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EXPLORING THE RELATIONSHIP BETWEEN WORD PROCESSING AND VERBAL SHORT-TERM MEMORY: EVIDENCE FROM ASSOCIATIONS AND DISSOCIATIONS

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A theory of the cognitive organisation of lexical processing, verbal short-term memory, and verbal learning is presented along with a summary of data that bear on this issue. We conceive of verbal STM as the outcome of processing that invokes both a specialised short-term memory and the lexical system. On this model, performance of verbal STM tasks depends on the integrity of lexical knowledge, access to that knowledge, and processes that encode serial order information.

INTRODUCTION

The goal of this article is to present a theoretical view of the relationship among three cognitive capacities: Lexical processing, verbal short-term memory (STM), and the ability to learn new verbal material. We operationalise "lexical processing" to mean the processes that, during comprehension, map the phonological representation of a word onto its meaning, and that, during production, map a meaning onto a phonological representation to be produced in spoken form. We operationalise "verbal short-term memory" to mean the set of processing mechanisms that are invoked in performance of an immediate serial recall task. By "learning new verbal material," we mean the learning of either a single new word, or a list (set) of new words.

Two considerations have motivated our examination of relationships between these abilities. First, although there is now a wealth of evidence from studies of STM performance from normal and impaired populations that indicates relationships among these abilities (e.g., Baddeley, Gathercole, & Papagno, 1998; Craik & Lockhart, 1972; Freedman & Martin, 2001; Gathercole & Baddeley, 1993; Hulme, Maughan, & Brown, 1991; N. Martin & Saffran, 1997, 1999; Saffran, 1990), the nature of these relationships is not well understood. Second, individuals with neurologically based language deficits frequently demonstrate deficits of verbal STM and verbal learning. The development of more effective interventions for individuals with these deficits will be enhanced considerably with increased understanding of the integrated roles of word processing and verbal STM in learning.

Our theoretical orientation is one that views performance of verbal STM tasks as being

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inextricably linked with the lexical processing system (rather than as drawing only on an independent short-term memory system). This theoretical view has evolved from four lines of work.

First, in several studies investigating the relationship between verbal STM and lexical processing in normal subjects, we have found evidence of very robust relationships between these abilities (Gupta, 2003; Gupta, MacWhinney, Feldman, & Sacco, in press). We have also provided evidence of serial position effects in repetition of individual polysyllabic nonwords similar to those in immediate serial recall of lists (Gupta, in press). These results have led us to a view of the relationship between verbal short-term memory and lexical processing that extends previous formulations, suggesting that the sequencing mechanisms underlying immediate serial recall of lists are also engaged in nonword repetition and in word learning.

Second, we have found that language impaired individuals (with aphasia) demonstrate differential influences of semantic and phonological abilities on primacy and recency effects in repetition span tasks (N. Martin & Saffran, 1997; N. Martin, Ayala, & Saffran, 2002). That is, the semantic and phonological processing abilities of aphasic patients impact their serial recall performance in systematic ways. We also have identified more specific correlations between span measures and semantic or phonological processing that reflect an interaction of the task demands and the nature of the lexical processing impairment (whether it is semantic or phonologically based). These results complement a large body of evidence indicating that properties of the language system impact performance in verbal short-term memory tasks, suggesting that the relationship between lexical processing and verbal short-term memory is bidirectional.

Third, we have been influenced by our study of the recovery patterns of an aphasic patient NC, who demonstrated severe STM and repetition impairment at acute stages of his illness. As NC recovered from his aphasia, his profile of "deep dysphasia" (semantic errors in single word repetition) gave way to a pattern more like that of a short-term memory deficit (semantic errors in multiple word repetition), suggesting continuity in the mechanisms underlying verbal STM and lexical processing (N. Martin, Dell, Saffran, & Schwartz, 1994; N. Martin, Saffran, & Dell, 1996). This, together with other results, has led us to the hypothesis of a continuum in the relationship between severity of lexical processing impairment in aphasia and verbal span, once again suggesting that impairments of lexical processing and verbal STM share a common underlying deficit.

In a fourth line of work, we have attempted to integrate evidence from the three domains, word processing, verbal STM, and word learning, through development of a computational model of various aspects of these relationships (Gupta, 1995, 1996a; Gupta & MacWhinney, 1997; N. Martin et al., 1996) that explicitly characterises the performance of verbal STM tasks as involving lexical processing mechanisms and the performance of lexical processing tasks as involving verbal short-term memory mechanisms. This effort is in keeping with other current models that aim to describe the ways in which the linguistic and nonlinguistic aspects of word processing and STM are functionally integrated as a system that supports the development, use, and temporary and long-term storage of language (e.g., Cowan, 1995; Crosson, 1992; R. C. Martin, & Freedman, 2003; Ruchkin, Corcoran, Grafman, & Berndt, in press).

Below, we discuss each of these lines of work, and how they together lead to the theoretical framework outlined above. The discussion of computational models will be interleaved with discussion of experiments, reflecting the co-evolution of our theoretical ideas and empirical investigations.

