formal paraphasias, .19; semantic + formal paraphasias, .06; target-related neologisms, .20; abstruse neologisms, .01; unrelated lexical errors, .01; formal paraphasias on a semantic error, .02; neologisms on a semantic error, .06; perseverations, .01; no response, .06.<sup>3</sup> The error corpus is listed in Appendix B.

Although the high rate of formal paraphasias suggests that they are distinct from phonologically related nonword errors (neologisms), it is necessary to demonstrate that these are lexically based errors rather than phonological errors that by chance create words. Accordingly, we conducted several analyses to justify the assumption that these errors were lexically generated.

### *Lexical Errors: Do They Arise by Chance?*

Our use of liberal criteria to classify errors as formal paraphasias made it necessary to demonstrate that the phonological similarity of these errors and their respective targets did not arise by chance. We established a chance measure of phonological similarity between the targets and errors in the following way: The corpus of 56 lexical errors (semantic, formal, semantic + formal, semantic  $\rightarrow$  formal and unrelated lexical paraphasias) was randomly assigned to the set of corresponding targets. For

<sup>2</sup> We thank Rita Berndt and Alfonso Caramazza for providing us with this test.

<sup>3</sup> These percentages are slightly altered from those reported in Martin & Saffran (1992) for several reasons. Some errors were reclassified (in particular, additional formal relations were noted in some semantic paraphasias and semantic relations in formal paraphasias, thus increasing the percentage in the F + S category and reducing the percentages in the S and F categories).

each target-error pair, it was then determined whether the members were phonologically related or not (irrespective of whether they were related semantically). We then tabulated the number of target-error pairs that were phonologically related and the number which was not. This randomization and scoring process was repeated three times. The distributions of phonologically related and unrelated pairs in NC's corpus of lexical errors and in the three randomizations are reported in Table 1. McNemar tests were used to compare each of these chance estimates of phonological relatedness between targets and lexical errors to the actual proportion of lexical errors in NC's corpus that held a phonological relationship with the target (45/56). In each case, the proportion of NC's lexical errors that were phonologically related to the target was significantly greater than that in the random corpus: Random 1,  $\chi^2(1) = 11.17, p < .01$ ; Random 2,  $\chi^2(1) = 10.02, p < .01$ ; Random 3,  $\chi^2(1) = 7.76, p < .01$ .

The same procedure was used to determine the probability that a semantic relationship between a target and an error could arise by chance. The actual rate of errors which were semantically similar to their targets (17/56) was compared to each of the randomly generated chance rates and found to be significantly greater in each case; Random 1,  $\chi^2(1) = 11.50, p < .01$ ; Random 2,  $\chi^2(1) = 15.05, p < .01$ ; Random 3,  $\chi^2(1) = 12.50, p < .01$ . Thus, we can conclude that the tendency for NC's lexical errors to be phonologically or semantically similar to the targets they replaced is far in excess of what would be expected by chance.

#### *Preservation of Target Characteristics in Formal Paraphasias*

Formal paraphasias, by definition, are phonologically related lexical errors. In addition to sharing phonological features of the target, we would expect them to share lexical characteristics as well. In the next two analyses we investigate the nature of both phonological and lexical relationships between the targets and formal errors produced by NC.

*Preservation of phonology.* We first examined the preservation of target phonology in NC's corpus of formal paraphasias to determine if the

TABLE 1  
Rates of Related and Unrelated Pairs in NC's Error Corpus and in Three Randomizations of NC's Error Corpus

| Relationship             | NC's lexical errors | Random corpora |    |    |
|--------------------------|---------------------|----------------|----|----|
|                          |                     | 1              | 2  | 3  |
| Phonologically related   | 45                  | 26             | 25 | 28 |
| Phonologically unrelated | 11                  | 30             | 31 | 28 |
| Semantically related     | 17                  | 2              | 0  | 1  |
| Semantically unrelated   | 39                  | 54             | 56 | 55 |

errors resembled the targets in any systematic way. Only responses to one and two syllable targets with stress on the first syllable were used ( $n = 25$ ) since the majority of formal paraphasias were produced in response to this class of targets. For each target-error pair, we examined the phonological similarity of the target and error across segmental positions of the target word. For one syllable targets we examined preservation of the initial consonant (IC), stressed vowel (SV) and final consonant (FC). For two syllable target words we examined six segmental positions of the target (first syllable: initial consonant (IC-1), stressed vowel (SV), final consonant (FC-1) and second syllable: initial consonant (IC-2), unstressed vowel (USV) and final consonant (FC-2)). A phoneme in the target was considered present in the error if it occurred anywhere in the error form. If a segmental position was filled with a consonant cluster or diphthong, half credit was given for presence of any phoneme in that cluster or diphthong.

To determine if the error corpus departed in any systematic way from chance expectations, a pseudocorpus of errors was generated and subjected to a similar analysis. The method of generating this random corpus was adopted from Blanken's (1990) procedure with one small change.<sup>4</sup> The method was as follows: (1) The frequency value of the formal paraphasia was obtained from Kucera & Francis (1967). (2) The formal paraphasia was decomposed into its consonant-vowel structure (e.g., pin → CVC). (3) The Kucera and Francis (1967) listing of words in order of frequency (as opposed to alphabetical order) was used to search for a word that shared the CVC structure of the formal paraphasia. This was done by finding the section of the listing that contained words that were one value higher in frequency than the *target*. Starting at a randomly determined point within that section of the list, we searched sequentially towards (alternately) the beginning or end of the section for the first word that shared the consonant-vowel structure of the formal paraphasia. This word was selected as the control word for the item.

The results of these analyses are shown in Figs. 2 and 3. A McNemar test revealed a significantly greater retention of targets' initial consonants in NC's corpus, relative to the random corpus: one syllable targets, .78 ( $\chi^2(1) = 4.17, p < .05$ ) and two syllable targets, .83 ( $\chi^2(1) = 6.67, p <$

<sup>4</sup> In the third step of this procedure to establish chance similarity of target and error phonology, Blanken (1989) alternated the start of a search through the frequency-based sublistings from the beginning and the end of the list. We found that because some of the Kucera & Francis (1967) frequency-based alphabetical sublistings have many members, this procedure often biased the selection of the pseudoerror towards words that start with letters from the beginning or end of the alphabet. Therefore we opted to begin our search for the pseudoerror at a random point in the alphabetical sublistings and proceed towards the beginning or end of the alphabet until a word that matched the CVC structure of the real formal paraphasia was identified.

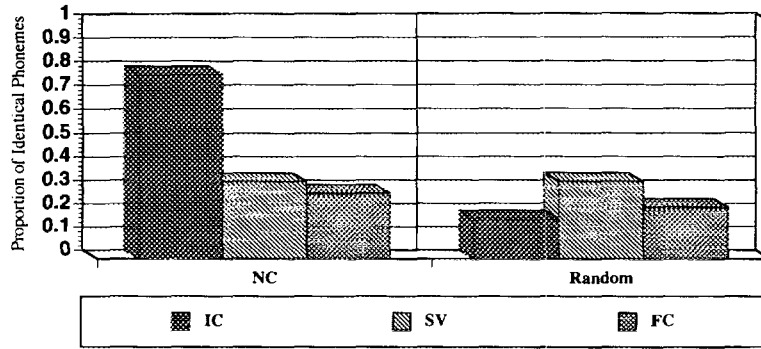


FIG. 2. Proportion of target phonology preserved in NC's formal paraphasic errors and a random corpus of errors (one syllable targets) in three segmental positions: IC, initial consonant; SV, stressed vowel; FC, final consonant.

.01). In contrast, NC's errors showed no more tendency to preserve stressed vowel information than that which would be expected by chance (one syllable:  $.22$ ,  $\chi^2(1) = .25$ ,  $p > .70$ ; two syllable:  $.38$ ,  $\chi^2(1) = .25$ ,  $p > .70$ , one tailed). Unlike Blanken's patient (RB), whose errors tended to preserve vowel information, NC's errors tend to preserve initial consonants, which is also the case with normal malapropisms (e.g., Fay & Cutler, 1977), thus providing further evidence that NC's formal paraphasias have lexical involvement.

*Preservation of grammatical category.* A tendency for errors to preserve grammatical category strongly indicates that they are generated lexically. On the other hand, if NC's formal paraphasias are actually phonological slips that by chance resemble words, grammatical category

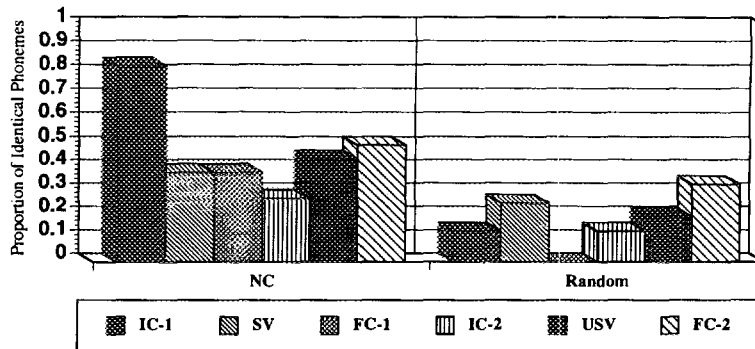


FIG. 3. Proportion of target phonology preserved in NC's formal paraphasic errors and a random corpus of errors (two syllable targets) in six segmental positions: IC-1, initial consonant-first syllable; SV-1, stressed vowel-first syllable; FC-1, final consonant-first syllable; IC-2, initial consonant-second syllable; SV-2, stressed vowel-second syllable; FC-2, final consonant-second syllable.

should not be respected even if the testing conditions (confrontation naming) bias the speaker to produce nouns. To determine if categorial status was maintained, we used the pseudocorpus of 25 errors generated for the analysis of phonological similarity (see (1) above) to estimate a chance rate of categorial relationship and compared it to the actual rate in NC's corpus of formal paraphasias. The rate of preservation in NC's corpus of formal paraphasias was quite high (28 out of 33 errors) and was significantly different than the chance estimate that target and error would share grammatical category (15 out of 25 "errors") ( $\chi^2(1) = 13.77, p < .001$ ).

We sought additional evidence on this point by examining the preservation of categorial information in a subset of NC's formal paraphasias, those that differed from the target by a single phoneme (e.g., rake → rook). Errors that differ from the target by a single phoneme are more likely to be phonological slips that happen to be words than are formal paraphasias that depart further from the target phonologically (e.g., mask → master). If these are, indeed, phonologically based errors, they should be less likely to preserve grammatical category than formal paraphasias that bear less phonological resemblance to the target. In this corpus, there were seven single phoneme errors that resulted in a word and all of these preserved the grammatical category of the target (noun). Thus, even in the cases of formal paraphasias that are most likely to reflect errors at the phonological level (a single phoneme slip), there are strong indications of lexical involvement.

#### *Target-Error Frequency Comparison*

One variable that should contribute to the production of a malapropism is the frequency of the error word. It follows that if NC's formal paraphasias are lexically based, they should tend to be high in frequency. It is difficult to say how high is "high" because the great proportion of lexical items are quite low in frequency. As a particularly stringent test, we examined whether NC's formal paraphasias were actually higher in frequency than the target words themselves.

A frequency analysis was conducted on NC's corpus of formal paraphasias collected from all three naming tests. The tendency for targets to be replaced by words of higher frequency approached significance (Sign test:  $N = 32, z = 1.59, p < .06$ , one-tailed).

#### *Preservation of Target Characteristics in Formal Paraphasias and Neologisms*

If formal paraphasias are lexically generated, we might expect them to bear less resemblance to the target than neologisms because their phonological form is presumably driven by a different lexical node than the

target. Neologisms, on the other hand, are likely to be phonologically based distortions of the target. In the following analyses, we examined the extent to which syllabic structure and segmental phonology were preserved in the formal paraphasias and neologisms in NC's corpus.

*Preservation of target phonology in neologisms and formal paraphasias.* This analysis was conducted on all formal paraphasias ( $n = 33$ ) and all target-related neologisms ( $n = 34$ ) in the corpus. To compare preservation of segmental and structural features of the target in neologisms and formal paraphasias, we used the following procedure. We first computed the total number of phonemes and total number of syllables in the target word and in the error form (e.g., mask (/mæsk/) (4 phonemes, 1 syllable) + master (/mæ-stə/) (5 phonemes, 2 syllables) = 9). We then computed the total number of phonemes that the target and error had in common (/mæs/ (3) + /mæs/ (3) = 6) plus a measure of preserved syllabic structure. For this latter measure, credit for preservation (total number of syllables of target and error) was given only if the target and error had the identical number of syllables (e.g., mask (1 syllable) + man (1 syllable) = 2). Otherwise, a value of zero was assigned to the target-error pair (e.g., mask (1 syllable) + master (2 syllables) = 0). The number of phonological and syllabic features shared by the target and error word were summed. As a measure of structural preservation, this sum takes into account those features which are present (phonemes and syllabic form) as well as those that are omitted. The proportions of phonemes that the two types of errors held in common with their targets were compared using the Mann-Whitney  $U$  test. This measure indicated that neologisms produced by NC tended to preserve more phonological and syllabic features of the target word (.58) than his formal paraphasias (.46) ( $U = 660, z = 1.97, p < .02$ ).

#### *Summary of Naming Analysis*

We have hypothesized that NC's formal paraphasias in naming are errors that reflect selection of a lexical node other than the target as opposed to phoneme substitutions that happen to be words by chance. As such, they differ from neologisms (target-related) which are likely to be generated from properly selected target nodes that do not sufficiently activate the corresponding phonology for production. Several lines of evidence support this view. The formal paraphasias are more similar to their target words than would be predicted by chance and show a specific pattern of phonological similarity to the target: a marked tendency to preserve the initial phonemes of the target. The neologisms are more similar to the target (in number of syllables and degree of phonological similarity) than the formal paraphasias, which suggests that the latter are more likely to be driven by a different (non-target) lexical node. There is

also a tendency for NC's formal paraphasias to preserve the grammatical category of the target and to be higher in frequency than targets they replace, indicating that they are lexically generated errors. The data therefore justify the assumption that NC's formal paraphasias reflect selection of a lexical node other than the target.

#### Repetition of Single Words and Nonwords

As noted in the Introduction, NC demonstrated a severe repetition disorder that affected his ability to reproduce even single words. Below, we summarize the results of several tests of this repetition performance.

The first repetition test administered to NC included one and two-syllable concrete, abstract, closed class words and pseudowords. There were 24 items in each group and the mean frequencies per million (Kucera & Francis, 1967) of the word groups were 57 (concrete), 151 (abstract) and 1197 (closed class). NC correctly repeated .58 concrete words, .17 abstract words, .21 closed class words and .03 nonwords, thus showing sensitivity to lexicality, form class and concreteness.

In a second test of repetition, 30 nonwords were contrasted with 30 one and two-syllable concrete nouns varying in frequency from 1 to 1772 per million (Kucera & Francis, 1967). On this set of items, the difference in NC's ability to repeat words (.97 correct) and nonwords (.10) was quite dramatic. He also showed little tendency to lexicalize nonwords in repetition (.19 lexicalizations).

In a third test (adapted from a reading list in Kay, Lesser, & Coltheart, 1987), we examined the effects of frequency and imageability on single word repetition. NC correctly repeated high imageability words significantly more often than (.53) low imageability words (.08) ( $\chi^2(1) = 17.2$ ,  $p < .001$ ) that were matched in frequency. Frequency did not affect his performance on this task. Oral reading of these same words was more accurate, but paralleled repetition in that it was influenced by imageability (high: .85 correct, low: .63 correct) ( $\chi^2(1) 4.13$ ,  $p < .05$ ), but not by frequency.

#### *Errors in Repetition*

On the adaptation of the Kay et al. (1987) word list, NC's errors included semantic paraphasias (.04), formal paraphasias (.20), semantic + formal paraphasias (.04), and target-related neologisms (.05). There were also many instances in which no response was given (.34).<sup>5</sup> Although the rate of semantic errors on this test was low, on another set of targets ( $n = 49$ ) which were all highly imageable (from the Low Frequency Nam-

<sup>5</sup> These figures differ slightly from Martin & Saffran (1992) because several errors were reclassified.

ing Test, Saffran, 1981), the rate increased to .14 (plus an additional .08 semantic + formal paraphasias), suggesting a possible relationship between imageability and the production of semantically related responses in repetition. NC's semantic errors were often single words (e.g., gravity → science) but sometimes were short descriptive phrases (e.g., blindfold → when you put on your eyes). We included both single words and short phrases as semantic errors in repetition in keeping with the literature in deep dysphasia (Morton, 1980) and its counterpart in reading, deep dyslexia (Coltheart, 1980). These errors are provided in Appendix C. Although short phrases may appear identical in character to semantic descriptions produced in picture naming (which were removed from the semantic paraphasia category), they are arguably quite different. Whereas description of an object need not necessarily reflect a failed attempt at producing the object name, phrasal responses in word repetition are very likely to represent efforts to reproduce the target.

*Summary of NC's language impairment.* As the preceding analyses have shown, NC exhibits a severe lexical retrieval disorder that affects both naming and repetition. The errors that he produces are both lexical and nonlexical and reflect semantic and phonological relationships with the target. Input processing (word recognition and comprehension), as well as the ability to temporarily store input are also severely affected, particularly in the auditory modality. Martin and Saffran (1992) hypothesized that a rapid decay of primed nodes in the semantic-lexical-phonological network could account for this pattern of impairments. We describe this proposal in more detail below, along with the results of computational studies carried out to test the decay hypothesis.

## PART II: LONGITUDINAL AND COMPUTATIONAL STUDIES IN SUPPORT OF A RAPID DECAY ACCOUNT OF NC'S NAMING AND REPETITION IMPAIRMENT

Martin and Saffran's (1992) account of NC's deficit pattern was based on inferences from Dell's (1986) model of lexical retrieval in language production. One of the strengths of the model, as developed in Dell's (1986) paper, was that in addition to generating hypotheses that were empirically testable, the model was implemented computationally. A virtue of a computational or formal instantiation of a theory is that it enables input-output relations to be accurately determined. This is particularly important when the theory has a highly nonmodular structure, that is, when many factors have the potential to influence some action, when the theory's input-output relations are computed by a non-linear system, and when there is a need to include stochastic processes. All of these are true of the model we are using to account for NC's performance. It may be possible to informally derive some qualitative features of a model's



behavior, as Martin and Saffran (1992) did in their application of Dell's model to some features of NC's naming and repetition disorder. But such applications provide no assurance that different informally derived qualitative features of the model are consistent with each other. In other words, does the same set of parameters that produces one desired behavior produce other desired behaviors as well? Furthermore, there is no assurance that an informally derived feature (e.g., greater decay leads to more formal paraphasias) has approximately the right quantitative character.

Below we report the results of computational studies carried out to determine whether the model would, in fact, behave as predicted under conditions of rapid decay. We also provide data on NC's error patterns as they changed in the course of recovery, and the results of efforts to simulate these changes in performance. Simulations were carried out for naming using a somewhat simplified version of the original Dell (1986) model (Dell & O'Seaghdha, 1991) and for repetition by reversing the direction of information flow through the model. Each of the simulation studies is introduced by a description of how the interactive activation model is assumed to operate, under normal conditions and under conditions of rapid decay.

### Naming

Martin and Saffran (1992) proposed that a high rate of formal paraphasias in naming could result from a pathological increase in the rate of decay of the target lexical node. Increasing the decay rate would still allow priming of the target node and phoneme nodes connected to it, which is necessary for the production of phonologically related word substitutions. With an increase in decay rate, however, the original activation of the target node would decay rapidly and would no longer sum with the activation provided by feedback from the phoneme level. The net result is to decrease the advantage that the target normally would have over phonologically related lexical nodes, or, more generally, to increase the likelihood of selecting competitors that are less affected by the pathologically high decay rate because they are activated later in the selection process.

Figure 4 shows the evolution of these feedforward and feedback priming processes through the semantic-lexical-phonological network extended over time from conception to lexical selection. The time steps in the figure demarcate stages of priming activity leading up to selection of a lexical node for output. Semantic and lexical nodes appearing more than once in the figure are actually the same nodes at different time steps. Although we have depicted the process in five steps, this number is arbitrary and the figure is meant primarily to show the processes by

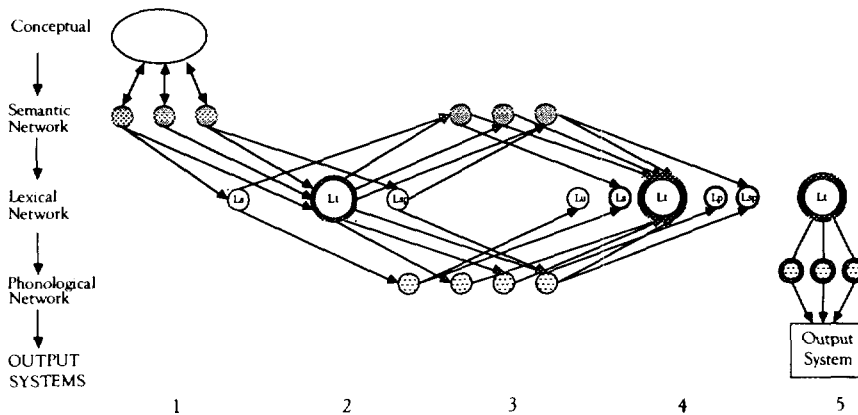


FIG. 4. A single pass through Dell's model of lexical retrieval subserving output processes. Priming activity leading to selection of the target or some related lexical node is depicted over five arbitrarily set time steps.

which the selection probabilities of the lexical target and its competitors are established.

As shown in Fig. 4, lexical selection in this spreading activation model occurs in the following way. In Time Step (TS) 1, conceptual processes prime targeted semantic nodes which in TS 2 feedforward to prime the target (Lt) and, to a lesser extent, semantically related (Ls) as well as semantically + phonologically (Lsp) related lexical nodes. (The Lsp nodes are activated on the basis of their semantic relation to the target, but, by chance, hold a phonological relationship to the target as well.) In TS 3, activation from the primed lexical nodes (target and competitors) feeds back up to semantic levels to reinforce activation of those nodes and also feeds forward to activate corresponding phonological nodes. In TS 4, the primed lexical nodes (target and competitors) activated in TS 2 receive feedback from activated phonological nodes and reverberating feedback from the semantic nodes. It is in this step that phonologically related lexical nodes (Lp) get activated by feedback from phonological nodes (the origin of the potential formal paraphasia). There is also the possibility of priming a seemingly unrelated lexical node (Lu) via feedback activation from phonological nodes corresponding to the semantically related lexical competitor primed in TS 2. When lexical selection processes are initiated, the most active lexical node is selected and the activation is passed on to phonological encoding processes. Since the target receives most of the initial activation, its probability of being selected is far greater than that of any of the competitors.

The decay component in this model applies at each time step and a certain level of decay is necessary to keep the system responsive. A node is activated, sends a proportion of this activation to the next level, and

then decays by some proportion before feedback from a higher or lower level returns to reinforce its activation. If nodes do not decay, they will interfere with activation and selection of other primed nodes. On the other hand, if nodes decay too quickly after they are primed, the result is an alteration in the relative activation levels of the target node and its competitors in the 4th time step before selection. Specifically, activation levels (and consequently, the selection probabilities) of the target and semantically related lexical nodes are reduced relative to those of the phonologically related lexical nodes for the simple reason that these nodes are activated later (first primed in TS 4) and thus are subject to less decay than the target and semantically related lexical nodes (first primed in TS2). These circumstances should lead to a higher than normal rate of formal paraphasias in naming (Martin & Saffran, 1992).

To test this hypothesis, we examined the effects of increasing the decay rate in a computational model used to generate the pattern of naming error observed in normals (Dell & O'Seaghdha, 1991). Additionally, we simulated the evolution of NC's error pattern as recovery occurred on the assumption that such recovery would reflect the resolution of the rapid decay rate towards normal levels.

#### *Simulation of Normal Error Patterns*

As a first step in examining the effects of rapid decay of nodes in the semantic-lexical-phonological network, it was necessary to establish a baseline simulation of normal error patterns. Evidence suggests that although normal speakers tend to make few errors (Garnham, Shillcock, Brown, Mill, & Cutler, 1981), they produce more semantic errors than malapropisms (formal paraphasias) (Hotopf, 1980; Stemberger, 1989; Martin et al., 1989). Additionally, normals tend to produce more mixed (semantic + formal) errors than semantic errors when available opportunities are taken into account (Martin et al., 1989) and relatively few non-word substitutions (noncontextual phoneme substitutions) (Stemberger, 1989).