IMMEDIATE SERIAL RECALL, NONWORD REPETITION, AND WORD LEARNING

Recent thinking has emphasised the importance of verbal short-term memory (as measured by immediate serial recall) in the study of word learning and in the processing of nonwords. In children, reliable correlations have been obtained between digit span, nonword repetition ability, and vocabulary achievement, even when other possible factors such as age and nonverbal intelligence have been factored out (e.g., Gathercole & Baddeley, 1989; Gathercole, Service, Hitch, Adams, & Martin, 1999; Gathercole, Willis, Emslie, & Baddeley, 1992). Nonword repetition ability has been shown to be an excellent predictor of language learning ability in children learning English as a second language (Service, 1992; Service & Kohonen, 1995), and is also associated with more rapid learning of the phonology of new words by children in experimental tasks (Gathercole & Baddeley, 1990b; Gathercole, Hitch, Service, & Martin, 1997; Michas & Henry, 1994). It also appears that there is a population of neuropsychologically impaired patients in whom language function is largely preserved, but who exhibit relative difficulty in immediate serial recall, nonword repetition, and word learning ability (Baddeley, 1993; Baddeley, Papagno, & Vallar, 1988). Overall, there is now a considerable body of evidence to suggest that word learning, immediate serial recall, and nonword repetition are a related triad of abilities, at least in children and in neuropsychologically impaired populations (Baddeley et al., 1998; Gathercole & Baddeley, 1993). An emerging view of this relationship is that immediate serial recall and nonword repetition are both tasks that draw on the mechanisms of verbal short-term memory fairly directly, and that the learning of new words is also in some way supported by verbal short-term memory (e.g., Baddeley et al., 1998; Brown & Hulme, 1996; Gathercole et al., 1999).

There are, of course, many questions that remain unanswered by this very general formulation. In particular: What are the mechanisms underlying these abilities? How do they work? Why are performances on these tasks related? Attempting to answer these questions, Gupta (1995, 1996b; Gupta & MacWhinney, 1997) proposed a computational model that provided a mechanistically specified account of relationships between immediate serial recall, nonword repetition, and word learning. The essence of this model is depicted in Figure 1. This work incorporates a

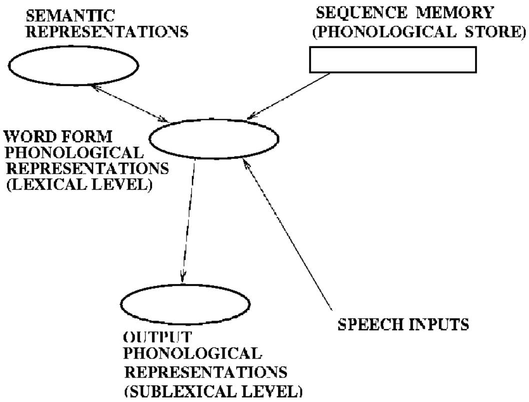

Figure 1. *A model of immediate serial recall, nonword repetition, and word learning (Gupta & MacWhinney, 1997).*

simple model of lexical and sublexical processing, and a sequence memory. For present purposes, the relevant aspects of the lexical model are that when a sequence of sounds constituting a word form (either known or unknown) is input to the system (as a sequence of phonemic representations), this leads to the activation of an internal phonological representation of the word form (again, known or unknown). The output (sublexical) level consists of representations of phonological constituents. The connection weights from the lexical to the sublexical level constitute an encoding of what the sublexical constituents of a word form are, and what their serial order is; these connection weights thus represent long-term phonological knowledge. Immediate repetition of a nonword requires the rapid creation of connection weights from the lexical to the sublexical level. Learning a new word requires that these weights be encoded sufficiently strongly to resist decay over time, and additionally that long-term connection weights be created between the lexical and semantic levels.

The sequence memory has short-term connection weights to the word form (lexical) level of representation. When a list of words is presented to the system, as in immediate serial recall, this leads to a sequence of activations at the lexical level. The sequence memory encodes the serial order of this sequence of activations at the lexical level via temporary learning in its short-term connection weights to the lexical level. That is, the sequence memory takes "snapshots" of the activations of linguistic representations as they occur in sequence at the lexical level of representation as a result of presentation of a list of word forms. As long as its short-term connection weights have not decayed too much, the sequence memory can cause that sequence of activations to be replayed and thus recalled; in the model, such recall exhibits typical serial position effects. The sequence memory is thus a specialised short-term sequencing mechanism; it corresponds roughly to the working memory model's phonological store, but with the important difference that it is not really a store into which items are entered (which appears to be the view outlined in Baddeley et al., 1998), but rather a serial ordering device that sets up associations to a sequence of activations in the lexical system. In this respect, the sequence memory's function is akin to one function of Cowan's (1988) central executive that regulates voluntary attention and selective recall of temporarily activated representations in STM. Moreover, it is also consistent with serial order devices in several other recent models of immediate serial recall (e.g., Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1992, 1999; Hartley & Houghton, 1996; Page & Norris, 1998; Vousden, Brown, & Harley, 2000), and indeed incorporates mechanisms from some of the earlier models (in particular, Burgess & Hitch, 1992; Hartley & Houghton, 1996). However, the aims of the Gupta model were largely complementary to the aims of these other models, being concerned more with explaining relationships between immediate serial memory and aspects of linguistic processing and less with accounting for the many phenomena of immediate serial recall per se. It offered an account of word learning, nonword repetition, and immediate serial recall, incorporating the notion that verbal short-term memory mechanisms work closely with linguistic representations at the lexical level. It suggested that the relationship between these abilities arises because performance in all three tasks is dependent on the integrity of linguistic knowledge, especially the long-term phonological knowledge embodied in the connection weights from the lexical to the sublexical levels of representation. It has remained the only implemented computational model that directly addresses the relationships between verbal short-term memory and lexical processing and learning, and the only implemented model to address issues of serial ordering at both the lexical and sublexical levels.