To simulate normal error patterns, the simple network from Dell and O'Seaghdha (1991) was used with a few minor changes. The Dell and O'Seaghdha network contained nodes for semantic features (10 per word) and word nodes for *cat* (the target); one semantically related word, *dog*, which shared one semantic feature with *cat*; one phonologically related word, *mat*; two words that were phonologically related to a semantically related word, *log* and *fog*; and one word that was both semantically and phonologically related, *rat*. The network also contained phoneme nodes corresponding to these words. One modification that we made was to change the semantic/phonologically related word, *rat*, into the word *hat*. This created a second purely phonologically related word and eliminated

the mixed word, resulting in what we felt was a more realistic neighborhood, as few words have semantic/phonological neighbors. *Rat* was made into *hat* simply by eliminating the connection between the semantic feature shared by *cat*, *rat*, and *dog* and *rat* word node, and relabeling the phoneme node *r* as *h*.

In this simulation, selection of a word node (in production) involves activation of semantic features followed by a spreading process that ultimately activates a lexical node and phonological segments. The spreading process occurs over  $n$  time steps. During each time step, any node with activation greater than zero sends a portion of its activation (connection strength,  $p$ ) to all nodes to which it is connected thus adding to the overall activation level of these nodes. Additionally, at each time step, a node's activation decays by some percentage ( $q$ ) toward a resting level which is 0 for all nodes. Connection strength and decay rate are each set at some value between 0 and 1. Each word node is connected to 10 semantic features and semantically related words share 1 of these features.<sup>6</sup> The word nodes are also connected to corresponding phonological segment nodes, and phonologically related words share two out of three segments. The activation function is linear provided that activation is nonnegative.

To simulate naming, 100 units of activation were given to the semantic features of *cat* (10 per semantic feature). This activation was allowed to spread through the network according to the following rules:

(1) *Updating function*:  $a(j,t) = a(j,t-1)(1-q) + \text{Input}(j,t)$ . In this standard linear activation function,  $a(j,t)$  is the activation of unit  $j$  at time  $t$ ,  $\text{Input}(j,t)$  is the input to  $j$ , and  $q$  is the decay rate.

(2) *Input function*:  $\text{Input}(j,t) = \sum_i (i,j) a(i, t-1)$ . In this standard weighted sum rule,  $w(i,j)$  is the weight from unit  $i$  to unit  $j$ . All weights, with the exception noted below, are equal to  $p$ ,  $0 < p < 1$ , and summation is over all units.

(3) All connections are bidirectional.

(4) *Noise*.  $X_1 + X_2$  is added to each node for every time step.  $X_1$  (intrinsic noise) is a value sampled from a normal distribution of mean = 0 and  $SD = S_1$ .  $X_2$  (noise related to activation level) is sampled from a normal distribution of mean = 0, and  $SD = S_2 \cdot a(j,t)$ .

After  $n$  time steps, the lexical node with the highest activation level was selected. It was given another jolt of activation (100 units) and after  $n$  more time steps the most activated phonological nodes were selected. A

<sup>6</sup> The semantic relatedness parameter used in this simulation is not based on any theory of semantics that distinguishes among types of semantic relations (e.g., categorical vs. associative), nor does it entail any estimate of the degree of relatedness that any semantic error actually holds with the target. Rather, this means of representing semantic relatedness is intended only to enable us to measure the effects of this variable on lexical selection processes.

single onset, vowel, and coda node were chosen, constituting the models' encoding of the target word.

The simulation entailed the setting of five parameters:  $p$ ,  $q$ ,  $n$ ,  $S1$ , and  $S2$ . The first three,  $p$ ,  $q$ , and  $n$ , were set as in Dell and O'Seaghdha's (1991) second simulation and were not varied:  $p = .1$ ,  $q = .4$ , and  $n = 8$  time steps.  $S1$  and  $S2$  were allowed to vary in an attempt to approximate normal performance. Also, the connection weight between the semantic feature common to *cat* and *dog* and the word node for *dog* was allowed to vary. The effect of this change could also be achieved by varying the number of common features, or adding another semantically related word, but it was simply more convenient to vary the connection weight in the implementation. After some exploration of the parameter space,  $S1$  was set at .01,  $S2$  was set at .18 and the common semantic feature/dog weight was set at  $1.5p$ . The results of a simulation with these parameters are shown in Table 2. The percentages represent the proportion of responses in each response category in 100,000 trials of naming and illustrate the main characteristics of normal performance. Lexicalization is quite accurate (a little more than one error per 1000 trials, e.g., as in Garnham et al., 1981) and there are more semantic than formal and non-word errors.

It is instructive to consider the fact that the network we are using contains a very small and constrained subset of English. We did this to

TABLE 2  
Simulation of Normal Naming

| Parameters             |  |                            |
|------------------------|--|----------------------------|
| Connection strength:   |  | $p = .1$                   |
| Decay rate:            |  | $q = .4$                   |
| Rate:                  |  | 8 time steps per selection |
| Intrinsic noise:       |  | $S1 = .01$                 |
| Noise from activation: |  | $S2 = .18 a(jt)$           |

| Possible Outcomes | Target: "Cat"<br>Error category                  | Response rate |
|-------------------|--|---------------|
| "cat"             | Correct (C)                                      | .99888        |
| "dog"             | Semantic (S)                                     | .00082        |
| "mat", "hat"      | Formal (F)                                       | .00018        |
| "lat", "mot"      | Neologism (N)                                    | .00012        |
| "mog", "dat"      | Neologism of semantic error (S → N) <sup>a</sup> | 0             |
| "log", "fog"      | Formal paraphasia of semantic error (S → F)      | 0             |

<sup>a</sup>  $S \rightarrow N$  = proportion of times the semantic error (*dog*) was selected at the lexical level minus the proportion of times it was actually "spoken" (i.e., its phonemes were selected at the phoneme level).

allow for easy interpretation of error phenomena and for efficient exploration of the parameter space. The alternative of actually trying to include in the model the test words used in standard patient batteries together with their phonological and semantic neighborhoods would require many arbitrary decisions as well as taking away from efficient exploration. The limitations of a small constrained vocabulary are equally clear. One should view the quantitative properties of the model's output, as opposed to qualitative trends, skeptically because the quantitative characteristics of the lexical neighborhoods in the model do not match those of words used in the studies. We note, however, that qualitative tendencies of small models should be preserved in large models (with appropriate parameter scaling) because of the local representations (each additional word simply adds an additional word node and appropriate connections) and the linear activation function. We do acknowledge, though, that the actual neighborhood structure of the model's network has a large influence on the probabilities of errors of particular types (e.g., if a word has no semantic neighbors, there can be no semantic errors). Consequently, we will attempt to show that all of the key characteristics of the model apply when differing neighborhoods are used.

#### *Simulation of Naming under Conditions of Rapid Node Decay*

In order to simulate the effects of a decay impairment on naming performance, all parameter settings (including noise) were held constant except the decay rate ( $q$ ) which was increased to .92. The distribution of responses that NC produced in an attempt to name 172 pictures is shown in the top part of Fig. 5. Since the simulation used in this study cannot produce a "no response," we took the instances in which NC made no attempt to respond and distributed them proportionately across all *error* categories with the assumption that had he made the attempt to name these pictures, he would have made an error. Because we do not know what this error would be, we made the null assumption that this error would not alter the relative proportions of obtained error responses.<sup>7</sup> In the bottom half of Fig. 5 we show the distribution of responses resulting from the simulation of naming when the decay rate was increased to .92. As the figure shows, the relative proportions of responses across error types produced by NC and the model are quite similar. There are relatively high percentages of formal paraphasias (F) and neologisms (N), a relatively lower rate of semantic errors and low rates of "double errors" (formal paraphasia on a semantic error ( $S \rightarrow F$ ), neologism of a semantic error ( $S \rightarrow N$ )).

<sup>7</sup> Although NC's semantically related descriptions and his mixed, unrelated, and perseverative naming errors were not included in the figure, the "no responses" were also redistributed proportionately across these error categories.

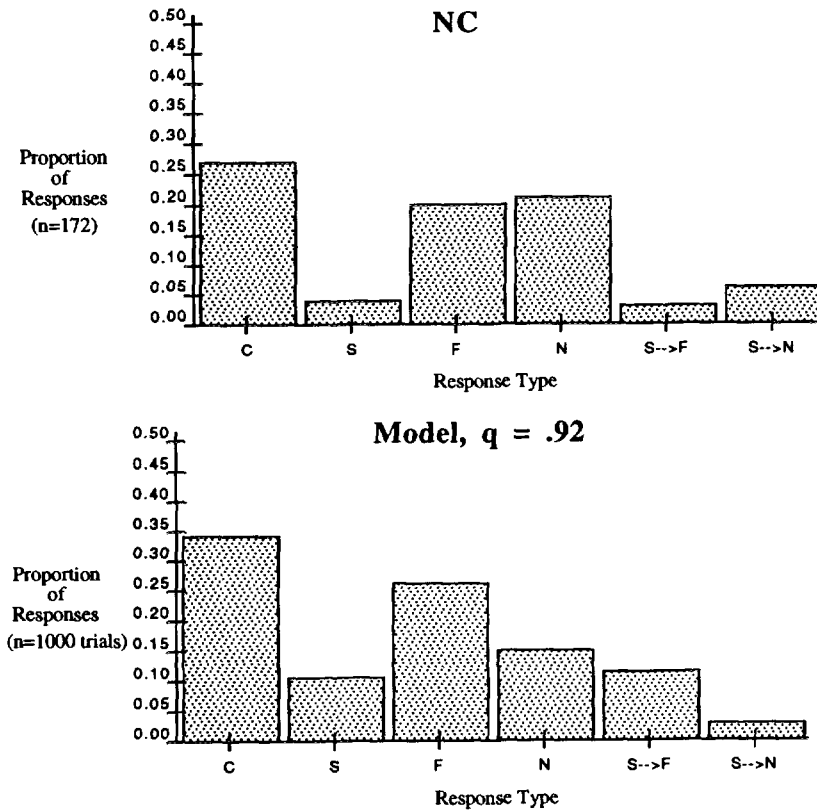


FIG. 5. Proportion of naming responses (NC and simulation of decay impairment) in each response category: C, correct; S, semantic paraphasia; F, formal paraphasia; N, neologism; S  $\rightarrow$  N, neologism on a semantic paraphasia; S  $\rightarrow$  F, formal paraphasia on a semantic paraphasia.

The increase in decay rate can be thought of as having two effects in the model. First, it simply amplifies any error tendencies present in the model when parameters are set at normal levels. When activation levels are lower than normal, noise in the network has a greater effect on what units are chosen, increasing the likelihood of errors that are extremely unlikely in normals (such as those in the S  $\rightarrow$  N or S  $\rightarrow$  F categories). This amplification of normal error tendencies would result from any change that lowers activation levels or increases random noise; hence, it is not a crucial test of the decay hypothesis, although it does speak to the error-induction characteristics of the model in general. The second effect associated with the increase in decay rate, and more critical in the present context, is the relatively greater percentage of formal paraphasias in naming (compared to normal). This is a specific effect of the decay

increase coupled with the assumed time course of processing in naming and would not result from a general loss of activation or increase in noise.

Table 3 shows the results of normal and impaired simulations under conditions of three different neighborhood configurations. The characteristics of the lexical neighborhood do have an effect on the distribution of errors. If there are more semantically related nodes in the neighborhood of the target word, for example, we would expect more semantically related errors. However, regardless of the configuration of the lexical neighborhood, the effect of increasing the decay rate is to increase the relative rate of formal paraphasias in production. The first configuration noted in Table 3 is the one used to simulate NC's error pattern. The second uses the same lexical nodes but designates *dog* as the target. The third configuration replaces one of the phonologically related lexical nodes, *hat*, with a semantically and phonologically related node (a potential mixed error), *rat*. This third simulation demonstrates another feature of the model: given equal opportunity for the occurrence of semantically related, phonologically related and mixed lexical errors, the rate of mixed errors should be highest. This is an unlikely lexical neighborhood under normal speaking circumstances, but when opportunities are controlled, normal speakers do tend to produce more mixed errors than semantically or phonologically related substitutions (Martin, et al., 1989).<sup>8</sup> In all three simulations, error distributions shift in predictable ways depending on the configuration, but in each case, the increase in decay rate has the effect of shifting the relative rates of semantic and formal paraphasias. Thus, alteration of the error pattern with an increased decay rate does not appear to be specific to the characteristics of the lexical neighborhood used in the original simulation.

The other aspect of the simulations that needs to be addressed has to do with the nature of the disruption to the processing system that we have hypothesized, that is, a rapid decay of node activation in the semantic-lexical-phonological network. Could another type of impairment, for example, a decrease in connection strength, account for the unusual features of NC's error patterns in naming and repetition? As noted in the introduction, the theoretical model predicts that it could not because the impact of decreasing connection strength would be especially great at later stages of the lexical selection process, which is where the phonologically related lexical node (formal paraphasia) is activated. The consequence of reducing connection strength should be fewer lexical errors (semantic and formal paraphasias) and more neologisms. To demonstrate the specificity of the effect of an increase in decay rate, we simulated a

<sup>8</sup> In order to estimate what the actual rate of mixed errors would be in normals or patients the rate obtained in this simulation would have to be scaled down by some arbitrary estimate or measurement of the percentage of opportunities for a mixed error to occur.



TABLE 3  
 Simulated Effect of Lexical Neighborhood on Normal and Impaired Naming: Proportion of Responses in Each Response Category as a Function of Neighborhood Configuration

| Neighborhood configuration | Condition            | Response type    |                  |             |             |                      |                    |        |
|----------------------------|----------------------|------------------|------------------|-------------|-------------|----------------------|--------------------|--------|
|                            |                      | Correct<br>(cat) | F<br>(mat + hat) | S<br>(dog)  | N           | S → F<br>(log + fog) | S → N <sup>a</sup> | S + F  |
| 1. Target: cat             |                      |                  |                  |             |             |                      |                    |        |
| 1 Semantic (dog)           | Normal naming        | .99888           | .00018           | .00082      | .00012      | 0                    | 0                  | —      |
| 2 Formal (hat, mat)        | Naming ( $q = .92$ ) | .343             | .260             | .106        | .150        | .114                 | .027               | —      |
| 2 S → F (log, fog)         |                      | (dog)            | (log + fog)      | (cat + rat) | (mat)       |                      |                    |        |
| 2. Target: dog             |                      |                  |                  |             |             |                      |                    |        |
| 2 Semantic (rat, cat)      | Normal naming        | .99865           | .00012           | .00013      | .0011       | 0                    | 0                  | —      |
| 2 Formal (log, fog)        | Naming ( $q = .92$ ) | .422             | .208             | .136        | .147        | .045                 | .042               | —      |
| 1 S → F (mat)              |                      | (cat)            | (mat)            | (dog)       | (log + fog) | (rat)                |                    |        |
| 3. Target: cat             |                      |                  |                  |             |             |                      |                    |        |
| 1 Semantic (dog)           | Normal naming        | .99428           | .00004           | .00076      | .00020      | 0                    | .00003             | .00469 |
| 1 Formal (mat)             | Naming ( $q = .92$ ) | .326             | .119             | .099        | .149        | .056                 | .026               | .225   |
| 1 S + F (rat)              |                      |                  |                  |             |             |                      |                    |        |
| 2 S → F (log, fog)         |                      |                  |                  |             |             |                      |                    |        |

Note. Normal naming was simulated with 100,000 trials per configuration and naming at  $q = .92$  was simulated with 1000 trials per configuration.

<sup>a</sup> S → N = proportion of times that the semantic errors (1, dog; 2, rat, cat; 3, dog) were selected at the lexical level minus the proportion of times that they were actually "spoken" (i.e., selected at the phoneme level).

hypothetical case in which the impairment primarily involves a reduction in connection strength ( $p = .001$ ,  $q = .4$ ). This simulation was compared to that of NC's naming (the decay impairment,  $p = .1$ ,  $q = .92$ ) (Table 4). Although the decrease in connection strength reduces accuracy to the same level and creates a pattern somewhat similar to that of increased decay rate, we can reject a connection strength lesion as an account of NC's error pattern. The decay rate lesion produces a strong tendency for formal paraphasias, while the connection strength lesion does not. To illustrate this, we directly assessed the computational model's tendency to select phonologically related lexical nodes relative to its tendency to select a completely unrelated node at the lexical level. This was done by including such a node in the simulation, allowing it to experience the same noise-induced activation as other nodes in the network and thus allowing it a chance to be selected. The results of this procedure showed that for the simulation of a decay impairment ( $q = .92$ ) in naming, a given F word node was 12.4 times more likely to be selected than a given unrelated word node, while under conditions of decreased connection strength, an F node is only 1.4 times as likely to be selected than an unrelated node. Thus, the decay rate impairment provides the better account of NC's lexical error pattern in naming.

#### *Simulation of Error Patterns after Some Recovery Has Occurred*

We first began testing NC soon after his operation, and he has been participating in our research program for almost 2 years. We were pre-

TABLE 4  
Simulated Effects of Decreasing Connection Strength and Increasing Decay Rate on Error Distributions in Naming: Proportion of Responses in Each Response Category as a Function of Model Parameters

| Parameter settings                                  | Response type    |                  |            |      |                      |                    |
|---|------------------|------------------|------------|------|----------------------|--------------------|
|   | Correct<br>(cat) | F<br>(mat + hat) | S<br>(dog) | N    | S → F<br>(log + fog) | S → N <sup>a</sup> |
| Increased decay rate<br>$p = .1, q = .92$           | .343             | .260             | .106       | .150 | .114                 | .027               |
| Decreased connection strength<br>$p = .001, q = .4$ | .345             | .126             | .053       | .345 | .082                 | .049               |

Note. 1000 trials were used to simulate naming under each parameter setting.

<sup>a</sup>S → N = proportion of times that the semantic error (dog) was selected at the lexical level minus the proportion of times that "dog" was actually spoken (i.e., selected at the phoneme level).

sented, therefore, with the opportunity to observe changes in his language pattern as he recovered. In general, his naming has improved over time, but errors are still present. If the underlying impairment to NC's language system involves pathologically rapid decay of primed nodes in the semantic-lexical-phonological network, recovery should entail resolution of the decay rate toward normal values. Thus, recovery can be simulated by gradually reducing the decay rate toward a level that successfully simulates normal error patterns in naming (semantic > formal paraphasias). In conjunction with resolution of the decay rate, we should also observe a shift in the ratio of semantic and formal paraphasias (F > S) towards the normal ratio of semantic > formal. The top half of Fig. 6

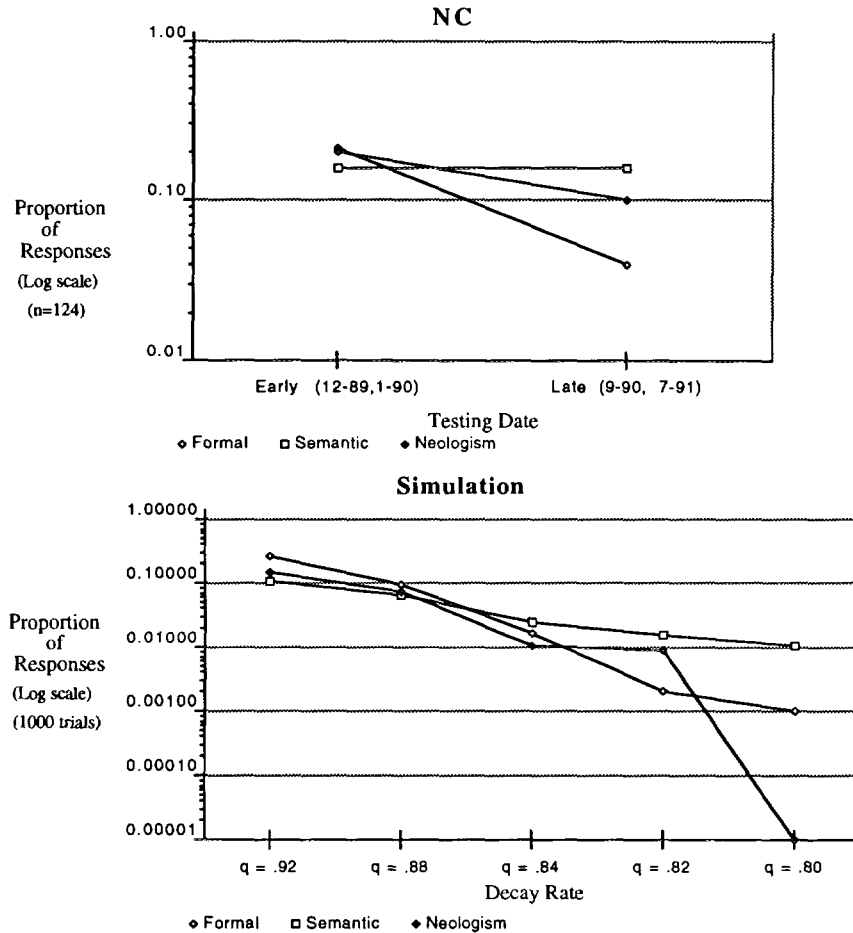


FIG. 6. Recovery in naming: Proportion of errors in three categories produced by NC and model's simulation of decay impairment at early and late testing dates. The proportion of neologisms at  $q = .80$  reported as .00001, on this log scale was essentially zero.

shows data from NC's performance on two naming tests (the Boston Naming Test and the Low Frequency Naming Test) that were administered soon after onset and much later in the course of NC's recovery. Initially, the rate of Fs is greater than the rate of Ss, but over time, the pattern changes. The rate of Fs drops dramatically while the decline of Ss is much slower. At this later testing date, the *relative* occurrence of Ss and Fs is similar to normals ( $S > F$ ). In the lower half of Fig. 6, we show the simulation of recovery. As the rate of decay decreases towards normal, the rate of Fs (initially greater than Ss) drops more rapidly than the rate of Ss, so that eventually their relative rates also resemble the normal pattern ( $Ss > Fs$ ).

#### Extending the Rapid Decay Hypothesis to Account for NC's Repetition Impairment

The Dell (1986) model was developed as an account of language production processes, but as Martin and Saffran (1992) noted, the same framework can, in principle, be applied to input processes as well. Instead of activating the network from conceptual representations, as in Fig. 4, activation can be initiated at the phoneme level, as would presumably occur in comprehending a spoken word or, of more relevance for present purposes, in repeating one.

Figure 7 shows how the Dell model would operate in reverse in comprehension and/or repetition. Again, the lexical selection process is depicted over 5 arbitrarily designated time steps. In TS 1, the phonological nodes are primed by auditory input and in TS 2 these feedforward to prime the target lexical node (Lt) and, to a lesser extent, phonologically related (Lp) and phonologically + semantically related (Lsp) lexical nodes. In TS 3, the primed lexical nodes send activation forward to corresponding semantic nodes and back to decaying phonological nodes. In TS 4, the target and phonologically related nodes receive feedback from phonological nodes and activated semantic nodes. Also, at this time, semantically related lexical nodes (Ls) are activated by feedback from activated semantic nodes. These nodes are activated late in the lexical selection process and are unlikely to be selected under normal conditions. In fact, since phoneme nodes primed at input are likely to remain activated, the likelihood of errors in normal repetition is very low.

When activation in the network decays at pathologically rapid rates, the relative activation levels of the target and of phonologically related and semantically related lexical nodes are altered at TS 4 compared with the normal state. As in naming, nodes primed early are disadvantaged relative to nodes primed later in the selection process. However, the effect of increased decay rate on repetition is in the opposite direction from the effect observed in word production (naming). In repetition, phonologically related lexical competitors are activated earlier and therefore

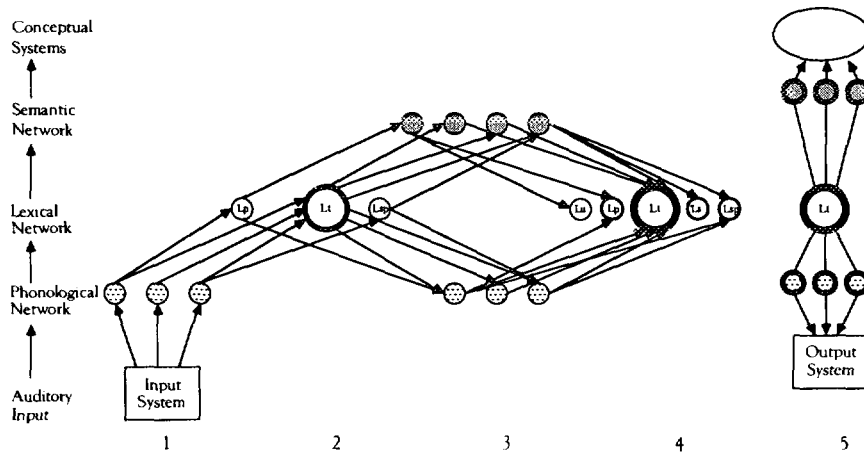


FIG. 7. A single pass through Dell's model of lexical retrieval subserving input processes. The priming activity leading to selection of the target or some related lexical node is depicted over five arbitrarily set time steps.

suffer more of an effect of increased decay than the late-activated semantic competitors. The effect is to increase the likelihood of semantic errors relative to formal paraphasias.