It seems intuitively obvious why there might be a relationship between nonword repetition and word learning; after all, every known word was once a nonword to the learner, so we might expect greater facility in processing nonwords to lead to greater facility in eventually learning them. But what is the relationship between nonwords and immediate serial memory? Why are these abilities correlated? Our computational model offered one account: Nonword repetition and verbal short-term memory both rely on the integrity of phonological knowledge (Gupta, 1996b) and so these abilities are correlated during development, as phonological knowledge is developing.

However, another possibility is that a nonword is literally processed like a list when it is first encountered; this notion is implicit in some accounts of the phonological loop (e.g., Baddeley et al., 1998), although it has not previously been made explicit. If this were the case, it would make sense that sequencing mechanisms similar to those underlying recall of a list of verbal stimuli in a typical immediate serial recall task might also be engaged in recall of the sequence of sounds comprising a nonword; this would provide a simple explanation of the relationships observed between immediate serial recall and nonword repetition.

How might we examine such a hypothesis? One of the hallmark characteristics of performance in immediate serial recall tasks is the presence of primacy and recency effects that result in a bowed serial position curve. If mechanisms similar to those underlying immediate serial recall are operative in the repetition of nonwords, we would expect to observe serial position effects in repetition of the sequence of sounds comprising nonwords. This raises the question of what might constitute the "list items" in a nonword. There is considerable evidence to suggest that the syllable, rather than the phoneme, is a natural unit of

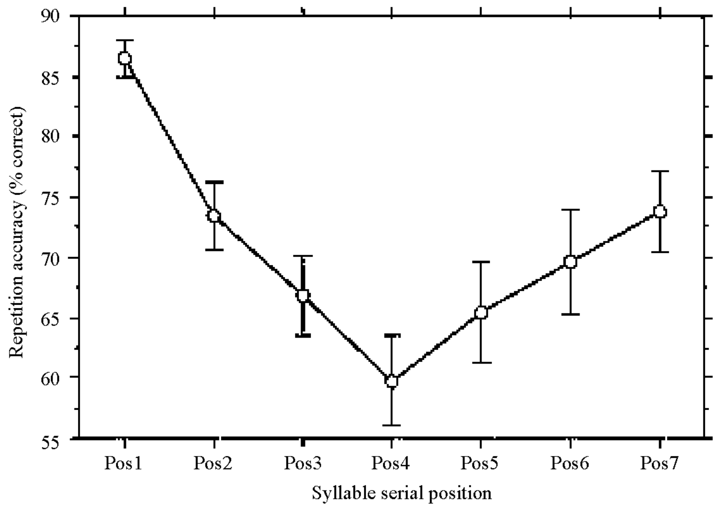

Figure 2. *Primacy and recency effects in repetition of four-syllable nonwords (results of Experiment 3, Gupta, in press).*

phonological analysis (e.g., Jusczyk, 1986, 1997; Massaro, 1989). It therefore seems plausible that, if nonwords are in some sense lists, the list items are syllables. Therefore, it should be possible to detect effects of syllable serial position on repetition of polysyllabic nonwords.

We conducted three experiments to test this prediction (Gupta, in press). Experiment 1 demonstrated significant primacy and recency effects in repetition of four-syllable nonwords. Experiments 2 and 3 showed that these effects were not due to the controlled duration of the nonwords, nor to the requirements of concurrent articulation, nor to the procedure by which nonwords were created. Figure 2 shows the results of Experiment 3, which used seven-syllable nonwords. Both primacy and recency effects were statistically significant (Gupta, in press).

These results suggest a possible revision of the computational model described earlier (Gupta, 1995, 1996b; Gupta & MacWhinney, 1997), to have the conceptual structure shown in Figure 3. For our present purposes, the key aspect of the reformulation is the addition of direct short-term connections from the sequence memory to the sublexical level of representation, which introduces a direct role for the sequence memory in temporarily maintaining and repeating the sequence of sublexical constituents (i.e., syllables) that comprise an individual nonword. This would offer a simple account of the finding of primacy and recency effects in repetition of individual polysyllabic nonwords: They arise for the same reason as in serial recall of lists of lexical items, because of the involvement of the sequence memory at both levels.

The original model also allowed for serial position effects in repetition of individual nonwords,

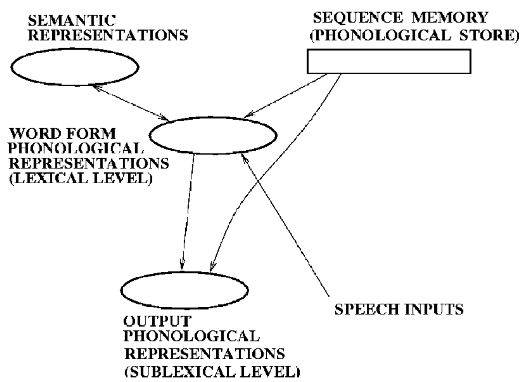

Figure 3. *Revised model of immediate serial recall, nonword repetition, and word learning (Gupta, in press).*

but attributed them to independent serial order encoding mechanisms contained within each word form level representation, rather than to the sequence memory. Which of the two accounts is to be preferred? The two formulations of the model can be distinguished by differing predictions with regard to correlations between immediate serial recall, nonword repetition, and word learning. The earlier formulation offered an account of the developmentally observed correlations between these measures, but predicted that these correlations would not persist in adulthood. In that model, as noted briefly above, the correlations between these abilities arose from the development of the linguistic system; as this system is no longer developing in adulthood, there is a predicted loss of correlations. The revised formulation predicts that such correlations will obtain not only developmentally, but also in adulthood because of the direct involvement of the sequence memory in sequencing at both the lexical and sublexical levels. Correlations between immediate serial recall, nonword repetition, and word learning in adults would thus serve to discriminate between the two models.