It is possible to accommodate other features of NC's repetition under the decay hypothesis as follows:

(1) Imageability effects in repetition and lexical decision can be accounted for by assuming that priming activation from semantic nodes is more effective for high- than low-imageability targets. This assumption is supported by evidence that lexical decision latencies in normals are sensitive to imageability (Kroll & Merves, 1986), as are ratings of the ease of generating statements using a particular word (Jones, 1985).

(2) NC's inability to repeat nonwords reflects the rapid decay of activation at phoneme nodes. Even if repetition of nonwords receives some support from lexical levels as a result of their similarity to real words, that support is also reduced by the decay impairment, which applies throughout the lexical network.

Thus the decay hypothesis can be extended to account for salient features of NC's repetition performance, as well as his error pattern in naming. Below we report a preliminary attempt to test the decay hypothesis for repetition by examining the model's ability to "repeat" words at normal decay rates and under conditions of rapid decay.

#### *Simulation of NC's Lexical Error Pattern in Repetition*

Using the same network and parameter settings that were used in naming, we simulated repetition by reversing the direction of activation flow

through the network, that is, by initiating activation at phoneme nodes rather than at semantic nodes, as had been done in simulating naming. In adapting the network model for this purpose, it is not our intention to propose this as a complete account of word repetition; in fact, as will be seen, the model does not do a very good job of simulating normal performance. However, to the extent that the repetition process engages the lexical network, and NC's performance indicates that it does, it is reasonable to use the network model in a first-pass attempt at simulating his repetition performance. The primary objective of this simulation was to test the prediction that the probability of a semantic error in repetition (essentially zero in normal repetition) would increase as a consequence of increasing the decay rate.

As noted above, to test this hypothesis, we used the same network and parameter settings that were used in naming, but reversed the flow of spreading activation. Thus, activation input (100 units) was distributed over the three phonological segments of *cat* (/k/-/æ/-t/) and allowed to spread throughout the network according to the same rules used in the simulation of naming. Although input first primes phonological nodes, selection of the lexical node, the addition of 100 units of activation to that node and selection of the phonological nodes proceeded in the same way for naming and repetition. In Fig. 8 we compare the distribution of NC's responses to the set of 80 words (Kay et al., 1987) presented to him for repetition (reported in Part I) with the simulation of repetition responses produced by the network with a decay rate increased to .92. In repetition, there were many words that NC made no attempt to repeat; these "no responses" were distributed proportionately across all *error* categories as they were in naming. Although the simulation did not reproduce NC's performance pattern as closely as the simulation of naming, it did generate semantic errors, albeit at a lower rate than NC. Further comparison of the patient and simulation data is available from Fig. 9, which compares NC's repetition performance early and late in recovery with the simulation at several decay rates that gradually decrease toward the "normal" rate. As the graphs indicate, the error distributions are initially similar to those generated by NC (and the simulation) in naming: Fs are more frequent than Ss. The notable feature of the recovery patterns is that in the simulation, as in NC, the rate of semantic errors, declines more quickly than the rate of formal paraphasias.

One feature of the repetition simulations is that normal repetition is not nearly as good as it should be (see Table 5). In particular, the simulations with the current normal parameter settings and neighborhood structure often misperceive a word as a phonologically related word. In addition, although not simulated, it can be seen that the model is unlikely to fare very well in repeating non-words. Clearly, the network model will have to be elaborated to accommodate normal repetition, and the inade-

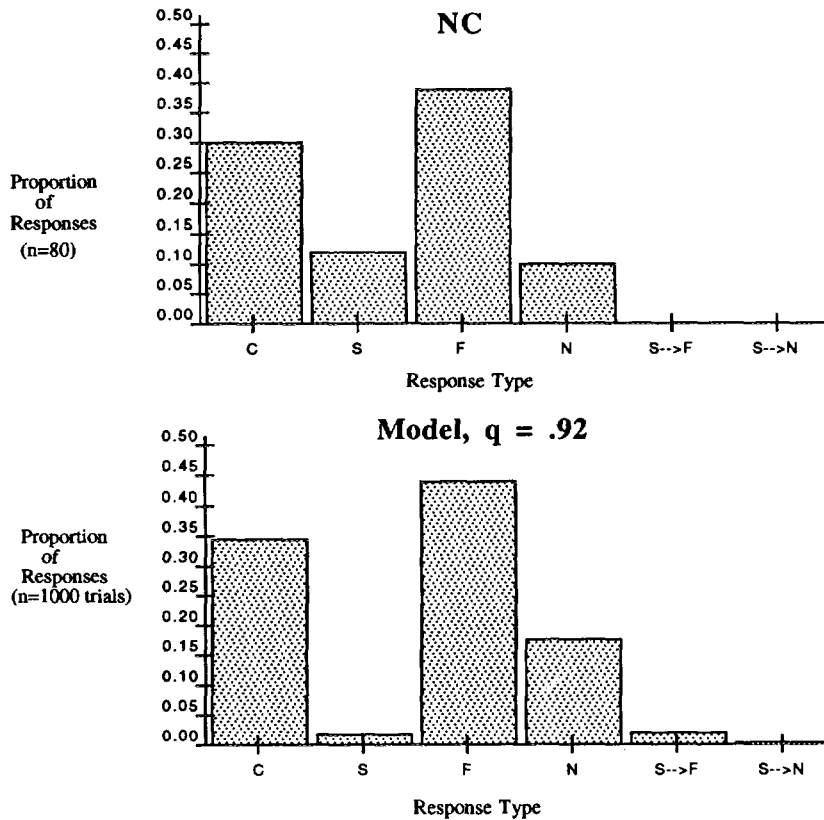


FIG. 8. Proportion of repetition responses (NC and simulation of decay impairment) in each response category: C, correct; S, semantic paraphasia; F, formal paraphasia; N, neologism; S  $\rightarrow$  N, neologism on a semantic paraphasia; S  $\rightarrow$  F, formal paraphasia on a semantic paraphasia.

quacies evident in the simulation results are indicative of some of the modifications that will be need to be made. In particular, it will be necessary to increase the influence of phonological representations beyond the advantage they receive from early activation. In acknowledging these shortcomings we should not, however, lose sight of the major purpose of this simulation. The increase in decay rate did have the general effect of increasing the relative rate of semantic errors in repetition. Moreover, as shown in Table 5, the shift in selection probability in favor of later primed semantically related lexical nodes is evident even when the characteristics of the lexical neighborhood are altered in the same way that they were to assess neighborhood effects in naming. Although characteristics of a target's lexical neighborhood affect the distribution of errors,

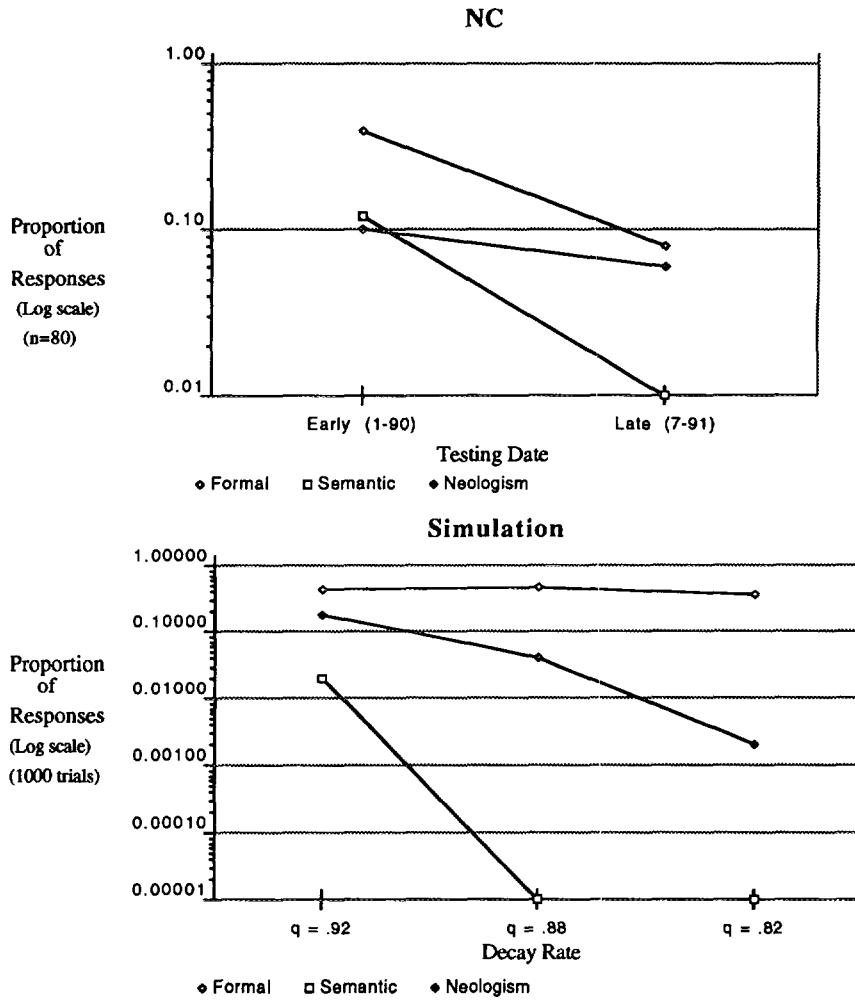


FIG. 9. Recovery in repetition: Proportion of responses in three error categories produced by NC and model's simulation of decay impairment at early and late testing dates. The proportions of semantic errors at  $q = .88$  and  $q = .82$ , marked as .00001 on this log scale, were essentially zero.

in each neighborhood configuration, the probability of semantic errors increases under conditions of rapid decay.

As we did for naming, we also examined the possibility that NC's error pattern could be simulated by altering connection strength in the lexical network. A simulation of a hypothetical impairment to connection strength (decay rate held at the "normal" rate of .4 and connection strength decreased to .001) generated some semantic errors, but the pro-



TABLE 5  
 Simulated Effect of Lexical Neighborhood on Normal and Impaired Repetition: Proportion of Responses in Each Response Category as a Function of Neighborhood Configuration

| Neighborhood configuration       | Condition                    | Response type    |                         |                   |          |                                    |                                  |                              |
|----------------------------------|------------------------------|------------------|-------------------------|-------------------|----------|------------------------------------|----------------------------------|------------------------------|
|                                  |                              | Correct<br>(cat) | <i>F</i><br>(mat + hat) | <i>S</i><br>(dog) | <i>N</i> | <i>S</i> → <i>F</i><br>(log + fog) | <i>S</i> → <i>N</i> <sup>a</sup> | <i>S</i> + <i>F</i><br>(rat) |
| 1. Target: cat                   |                              |                  |                         |                   |          |                                    |                                  |                              |
| 1 Semantic (dog)                 | Normal repetition            | .672             | .328                    | 0                 | 0        | 0                                  | 0                                | —                            |
| 2 Formal (hat, mat)              | Repetition ( <i>q</i> = .92) | .344             | .440                    | .017              | .175     | .020                               | .004                             | —                            |
| 2 <i>S</i> → <i>F</i> (log, fog) |                              | (dog)            | (log + fog)             | (cat + rat)       |          | (mat)                              |                                  |                              |
| 2. Target: dog                   |                              |                  |                         |                   |          |                                    |                                  |                              |
| 2 Semantic (rat, cat)            | Normal repetition            | .730             | .207                    | 0                 | 0        | 0                                  | 0                                |                              |
| 2 Formal (log, fog)              | Repetition ( <i>q</i> = .92) | .420             | .361                    | .016              | .192     | .006                               | .005                             | —                            |
| 1 <i>S</i> → <i>F</i> (mat)      |                              | (cat)            | (mat)                   | (dog)             |          | (log + fog)                        |                                  | (rat)                        |
| 3. Target: cat                   |                              |                  |                         |                   |          |                                    |                                  |                              |
| 1 Semantic (dog)                 | Normal repetition            | .639             | .125                    | 0                 | 0        | 0                                  | 0                                | .236                         |
| 1 Formal (mat)                   | Repetition ( <i>q</i> = .92) | .329             | .207                    | .018              | .144     | .007                               | .006                             | .289                         |
| 1 <i>S</i> + <i>F</i> (rat)      |                              |                  |                         |                   |          |                                    |                                  |                              |
| 2 <i>S</i> → <i>F</i> (log, fog) |                              |                  |                         |                   |          |                                    |                                  |                              |

*Note.* Normal repetition and repetition with *q* = .92 were each simulated with 1000 trials per configuration.