Two experiments designed to investigate this issue (Gupta, 2003). established that the developmental association between word learning, nonword repetition, and immediate serial recall extends into adulthood. The results are shown in Table 1, which compares the two experiments in Gupta with the developmental correlations (e.g., Gathercole, Willis, Baddeley, & Emslie, 1994). These experiments thus supported the revised model over the original model.

The correlations between nonword repetition, immediate serial recall, and word learning suggest that the relationships between these abilities may be a fundamental aspect of the human cognitive architecture, holding up as they do in normal children (e.g., Gathercole et al., 1994) and normal adults (Gupta, 2003), and under conditions of delayed linguistic development in children (e.g., Gathercole & Baddeley, 1990a) and under neurological insult in adults (e.g., Baddeley, 1993; Baddeley et al., 1988). The revised version of our model in effect incorporates such a view, in that there is a functional relationship between the abilities, all of which invoke the same sequencing mechanisms. But how robust are these correlations?

Little is known about the impact of early neurological injury on the development of these abilities. In the case of early lesions, there is a real possibility for remission of deficits as a result of developmental neural plasticity. Previous studies of the development of language in children with early focal lesions suggest that there is a generally favourable prognosis for language acquisition, although this is accompanied by selective deficits

Table 1. *Correlations between nonword repetition, immediate serial recall, and word learning in children and adults*

	Gathercole et al. (1994)					*Gupta (2003) (Adults)*		*Gupta et al. (in press) (5–10 years)*	
Correlation between	*4 yrs*	*5 yrs*	*8 yrs*	*13 yrs*	*Correlation between*	*Expt 1*	*Expt 2*	*Exptl*	*Control*
Span & CN rep					*Span & NWR*				
Simple	.520‡	.667‡	.445†	.320‡	Simple	.409‡	.363†	.891**	.522**
Partial					Partial	.314†	.267†	.658†	
Span & vocab					*Span & WL*				
Simple	.284†	.376‡	.355‡	.450‡	Simple	.388†	.373†	.898**	.447**
Partial	.107	.122	.266†	.390‡	Partial	.284†	.281†	.804*	
Vocab & CN rep					*WL & NWR*				
Simple	.413‡	.419‡	.284†	.390‡	Simple	.357†	.353†	.798‡	.657**
Partial	.397‡	.387‡	.151	.370‡	Partial	.236	.252	.600	

† $p < .05$; ‡ $p < .01$; * $p < .005$; ** $p < .001$.

or delays, especially in the more complex aspects of language processing (e.g., Aram, Ekelman, Rose, & Whitaker, 1985; Aram, Ekelman, & Whitaker, 1986; Lenneberg, 1967; MacWhinney, Feldman, Sacco, & Valdès-Pérez, 2000; Marchman, Miller, & Bates, 1991; Thal, Marchman, Stiles, Trauner, Nass, & Bates, 1991). If the relationship between nonword repetition, immediate serial recall, and word learning is indeed a fundamental functional aspect of cognition, we would expect relationships between them to obtain even following early injury across a variety of lesion sites.

Gupta et al. (in press) examined this question by administering tests of vocabulary learning, nonword repetition, and immediate serial recall to two groups of children aged 5 through 10 years. One group of 11 children had suffered perinatal brain injury that resulted in focal lesions; all but two of the lesions were to the left hemisphere, but across a variety of sites. The second group consisted of age-matched controls. The experimental group of children was part of a large-scale investigation, other aspects of which were reported in MacWhinney et al. (2000). It was therefore possible to compare results from the present investigations with a broader profile of results that has been established for the same children. Table 1 shows the patterns of correlation, both simple and partial, between these abilities in the experimental and control groups in the Gupta et al. study and also summarises developmental results for normally developing children (e.g., Gathercole et al., 1994). The results suggest that the relationships between digit span, nonword repetition, and word learning are similar to those observed in the other populations, even under conditions of early brain injury. Given that the lesions in the experimental group were quite widely varied (as detailed in Gupta et al., in press), it seems very unlikely that the brain areas subserving immediate serial recall, nonword repetition, and word learning were uniformly impaired across the experimental group. Gupta et al. therefore suggested that the results were best interpreted as indicating that this triad of abilities is functionally related. These findings thus provide further support for the functional architecture of our revised model.