<sup>a</sup>*S* → *N* = proportion of times that the semantic errors (1, dog; 2, rat, cat; 3, dog) were selected at the lexical level minus the proportion of times that they were actually "spoken" (i.e., selected at the phoneme level).

portion was no greater than that of target-unrelated lexical errors. A given S node was only slightly (1.2 times) more likely to be selected at the lexical level than an unrelated node. In contrast, under conditions of rapid decay (decay rate set at .92), the probability of selecting an S word node was 21 times greater than that of selecting an unrelated node. Thus, in repetition, as in naming, NC's lexical error pattern is simulated more successfully by increasing decay rate than by decreasing connection strength.

#### *Discussion of Simulation Studies*

The purpose of these computational studies was to test the hypothesis that, relative to "normal" naming and repetition, an increase in decay rate would increase the probability of form-related substitutions in naming and semantic substitutions in repetition, thus providing a formal account of NC's lexical error pattern. To that extent, the computational studies confirm Martin and Saffran's (1992) account of NC's naming and repetition impairment. The simulations demonstrated, further, that shifts in NC's lexical error patterns with recovery could be reproduced by decreasing the decay rate in the direction of normal values. These studies also showed that the effects of increased decay rate are robust, in that they emerge despite variations in lexical neighborhood, and specific, in that they do not emerge with an alternative type of "lesion" to the lexical network, a decrease in connection strength.<sup>9</sup>

The simulations did not reproduce NC's performance patterns precisely, but the theory should not be held to quite so stringent a test. In the case of the simulations, error distributions can be expected to vary somewhat as a function of the characteristics of the lexical neighborhood (cf. Table 5 and Appendix D). The patient's data will also be affected by neighborhood characteristics, as well as other features of the stimuli administered to elicit word production. Martin and Saffran (1992) found that NC's naming performance was affected by factors such as frequency and syllable length, and that, although the number of formal paraphasias in each case exceeded the number of semantic errors, performance patterns differed somewhat across the three lists that were administered.

<sup>9</sup> Of course, we cannot reject an impairment for NC that affects both decay rate and connection strength. In fact, we believe that the two deficits may often co-occur because each of the model's nodes is equivalent to a large number of elements in a real neural system. The model's decay properties might then correspond to the excitatory and inhibitory influences of these neurons upon one another, and its connection weights to such influences between sets of neurons corresponding to nodes at different levels. Consequently, one might expect damage to often have effects that correspond in the model to decay *and* connection weight effects. In the case of NC, we are arguing that there must be at least a decay impairment, and furthermore that this is sufficient to account for the data.

These considerations suggest that it would be unreasonable to expect the simulation results to correspond exactly to the empirical data. It is sufficient, here, to demonstrate that altering the decay parameter shifts the relative rates of the different types of error responses in the direction of the patient's pattern.

### GENERAL DISCUSSION

In attempting to account for NC's overall language pattern with Dell's (1986; Dell & O'Seaghdha's 1992) interactive spreading activation model, we were presented with several challenges. In naming, the model would have to generate a high rate of formal paraphasias, which could only occur via feedback from primed phonological nodes. Any damage to connections between lexical and phonological levels of representation would be expected to decrease the likelihood of their occurrence. An analogous problem was present in repetition: how to account for the occurrence of semantic errors, which, like formal paraphasias, are primed by feedback and so not likely to occur if connections transmitting activation through the system are weakened or disrupted.

The hypothesis that NC's impairment involves a pathologically rapid decay of activation of nodes that are initially primed at normal levels appeared to solve these problems because it allowed all levels of linguistic representation to be primed and hence to influence the distribution of errors. The simulation studies affirmed the logic of the decay hypothesis: a global increase in the decay parameter of Dell's spreading activation model generated a lexical error pattern parallel to that of our subject, NC, not only when his impairment was quite severe, but also as he recovered. This was accomplished by using a network with parameters set to model normal error patterns and by using identical "pathological" parameter settings for both naming and repetition simulations. Under normal conditions, formal paraphasias (or malapropisms in normals) should be less likely than semantic errors in naming (Fig. 4), because the phonologically related lexical node is activated quite late prior to lexical selection and is only primed by bottom-up feedback. In repetition (Fig. 7), semantic errors are unlikely for the same reason: semantically related lexical nodes are activated late in the priming process and only by top-down reverberating semantic feedback. But, paradoxically, as we have seen, under pathologically rapid decay rates, when nodes at all levels are primed but decay quickly, the probability of these "late" occurring errors increases *because* their lexical nodes are activated late and are, therefore, privileged relative to the target node, which loses the advantage it normally enjoys from early activation.

In addition to the need to account for unusual error patterns such as those produced by NC, modelling efforts are challenged by recent

neuropsychological studies that indicate that the relationship between error type (semantic, phonological) and processing impairment need not be direct or transparent. Such a relationship is implied by independent two-stage models of lexical production which maintain that lexical selection at a semantic level precedes any activation at a phonological level and occurs entirely independently of it (Garrett, 1975; Levelt, 1983, 1989, 1991). For example, Levelt, Schriefers, Vorberg, Meyer, Pechmann, and Havinga (1991) explicitly state that "there is no phonological, but only semantic, activity during stage one. For the most stringent view, there is no semantic, but only phonological, activity during stage two." (p. 123). It follows on this model that semantic substitutions must reflect some failure in the process of selecting a semantic representation of a word, and that phonologically related lexical errors must reflect perturbation at the level of a phonologically specified lexicon (Garrett, 1975; Fay & Cutler, 1977). Caramazza and Hillis (1990) have shown, however, that aphasics may produce semantic errors not only in the context of semantic deficit but also as a result of lexical phonological impairment, indicating that the relationship between error type and locus of impairment is not as transparent as strictly serial models would suggest. Other case studies confirm that the generation of errors with a particular relationship to a target (semantic and/or phonological) does not necessarily imply damage to the level(s) of representation reflected in that relationship (see Ellis & Young, 1988, for discussion of varieties of naming impairments). The interactive model would appear to provide a natural framework for the explanation of these phenomena.

In accounting for NC's error pattern, we have hypothesized a global decay impairment that affects semantic, lexical and phonological activation processes uniformly. In theory, of course, it is possible to have more selective impairments, and in such cases, specific predictions about error patterns could be generated and tested via simulation, as we have done here for the global impairment. Predictions with respect to damage-related error patterns are guided by architectural features and temporal constraints of the model. Thus, for example, we would predict that disruption of activation should have different effects at early and late stages of activation: in production tasks, disrupting activation at the semantic level should have a greater impact on activation of phonological representations than disruption at the phonological level should have on activation at the semantic level; in input tasks (assuming a single lexicon model), the relative effects of disruption at semantic and phonological levels should be reversed.

An additional theory-bound constraint is the nature of damage to the language system which, in this model, includes any pathologically-induced decrease in the strength of connections between nodes or duration of activation at nodes in the lexical network. In this paper, we have

investigated the consequences of an impairment affecting decay rate; elsewhere we explored the effects of a reduction in connection strength as a possible account of the error pattern in jargon aphasia (e.g., Schwartz, Saffran, Bloch, & Dell, 1994). As we pointed out earlier in this paper, the two different types of "lesions" would be expected to result in different error patterns. Comparison of simulations of a decay rate increase and a decrease in connection strength (Table 5) confirmed this expectation.

#### Is This a General Account of Deep Dysphasia?

Apart from NC, only 9 other subjects who produce semantic errors in repetition have been reported in the literature (see Howard & Franklin, 1988 for review; Katz & Goodglass, 1990, and Trojano, Stanzione & Grossi, 1992, for recent case reports). Even so, the patterns of error in naming and repetition (to the extent that they have been described) vary across these patients. Metz-Lutz and Dahl (1984), for example, report a patient, GL, who produced only semantic errors in repetition and phonological errors in naming. At a later date, no naming errors occurred at all. The naming test from the Boston Diagnostic Aphasia Examination (35 items sampling 6 categories) was used to assess naming. This test is fairly easy compared to the naming assessments used in this study, and it is possible that the naming profile would change with a more difficult and extensive sample. With respect to the exclusive occurrence of semantic errors in repetition, however, one possible account of GL's performance might involve a selective increase in decay rate that significantly reduced activation at the phoneme nodes. Under these conditions, semantically related lexical nodes primed by feedback from semantic nodes should be much more stable than phonologically related lexical nodes primed by phonological input.

A particularly well-documented case of a patient who produced semantic errors in repetition is that of MK (Howard & Franklin, 1988). MK's error pattern is similar to NC's in that he produced a variety of error types in both naming and repetition. However, the rates of error types in each condition were generally lower than observed in NC, and he generated relatively fewer formal paraphasias in naming. A possible account of MK's performance is that his impairment is similar to NC's (global increase in decay rate), but less severe. This is a reasonable hypothesis given that NC's error pattern (in naming, repetition and lexical decision) evolved, as he recovered, to a pattern that was similar to MK's.

The generality of the account offered here clearly needs to be tested by attempts to simulate data from other patients classified as deep dysphasics. In developing accounts of their impairments, it will be necessary to consider variations in overall linguistic performance as well as features that such patients hold in common (e.g., semantic errors in repetition).

It seems very likely that different parameter settings will be required from patient to patient (as we have suggested for MK), and that it may be necessary to consider the possibility of varying parameter settings locally within the network (as suggested for GL). Although the interactive model, in its current form, can capture a variety of error patterns, we anticipate that behavioral data will serve to guide further development of the model. In fact, aphasic variability, long considered a nuisance factor in aphasia research, is potentially of great utility in testing a computational model. In turn, the model can help to make sense of this variability.

#### The Importance of Investigating Recovery Patterns

One implication of this investigation concerns the insights into the organization and breakdown of language that can be gained by tracing patterns of error during recovery. The evolution of NC's pattern of naming error from one that was distinctly abnormal (formal paraphasias > semantic paraphasias) toward one that resembled the normal pattern (semantic paraphasias > formal paraphasias) speaks to the differences between normal and aphasic language. The simulation demonstrated that when a normal parameter in the system (decay rate) is quantitatively altered to an extreme, it can result in an error pattern that is qualitatively different from the pattern observed in normals. NC's early pattern of error might be viewed, then, as a limiting case of "normal" breakdown as opposed to some new form of error pattern that is peculiar to brain damage.

The evolution of recovery also has implications for the classification of aphasic syndromes. It has long been observed that aphasic profiles evolve from one syndrome to another (e.g., Wernicke's aphasia to anomia) as patients recover (Kertesz & McCabe, 1977). Two characteristics that distinguish deep dysphasia from other repetition disorders, such as conduction aphasia, are the presence of semantic errors and imageability effects in single word repetition. As NC progressed in his recovery, these two features dropped out of his error pattern, although phonological errors and the inability to repeat nonwords, both characteristic of conduction aphasia, remained. NC's impairment currently corresponds most closely to the clinical profile of conduction aphasia. In a recent case study, Laine, Niemi & Marttila (1990) followed the recovery of an alexic patient whose reading profile evolved in a manner similar to that of NC's repetition abilities. Initially their subject had no reading ability, but with recovery displayed characteristics of deep dyslexia (semantic errors in reading and an inability to read non-words), which eventually evolved into phonological dyslexia (good reading of words coupled with an inability to read non-words). A similar pattern of recovery has been reported in other cases of deep dyslexia (Sartori, Barry, & Job, 1984; Glosser & Friedman, 1990). In each of these cases, the authors have suggested that deep and phonological dyslexia lie on a continuum of severity. NC's

recovery pattern suggests that it is also reasonable to consider the possibility that deep dysphasia and conduction aphasia represent two points on a continuum of repetition impairment. These syndrome designations, which serve as descriptors of patients' deficit patterns, carry with them the implication that the underlying impairments are qualitatively different. It appears that in some instances distinctly different deficit patterns may be due, instead, to quantitative variation. This observation, along with the demonstration that error type (e.g., semantic) does not necessarily bear a direct relationship to the underlying impairment (e.g., Hinton & Shallice, 1991; Caramazza & Hillis, 1990), indicates the need for a more computational approach to the modeling of aphasic behavior. As the present study illustrates, Dell's (1986; Dell & O'Seaghdha, 1992) interactive activation model, in which relative contributions of informationally distinct language components to speech output are determined by parameters such as connection strength, decay rate and speech rate, provides a finer grain of analysis that affords new insights into the nature of aphasic impairments. In turn, analysis of aphasic deficits within this theoretical framework provides the opportunity to observe the effects of parametric variation beyond the range that is characteristic of normal language.

#### APPENDIX A: CRITERIA FOR CLASSIFICATION OF NAMING AND REPETITION ERRORS

1. Correct (C): Phonologically accurate production of the target name or an acceptable alternative (e.g., chicken → hen).