EFFECTS OF LINGUISTIC VARIABLES ON VERBAL STM

So far, we have emphasised the role of verbal short-term memory mechanisms in lexical processing and learning. However, it is also important to keep in mind that the mechanisms of verbal short-term memory do not operate independently of linguistic representations or the lexical system. Evidence from normal (Hulme et al., 1991) and brain-damaged adults (e.g., R. C. Martin, Shelton, & Yaffee, 1994; Patterson, Graham, & Hodges, 1994) as well as developmental populations (e.g., Gathercole & Martin, 1996) indicates the impact of long-term linguistic knowledge on immediate serial recall and also on nonword repetition (e.g., Gathercole, 1995). These influences include phonological (e.g., Brooks & Watkins, 1990), lexical (Gathercole & Martin, 1996), semantic (Saffran & Marin, 1975; R. C. Martin et al., 1994), and conceptual (Potter, 1993; Saffran & Martin, 1999) aspects of language.

An important aspect of the computational model of Gupta (1995; Gupta & MacWhinney, 1997) was its suggestion that nonword repetition, immediate serial recall, and word learning each depend crucially on the strength of long-term phonological knowledge in the lexical system. Additionally, through interactive connections between phonological and semantic representations, this model allows for the influence of semantic factors on word repetition (e.g., imageability effects). Thus, it is quite conceivable that the mechanisms of verbal short-term memory may themselves draw on aspects of the linguistic system, rather than consisting of an isolated verbal short-term memory buffer that stores or temporarily maintains traces derived from a completely separate lexical system. That is, although one aspect of the functional relationship between these abilities is that they share a dependence on the serial ordering mechanisms of the sequence memory or phonological store, they are also related in that they depend on the fundamentals of lexical processing. A similar point has been made by Gathercole et al. (1997), who noted that the "phonological store" on which immediate serial recall, nonword repetition, and word learning rely is perhaps better conceived of as a system whose performance depends on both a specialised short-term sequence memory and the activation of representations in the lexical system. This notion is akin to formulations of the relation between linguistic processing and storage advanced by Cowan (1988), Crosson (1992), Ruchkin et al. (in press), and others.

Focusing on the linguistic contribution to verbal STM and serial order, N. Martin and Saffran found that performance on tests of lexical-semantic processing is strongly associated with primacy in immediate recall, while performance on tests of phonological processing ability is associated with recency. In that study, Martin and Saffran tested 15 aphasic subjects on one- and two-word strings varied for frequency and imageability. The word pairs were sufficiently taxing to these subjects' spans to reveal primacy and recency effects and their associations with semantic and phonological processing ability. We recently replicated this finding with a larger group of aphasic subjects with a wider range of span capacity (1–4 items) and aphasia severity (N. Martin & Ayala, 2003; N. Martin et al., 2002), which enabled us to observe associations between lexical processing and serial position effects at longer string lengths. As N. Martin and Saffran (1997) observed, performance on lexical semantic tests correlated with primacy in retrieval of phonemes within a single word and words within a two-word string.

N. Martin and et al. (2002) offered an account of the influences of linguistic processing on serial position effects within an interactive activation model of word processing that illustrates how the temporal course in which phonological and semantic representations are activated in a repetition span task affects the probabilities that words from different serial positions will be recalled. Their account assumes an interactive activation model based on Dell and O'Seaghdha, (1992) but with modifications introduced by Foygel and Dell (2000) that allowed for lesions of semantic-lexical and lexical phonological mappings instead of global lesions. For the present account, we will make the further assumption that deficits in mapping involve decay rate rather than reduced connection weight. Also, this account of linguistic influences on serial position is an elaboration of the contribution of the word processing components of Gupta's model above. It does not address the sequence memory's involvement in maintaining serial order, but assumes that linguistic processes work in conjunction with the action of a sequence memory to encode serial order.

When activation spreads between levels of representations within an interactive activation model of word processing, a series of feedforward-feedback cycles of activation are set into motion. These cycles of spreading activation serve to maintain the activation of a word's lexical representation over the course of speech comprehension or production. In the repetition task, lexical and semantic representations of words are activated after phonological representations. The cumulative effect of many interactive spreading activation cycles is that words in a sequence will have different proportions of semantic and phonological support. All things being otherwise equal, the first word in a sequence will have the greatest amount of semantic activation accumulated over the course of the span task, increasing its relative probability of being recalled (see Figure 4).

If activation of semantic representations decays too quickly, the lexical representations of initial words in an input string will not benefit from accumulating semantic support of these words and will be less active at recall (Figure 5). If activation of phonological representations decays too quickly, feedback from activated semantic representations will keep initial words active. This support from semantic feedback is *weakest at the end of the list.* Under conditions of rapid phonological decay, then, final words in a sequence would be supported by weak semantic support and recently activated but rapidly decaying phonological activation (Figure 6). Compared to earlier activated items with accumulated semantic support (from feedforward-feedback cycles) the probability of retrieving these final items would be lowered. These same principles would apply in repetition of nonwords or nonword sequences, but in that case, initial segments of a nonword or initial nonwords

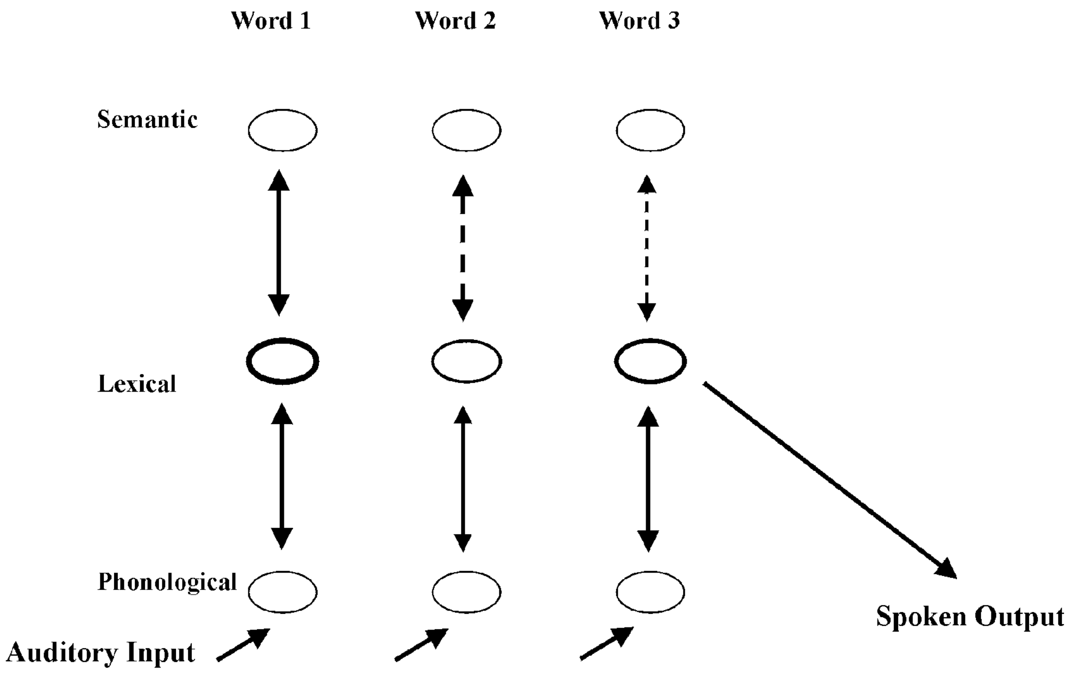

Figure 4. *Hypothesised activation of phonological ←→ lexical and lexical ← → semantic mappings of word representations at time of recall in a three-word repetition span task.*

in a sequence would normally receive extra support from spreading of activation between phonological and lexical levels.

An important implication of these data and the model is that the linguistic contribution to serial order is not linguistic per se, but is more related to processes that enable access to linguistic knowledge. This point is further supported by several findings and observations. First, we would expect primacy in nonword span to be less robust than in word span overall, because there is altogether less support from linguistic processes, but it should not be reduced in relation to recency. This was confirmed in one of our recent studies (N. Martin, 2003) examining recall of words and nonwords by normal adult subjects (aged 20–70 years). We found that overall, more items were recalled in word span than in nonword span, but primacy (as measured by % correct in position 1 / % correct in all positions) was no greater for words than nonwords. A similar finding was obtained when the same word and nonword span task was administered to 13 adult aphasic speakers. We found no difference in this group between word and nonword span tasks in either primacy: two words, $t(12) = -0.58$. $p = .47$; three words, $t(12) = -1.67$, $p = .12$: or recency effects: two words, $t(12) = -0.65$, $p = .52$; three words, $t(12) = 0.52$, $p = .62$.

We have shown that in aphasia, poor performance on tasks measuring lexical-semantic ability is associated with loss of primacy in serial recall tasks (N. Martin & Saffran, 1997). In semantic dementia, a disorder leading to degradation of representations, this same selective depression of recall at primacy positions is not observed (Knott, Patterson, & Hodges, 1997). This population performs similarly to aphasic patients with lexical-semantic impairment in that they both fail tests that require processing semantic information about words. However, the origins of their failures on these measures are very different. In cognitive terms, this difference is typically characterised in

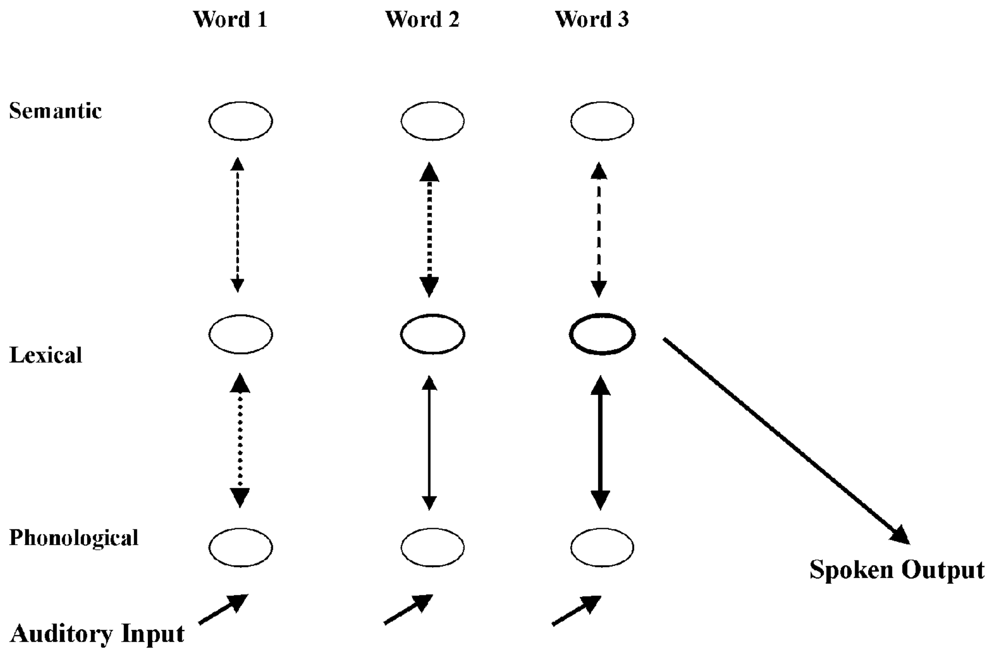

Figure 5. *Hypothesised activation of phonological ←→ lexical and lexical ← → semantic mappings of word representations at time of recall in a three-word repetition span task under conditions of impaired lexical ←→ semantic connections.*