2. Formal paraphasia (F): Lexical error which bears a phonological, but not semantic, resemblance to the target, minimally containing an identical consonant or stressed vowel (e.g., pencil → pepper; vacuum → volcano). The identical phonemes did not have to respect positional information. Allophonic pairs such as the dark /l/ in windmill) and clear /l/ in light were not considered identical. Also, the vocalic /r/ and syllabic consonants, /l/, /m/, /n/ were not considered identical to their consonantal counterparts which head a syllable (e.g., meter-roast, table-lock). Vowels did have to be stressed (including the vocalic /r/ and syllabic consonants /l/ /n/ and /m/) in both the target and the error to be considered identical.

3. Semantically related responses: Any response which provides information semantically related to the target. This general category includes the following:

Semantic substitution (S): Any lexical error which bears a semantic resemblance to the target but is unrelated phonologically to the target (e.g., radio → television).

Semantic description (Sd): A semantically informative description of

the target object with no attempt to name (e.g., funnel → you put stuff in that).

4. Formal + semantic paraphasia (F+S): Lexical error which bears both a semantic and phonological resemblance to the target (e.g., sea-horse → hound).

5. Target-related neologism (T-N): Non-lexical error which is related phonologically to the target and does not obviously relate to another target (e.g., snail → /snaIn/). Criteria for phonological relatedness are the same as defined for formal paraphasias. This category includes single phoneme errors (phonological paraphasias) and errors which include, in part, a lexical item but as a whole result in a nonword (e.g., bagpipes → windpeeg; wheelchair → chairweller).

6. Abstruse neologisms (A-N): Neologism in which no evident phonological relationship to a target is apparent (e.g., pyramid → /'vl-tfæz/).

7. Formal paraphasia on a semantic paraphasia (S → F): Lexical error which is phonologically related to an obvious semantic paraphasia (e.g., unicorn → house (NC's target is horse)). An error was placed in this category only if the subject indicated verbally or nonverbally the identity of the semantic error that was his intended utterance.

8. Neologism on a semantic paraphasia (S → N): Non-lexical error that has an obvious semantic paraphasia as its source (e.g., (sphinx → /'dʒi-zʌps/ (target: Egypt)). An error was placed in this category only if the subject indicated verbally or nonverbally the identity of the semantic error that was his intended utterance.

9. Unrelated lexical (UR): Lexical error which is unrelated to the target semantically or phonologically (e.g., thermometer → telephone).

10. No response (NR): No attempt to name the target.

## APPENDIX B: CORPUS OF ERRORS IN NAMING

The errors listed below come from three different naming tests. Occasionally a target was present in more than one test, but tests were not administered in the same session. Also, in some cases, the reference that NC makes in his semantic errors may not be clear (out of context) to the reader. In those cases, an explanation is provided.

### 1. Semantically Related to Target (Semantic Paraphasias)

#### *Low Frequency Naming Test*

candle → light

windmill → light something (referring to lighthouse)

eggbeater → whip



*Frequency and Syllable Length-Variied Naming Test (F & S Naming Test)*

windmill → light

*Boston Naming Test*

scroll → letters

bench → park

2. Semantically Related Descriptions (with No Attempt to Name the Target)

*Low Frequency Naming Test*

sickle → farmer's wigs, for wigs (target: weeds)

easel → artist, I don't know

hourglass → Wizard of Oz, it's for coke, cook, I don't know

spinning wheel → not a bike

*Boston Naming Test*

rhinoceros → It's an animal, but I don't know what they call it.

wreath → Christmas, I don't know, alot of people have them.

funnel → What is, that is . . . I know that too. At least I think I do.

You put stuff in that.

accordion → Carnival, there it goes. It's either, I don't . . . Why don't I know this stuff.

asparagus → It's green.

yoke → Keep them in purpose so they can stay together.

trellis → This is wood. I know there's a name. I mean doesn't every-thing have a number?

abacus → Chinese, that's one of those, one of those days. That's how they used to count the days.

3. Semantically and Phonologically Related to Target

*Low Frequency Naming Test*

banister → board

doorknob → knock

stethoscope → micro

giraffe → griffen

can opener → can

*F & S Naming Test*

anchor → hook

eskimo → Alaska

cigarette → cigar

*Boston Naming Test*

seahorse → hound  
 muzzle → mask for a dog  
 acorn → squirrel nut

## 4. Phonologically Related to Target (Formal Paraphasias)

*Low Frequency Naming Test*

parachute → cute  
 thermometer → beater  
 anchor → hulk  
 helmet → hang  
 cactus → cassock  
 suspenders → sting  
 safety pin → spin  
 pineapple → pin  
 saddle → stout

*F & S Naming Test*

bed → Ben  
 ladder → lather  
 rake → rook  
 pencil → pepper  
 harp → wok  
 tractor → tart  
 rabbit → rapid  
 mushroom → mush (/mʊʃ/)  
 skeleton → schools

*Boston Naming Test*

pencil → pent  
 harp → hanger  
 volcano → vacuum  
 stethoscope → snow  
 knocker → docker  
 scissors → Caesars  
 flower → flier  
 racquet (tennis) → peasant  
 hanger → hock  
 snail → nine  
 globe → blue  
 latch → limp

tongs → Tex  
 mask → master  
 camel → bicker

5. Formal Paraphasia on a Semantic Error (Semantic → Formal Paraphasia): The Semantic Error Presumed to Be NC's Target Is in Parentheses

*Low Frequency Naming Test*

umbrella → rating (raining)  
 palette → Arthur (artist)

*Boston Naming Test*

hammock → rob (rope)  
 pelican → bear (bird)  
 unicorn → house (horse)

6. Unrelated Lexical Error

*F & S Naming Test*

telephone → thermometer

7. Perseverations

*Boston Naming Test*

saw → Caesars

8. Target-Related Neologisms

*Low Frequency Naming Test*

octopus → /'ak-tə-vəs/  
 penguin → /'pɪŋ-wən/  
 strainer → /stren/  
 chalkboard → /'tʃaɪ-kərd/  
 igloo → 'ɛŋ-klo/  
 hippopotamus → /ho-pə-'han-təks/  
 mermaid → /'mɪ-pæ/  
 purse → /bɜ:s/  
 eyebrow → /'aɪ-flɪ/  
 bagpipes → /'wɪnd-pɪp/  
 typewriter → /'taɪ-paɪ-ɪ-waɪtə/  
 wheelchair → /'wi:l-tʃeə/

*F & S Naming Test*

robot → /'rɒ-bət/  
 broom → /prʊm/  
 owl → /ʊl/  
 chicken → /'sɪ-gət/  
 baby → /'peɪ-bə/  
 typewriter → /'taɪ-plən/  
 violin → /va-'lɛt/  
 clown → /klaʊ/  
 snail → /snaɪn/  
 zebra → /'ze-pə/  
 camel → /'kæl-mæn/

*Boston Naming Test*

helicopter (chopper) → /'tʃɒ-pə (chopper is an acceptable name for helicopter)  
 stilts → /tɪŋk/  
 toothbrush → /'tuθɹθ -bɑʊθ/  
 octopus → /'kʊ'tə/  
 pretzel → /'pi-zl/  
 canoe → /tə-'no/  
 beaver → /'bi-θ i/  
 harmonica → /'hɑ-rən/  
 dominoes → /'dɒg-wɪz/  
 escalator → /'ɛ-və-t əz/  
 wheelchair → /'tʃæə-we-lə/

## 9. Abstruse Neologisms

*Boston Naming Test*

pyramid → /'vɪ-tʃəz/

Neologism on a Semantic Error (Semantic → Neologism):  
 The Semantic Error Presumed to be NC's  
 Target Is in Parentheses

*F & S Naming Test*

pyramid → /'dʒɪ -əps/ (Egypt)  
 arrow → /'rɒ-bən/ (Robin Hood)  
 witch → /'wɪzəd/ (wizard)

*Boston Naming Test*

cactus → /lə-ˈvæk/ (Las Vegas—which is located in a desert area)  
 palette → /ˈɑːθəs/ (artist)  
 compass → /ˈzɛk-tə/ (vector)  
 igloo → /ˈziː-ri-o/ (zero—referring to cold temperature)  
 noose → /kal/ (collar)  
 sphinx → /ˈdʒi-zəps/  
 protractor → /ˈzæn-gə-ləs/

## APPENDIX C: CORPUS OF LEXICAL ERRORS IN REPETITION

These errors include responses to the targets from the Low Frequency Naming Test (49 of 60 items) and the 80 item list Kay, Lesser, and Coltheart (1987) list used in the analysis.

## 1. Semantically Related to Target (Single Words and Short Phrases)

*Low Frequency Naming Test*

thermometer → sick  
 walrus → animal  
 eyebrow → your eyes  
 accordion → that Polish  
 parachute → plane that jumps out  
 octopus → there's like eight male hands  
 blindfold → when you put on your eyes

*Kay, Lesser, and Coltheart (1987) List*

pupil → behavers  
 gravity → science  
 attitude → everybody has one of those days (refers to slang meaning of attitude that is a shortening of “bad attitude” as in “He has a real attitude . . .)

## 2. Semantic and Phonologically Related to the Target

*Low Frequency Naming Test*

banister → steps  
 dinosaur → horse  
 rainbow → red  
 bagpipes → pipe

*Kay et al. (1987) List*

potato → tomatoes  
 mercy → priest  
 realm → crown

### 3. Phonologically Related to the Target (Formal Paraphasias)

#### *Low Frequency Naming Test*

sickle → seagull  
easel → weasels  
cactus → cackle  
strainer → squeezers  
windmill → witch  
chimney → animal

#### *Kay et al. (1987) List*

woe → wool  
plea → plague  
effort → ever  
picture → mixture  
letter → test  
deed → red  
pill → bill  
pact → back  
elbow → behave  
thing → thinker  
funnel → thunder  
axe → racks  
opinion → condition  
irony → dissonant  
miracle → marital  
analogy → hygiene

### 4. Formal Paraphasia on a Semantic Error (Semantic → Formal Paraphasia): The Semantic Error Presumed to Be NC's Target Is in Parentheses

#### *Low Frequency Naming Test*

hourglass → pate (pane)  
covered wagon → whale (wheel)

### 5. Unrelated Lexical Errors

#### *Low Frequency Naming Test*

collar → food  
flashlight → wheel

*Kay et al. (1987) List*

radio → school  
 hand → I thought it was eight.

## Target-Related Neologisms

*Low Frequency Naming Test*

lighthouse → /'le-si/  
 penguin → /'wi-gl/  
 igloo → /glʌb/  
 suspenders → /sa'vEn-dəz/  
 seesaw → /'si-zlz/  
 umbrella → /ʌm-'brɛ-lə/  
 microscope → /'maɪ-krə-spɒn/  
 doorknob → /'dɔə-bam/  
 typewriter → /'taɪp-ɹ-tə/  
 safety pin → /'self-tɪl/ -/spɪn/

*Kay et al. (1987) List*

village → /'vɛm-pl/  
 spider → /'smaɪ-də/  
 concept → /'ka-mɛks/  
 wrath → /'rɛɪ-zl/

## 7. Abstruse Neologisms

*Kay et al. (1987) List*

satire → /'hɪp-nəs/

## APPENDIX D: EFFECTS OF NEIGHBORHOOD ON ERROR PATTERNS IN NAMING AND REPETITION RECOVERY

The simulations that follow are intended to demonstrate that changes in relative rates of formal and semantic paraphasias as decay rate is decreased are not related to the configuration of the target word's lexical neighborhood.

The proportions listed below represent responses at the lexical level (except for nonwords, N). They are derived from the number of times that a word node was selected at the lexical level before its constituent phonemes were selected at the phonemic level. C, correct responses; E-lex, number of lexical errors; F-lex, number of formally related lexical errors; S-lex, number of semantically related lexical errors; S + F-lex, number of semantic + formally related lexical errors; N, number of non-

words and  $S \rightarrow N$  errors; F-lex/E-lex, proportion of lexical errors that are formal paraphasias; S-lex/E-lex, proportion of lexical errors that are semantic paraphasias; S + F-lex/E-lex, proportion of lexical errors that are semantic + formal paraphasias.