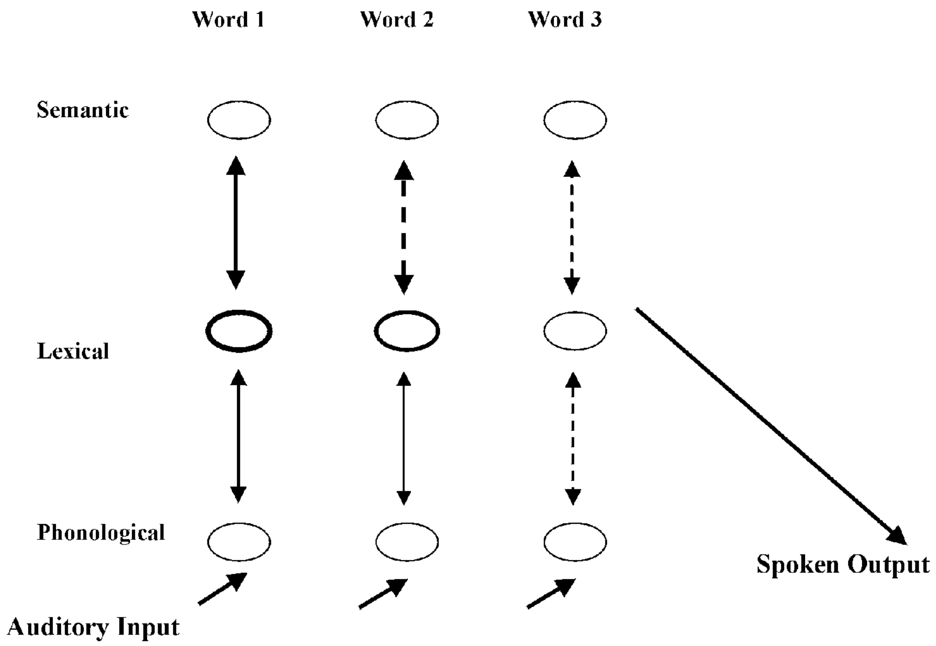

Figure 6. *Hypothesised activation of phonological ←→ lexical and lexical ← → semantic mappings of word representations at time of recall in a three-word repetition span task under conditions of impaired phonological ←→ lexical connections.*

terms of access vs. knowledge deficits; aphasics have difficulty accessing semantics and individuals with semantic dementia experience a degradation of the semantic representations themselves (see discussion below). If the association between primacy and performance on lexical-semantic tasks were related to the integrity of semantic knowledge per se, we would expect a loss of primacy in the verbal span performance of these individuals. This is not observed, providing further evidence that primacy is supported by the integrity of processes that access and maintain representations of words rather than the long-term semantic knowledge of words.

Our account of the lexical-semantic deficit in aphasia is one of access caused by premature decay of activation spreading to lexical-semantic representations. This account predicts that imageability and frequency variables associated with lexical and semantic representations should *not* lead to selective increases or reductions in recall of items from primacy portions of the input string in a span task. Rather, their effects should be constant across the word string with no *additional* advantage in recalling primacy portions of the word string. We investigated this hypothesis in a repetition span task that varied imageability and frequency effects on serial position in an immediate serial recall task (19 aphasic participants) and found that both variables affected overall accuracy of recall. Span was greater on average for high- than low-imageability words (2.62 vs. 2.21, $p < .0045$) and greater for high- than low-frequency words (2.53 vs. 2.25, $p < .0002$). Importantly, the difference between accuracy on high- and low-imageability words and high- and low-frequency words was significant for *all positions* of the input string. There was no additional advantage related to imageability or frequency at initial positions. Thus, recall of initial items in a list does not seem to benefit because of lexical or semantic status per se, but rather because of the temporal course over which these representations are activated and its effect on the cumulative activation support to the maintenance of these words during an immediate recall task.

How does the interactive activation model account for the observation that repetition span in semantic dementia does not suffer from loss of primacy in the way that semantic access aphasia does, but in both disorders, word retrieval is impaired? In a repetition task, phonological activation spreads upward to lexical and then semantic representations and then feeds back down to lexical and phonological representations again. In naming, conceptual semantic representations send activation to corresponding and related lexical nodes and then to phonological representations. When impairment affects the mapping between lexical and semantic representations (as in aphasia), this should disrupt semantic encoding and its support to short-term maintenance of words and subsequent learning of new verbal information. This should result in a reduction of imageability effects and tendency to show reduced primacy. It should also affect the output mapping between semantic and lexical representations and disrupt naming. When the conceptual representations that constitute semantic representations are degrading, as presumed in the case of semantic dementia, spreading activation from phonological input should access lexical and semantic representations of words with varying stability. Those semantic representations that are only partially degraded should provide support to primacy that would not be evident in an access impairment. This support, however, would be dependent on the severity of degradation; if substantial (i.e., if the meaning of these words is no longer "known" to the individual), there would be little support to primacy because there would be no representations for intact access processes to retrieve. Thus, as semantic memory becomes increasingly degraded, we might expect to observe a reduction in primacy in verbal span tasks. In contrast, naming would be disrupted by semantic feature degradation even in milder cases because it is this very stage of processing where naming begins.