### Naming Recovery

#### Configuration 1

Target (cat), 1 Semantic (dog), 2 Formal (hat, mat), 2  $S \rightarrow F$  (log, fog)

|             |      | q    |      |
|-------------|------|------|------|
| Response    | .92  | .88  | .82  |
| C           | .343 | .697 | .966 |
| F-lex       | .224 | .091 | .002 |
| S-lex       | .133 | .066 | .016 |
| N           | .177 | .049 | .003 |
| E-lex       | .476 | .182 | .018 |
| F-lex/E-lex | .471 | .500 | .111 |
| S-lex/E-lex | .279 | .362 | .889 |

#### Configuration 2

Target (dog), 2 Semantic (rat, cat), 2 Formal (log, fog), 1  $S \rightarrow F$  (mat)

|             |      | q    |      |
|-------------|------|------|------|
| C           | .422 | .825 | .984 |
| F-lex       | .155 | .028 | .000 |
| S-lex       | .178 | .052 | .005 |
| N           | .189 | .046 | .004 |
| E-lex       | .374 | .081 | .006 |
| F-lex/E-lex | .414 | .346 | .000 |
| S-lex/E-lex | .476 | .642 | .833 |

#### Configuration 3

Target (cat), 1 Semantic (dog), 1 Formal (mat), 1 S + F (rat), 2  $S \rightarrow F$  (log, fog)

|             |      | q    |      |
|-------------|------|------|------|
| C           | .326 | .629 | .883 |
| F-lex       | .110 | .033 | .004 |
| S-lex       | .125 | .060 | .009 |
| S + F-lex   | .199 | .134 | .058 |
| N           | .175 | .023 | .003 |
| E-lex       | .504 | .230 | .071 |
| F-lex/E-lex | .218 | .143 | .056 |



|                 |      |      |      |
|-----------------|------|------|------|
| S-lex/E-lex     | .248 | .261 | .127 |
| S + F-lex/E-lex | .395 | .583 | .817 |

## Repetition Recovery

*Configuration 1*

Target (cat), 1 Semantic (dog), 2 Formal (hat, mat), 2 S→F (log, fog)

|             |      |      |      |
|-------------|------|------|------|
|             |      | q    |      |
| Response    | .92  | .88  | .82  |
| C           | .344 | .555 | .627 |
| F-lex       | .475 | .445 | .364 |
| S-lex       | .021 | .000 | .000 |
| N           | .179 | .034 | .002 |
| E-lex       | .515 | .445 | .364 |
| F-lex/E-lex | .922 | 1.00 | 1.00 |
| S-lex/E-lex | .041 | .000 | .000 |

*Configuration 2*

Target (dog), 2 Semantic (rat, cat), 2 Formal (log, fog), 1 S→F (mat)

|             |      |      |      |
|-------------|------|------|------|
|             |      | q    |      |
| C           | .420 | .630 | .715 |
| F-lex       | .388 | .318 | .282 |
| S-lex       | .021 | .001 | .000 |
| N           | .197 | .050 | .004 |
| E-lex       | .415 | .319 | .282 |
| F-lex/E-lex | .935 | .997 | 1.00 |
| S-lex/E-lex | .051 | .003 | .000 |

*Configuration 3*

Target (cat), 1 Semantic (dog), 1 Formal (mat), 1 S + F (rat), 2 S→F (log, fog)

|                 |      |      |      |
|-----------------|------|------|------|
|                 |      | q    |      |
| C               | .329 | .472 | .550 |
| F-lex           | .194 | .151 | .146 |
| S-lex           | .024 | .003 | .000 |
| S + F-lex       | .331 | .324 | .283 |
| N               | .150 | .030 | .001 |
| E-lex           | .552 | .478 | .429 |
| F-lex/E-lex     | .351 | .316 | .340 |
| S-lex/E-lex     | .043 | .006 | .000 |
| S + F-lex/E-lex | .600 | .678 | .660 |

## REFERENCES

- Behrmann, M., Moscovitch, M. & Mozer, M. C. 1991. Directing attention to words and nonwords in normal subjects and in a computational model: Implications for neglect dyslexia. *Cognitive Neuropsychology*, **8**, 213–248.
- Blanken, G. 1990. Formal paraphasia: A single case study. *Brain & Language*, **38**, 534–554.
- Bloch, D., & Schwartz, M. F. 1989. *Quantitative speech error analysis in a case of jargon aphasia*. Poster presentation, Academy of Aphasia, Santa Fe, NM.
- Buckingham, H. W. 1980. On correlating aphasic errors with slips of the tongue. *Applied Psycholinguistics*, **1**, 199–220.
- Burton, A. M., Young, A. W., Bruce, V., Johnston, R. A., & Ellis, A. W. 1991. Understanding covert recognition. *Cognition*, **39**, 129–166.
- Butterworth, B. 1979. Hesitation and production of verbal paraphasias and neologisms in jargon aphasia. *Brain & Language*, **8**, 133–161.
- Caramazza, A., & Hillis, A. 1990. Where do semantic errors come from? *Cortex*, **26**, 95–122.
- Coltheart, M. 1980. The semantic error: types and theories. In M. Coltheart, K. E. Patterson, & J. C. Marshall (Eds.), *Deep dyslexia*. London: Routledge.
- Dell, G. S. 1986. A spreading activation theory of retrieval in sentence production. *Psychological Review*, **93**, 283–321.
- Dell, G. S. 1988. The retrieval of phonological forms in production: Tests of predictions from a connectionist model. *Journal of Memory and Language*, **27**, 124–142.
- Dell, G. S. 1989. *The effects of practise on speech production errors*. Paper presented to the Psychonomics Society, Atlanta, GA.
- Dell, G. S. 1990. Effects of frequency and vocabulary type on phonological speech errors. *Language and Cognitive Processes*, **5**(4), 313–349.
- Dell, G. S., & Reich, P. A. 1981. Stages in sentence production: An analysis of speech error data. *Journal of Verbal Learning and Verbal Behavior*, **20**, 611–629.
- Dell, G. S., & O'Seaghdha, P. G. 1991. Mediated and convergent lexical priming in language production: A comment on Levelt, et al. (1990). *Psychological Review*, **98**, 604–614.
- Ellis, A. W., Miller, D., & Sin, G. 1983. Wernicke's aphasia and normal language processing: A case study in cognitive neuropsychology. *Cognition*, **15**, 111–144.
- Ellis, A. W., & Young, A. W. 1988. *Human cognitive neuropsychology*. Hillsdale: Erlbaum.
- Fay, D., & Cutler, A. 1977. Malapropisms and the structure of the mental lexicon. *Linguistic Inquiry*, **8**, 505–520.
- Fromkin, V. A. 1971. The nonanomalous nature of anomalous utterances. *Language*, **47**, 27–52.
- Garnham, A., Shillcock, R. C., Brown, G. D. A., Mill, A. I. D., & Cutler, A. 1982. Slips of the tongue in the London-Lund corpus of spontaneous conversation. *Linguistics*, **19**, 805–817.
- Garrett, M. F. 1975. The analysis of sentence production. In G. H. Bower (Ed.), *The psychology of learning and motivation*. New York: Academic Press.
- Glosser, G., & Friedman, R. B. 1990. The continuum of deep/phonological alexia. *Cortex*, **26**, 343–359.
- Goodglass, H., & Kaplan, E. 1972. *The assessment of aphasia and related disorders*. Philadelphia: Lea & Febiger.
- Harley, T. A. 1984. A critique of top-down independent levels models of speech production: Evidence from non-plan-internal speech errors. *Cognitive Science*, **8**, 191–219.
- Harley, T. A. 1993. Connectionist approaches to language disorders. *Aphasiology*, **7**, 221–249.
- Hinton, G., & Shallice, T. 1990. Lesioning an attractor network: Investigations of Acquired Dyslexia. *Psychological Review*, **98**(1), 74–95.

- Hotopf, W. H. N. 1980. Semantic similarity as a factor in whole-word slips of the tongue. In V. A. Fromkin (Ed.), *Errors in linguistic performance: Slips of the tongue, ear, pen and hand*. New York: Academic Press. Pp. 97–109.
- Howard, D. & Franklin, S. 1988. *Missing the meaning? A cognitive neuropsychological study of the processing of words by an aphasic patient*. Cambridge, MA: The MIT Press.
- Jones, G. V. (1985). Deep dyslexia, imageability and ease of predication. *Brain and Language*, **24**, 1–19.
- Kaplan, E., Goodglass, H., & Weintraub, S. 1976. *The boston naming test*. Boston: Veteran's Administration.
- Katz, R., & Goodglass, H. 1990. Deep dysphasia: An analysis of a rare form of repetition disorder. *Brain and Language*, **39**, 153–185.
- Kay, J., Lesser, R., & Coltheart, M. (1987). *The Newcastle-Birkbeck language assessment*. Unpublished test battery.
- Kertesz, A., & McCabe, P. 1977. Recovery patterns and prognosis in aphasia. *Brain*, **100**, 1–18.
- Kroll, J. F., & Merves, J. S. 1986. Lexical access for concrete and abstract words. *Journal of experimental psychology: Learning, Memory and Cognition*, **12**, 92–107.
- Kucera, H., & Francis, W. N. 1967. *Computational analysis of present-day American English*. Providence, RI: Brown University Press.
- Laine, M., Niemi, J., & Marttila, R. 1990. Changing error patterns during reading recovery: A case study. *Journal of Neurolinguistics*, **5**, 75–81.
- Levelt, W. J. M. 1983. Monitoring and self-repair in speech. *Cognition*, **14**, 41–104.
- Levelt, W. J. M. 1989. *Speaking: From intention to articulation*. Cambridge: The MIT Press.
- Levelt, W. J. M., Schriefers, H., Vorberg, D., Meyer, A. S., Pechmann, T., & Havinga, J. 1991. The time course of lexical access in speech production: a study of picture naming. *Psychological Review*, **98**, 122–142.
- Martin, N., & Saffran, E. M. 1990. Repetition and verbal STM in transcortical sensory aphasia: A case study. *Brain & Language*, **39**, 254–288.
- Martin, N., & Saffran, E. M. 1992. A computational account of deep dysphasia: Evidence from a single case study. *Brain & Language*, **43**, 240–274.
- Martin, N., Weisberg, R. W., & Saffran, E. M. 1989. Variables influencing the occurrence of naming errors: Implications for models of lexical retrieval. *Journal of Memory and Language*, **28**, 462–485.
- McClelland, J. L. & Rumelhart, D. E. 1981. An interactive activation model of context effects in letter perception. Part 1. An account of basic findings. *Psychological Review*, **88**, 375–407.
- Metz-Lutz, M. N., & Dahl, E. 1984. Analysis of word comprehension in a case of pure word deafness. *Brain & Language*, **23**, 13–25.
- Milner, B. 1971. Interhemispheric differences in the localization of psychological processes in man. *British Medical Bulletin*, **27**, 272–277.
- Morton, J. 1980. Two auditory parallels to deep dyslexia. In M. Coltheart, K. E. Patterson, & J. C. Marshall (Eds.), *Deep dyslexia*, London: Routledge.
- Patterson, K. E., Seidenberg, M. S., & McClelland, J. L. 1990. Connections and disconnections: Acquired dyslexia in a computational model of reading processes. In R. G. M. Morris (Ed.), *Parallel distributed processing: Implications for psychology and neuroscience*. London: Oxford University Press.
- Plaut, D. C. & Shallice, T. 1991. Effects of word abstractness in a connectionist model of deep dyslexia. *Proceedings of the 13th Annual Meeting of the Cognitive Science Society*, pp. 73–78, Chicago, IL.

- Plaut, D. C. & Shallice, T. 1993. Deep dyslexia: A case study of connectionist neuropsychology. *Cognitive Neuropsychology*, **10**, 377-500.
- Saffran, E. M., Schwartz, M. F., Linebarger, M., Martin N., & Bochetto, P. 1988. *Philadelphia comprehension battery*. Unpublished test battery.
- Saffran, E. M. 1981. *The low frequency naming test*. Unpublished test.
- Sartori, G., Barry, C., & Job, R. 1984. Phonological dyslexia: A review. In R. N. Malatesha & H. A. Whitaker (Eds.), *Dyslexia: A global Issue*. Boston: Martinus Nijhoff. Pp. 339-356.
- Schwartz, M. F., Saffran, E. M., Bloch, D., & Dell, G. S. 1994. Disordered speech production in aphasic and normal speakers. *Brain and Language*, **47**, 52-88.
- Shallice, T. & Warrington, E. K. 1980. Single and multiple component central dyslexic syndromes. In M. Coltheart, K. E. Patterson, & J. C. Marshall (Eds.), *Deep dyslexia*, London: Routledge.
- Stemberger, J. P. 1985. An interactive activation model of language production. In A. W. Ellis (Ed.), *Progress in the psychology of language, Volume 2*. London: Erlbaum. Pp. 143-186.
- Stemberger, J. P. 1989. Speech errors in early childhood language production. *Journal of Memory and Language*, **28**, 164-188.
- Trojano, L., Stanzione, M., & Grossi, D. 1992. Short-term memory and verbal learning with auditory phonological coding defect: A neuropsychological case study. *Brain and Cognition*, **18**, 12-33.