In a further set of investigations of how the properties of the lexical processing system impact performance in verbal short-term memory tasks, we have identified a number of associations between word processing measures and immediate verbal span. We began with two word processing measures that engage both semantic and phonological processing, picture naming and auditory lexical decision. We obtained data from 50 subjects on these two tasks as well as on four measures of verbal span: pointing and repetition span for digits and for words. Both the pointing and repetition span tasks involve auditory input of the stimuli to be recalled but differ with respect to the response mode. In the pointing task, the subject hears the sequence of words or digits and points to this same sequence from an array of nine items or nine pictures depicting the objects denoted by the words. The array is rearranged on each trial. In the repetition span task, the heard sequence is repeated immediately by the subject. First, we examined the relationship of two abilities that engage both semantic and phonological processing, word recognition, (auditory lexical decision) and word production (picture naming) with four span measures (pointing and repetition span for digits and for words). Span size was positively correlated with performance on each of these measures (Tables 2 and 3 below). The association of word recognition with span was robust and significant for concrete words and less so for abstract words. It is reasonable to suppose that this difference is most likely to be due to the fact that our span measures used concrete words, although the assumption needs to be investigated.

We used two measures of overall naming ability, percentage correct and percentage of "no response" errors. As the table indicates, all four span measures correlated with our two measures of naming. This finding is not altogether unexpected, although models with separate input and output buffers (e.g., Romani, 1992) might not predict an association between pointing span tasks that require no verbal output and a production task such as naming.

DEFICITS AND RECOVERY IN DEEP DYSPHASIA: A CONTINUUM BETWEEN LEXICAL PROCESSING AND STM

Additional support for a model of qualitative links between word processing and verbal span comes from studies of recovery from acquired language and verbal STM impairments. N. Martin and colleagues (1994, 1996) studied a deep dysphasic subject, NC, whose error pattern in the early stages of his recovery from a stroke included semantic errors in single word repetition. At that time, his repetition and pointing spans for digits or words were limited to a single item. With recovery, NC's span increased to two–three items and, although

Table 2. *Correlations between verbal span measures and measures of auditory word recognition (D-prime scores,* $n = 50$, $df = 48$*)*

Auditory lexical decision measure	*Digit point*	*Word point*	*Digit repetition*	*Word repetition*
Concrete	.24*	.44**	.32**	.43**
Abstract	.13	.24*	.19	.21
Total	.20	.39**	.27*	.39**

* $p < .05$, one-tailed test; ** $p < .01$, two-tailed test.

Table 3. *Correlations between performance on the Philadelphia Naming Test (percent correct and percent of 'No response' errors) and four measures of verbal span performance (*$n = 50$, $df = 48$*)*

Response type	*Digit point*	*Word point*	*Digit repetition*	*Word repetition*
Correct	.39**	.52**	.43**	.50**
No response	−.35**	−.37**	−.30**	−.35**

** $p < .01$, two-tailed test.

semantic errors were no longer present in single word repetition, they re-emerged in repetition of two words, particularly in recall of the second word. The Dell model assumes that activation processes that mediate lexical retrieval are regulated by two parameters, connection strength (the rate of activation spread) and decay rate (the rate of activation decline toward resting level). We hypothesised that NC's error pattern resulted from a pathologically rapid decay of primed nodes in the semantic-lexical phonological network. This hypothesis was tested and supported in a series of simulations that successfully reproduced NC's error pattern in *both* naming and repetition, with the same lesion to the model (N. Martin et al., 1994, 1996). The key notion that we have derived from this computational work is that interactive activation in the lexical system constitutes a means of maintaining information over time in the lexical system (via persistence of the activation of representations). That is, it is a form of short-term memory.

Models of this general type have been successfully applied not just to a single case like NC but characterising the deficits of a case series of 21 aphasic subjects (Dell, Schwartz, Martin, Saffran, & Gagnon, 1997). We were able to fit the model to patients' errors in picture naming quite accurately. Analysis of how the model fitted each patient led to a classification scheme in which each patient's deficits could be characterised in terms of two key parameters: connection strength and decay rate. This model consolidated our ideas about the importance of interactive activation in the lexical system as a form of memory, and demonstrated the value of fitting computational models to data from individual aphasic subjects.

Thus in our view, the ability to comprehend or produce single or multiple words is impacted by the severity of the impairment to those spreading activation processes responsible for maintaining activation of the representations of a word. If the impairment is severe enough, activation of representations of even a single word is affected, and disrupts performance on both single and multiple word language tasks (e.g., verbal span). In milder forms of this deficit, activation processes may be adequate to support processing of a single word but not multiple words, giving the appearance of an independent disruption of verbal short-term memory. On this proposed severity continuum, it is the case that all individuals with aphasia should also present with verbal STM deficits, but not all individuals with verbal STM deficits should present with obvious aphasia. In addition to the severity of impairment to activation maintenance, word processing and span impairments vary according to the level(s) of word representation that is affected (e.g., semantic or phonological; R. C. Martin et al., 1994) and the task used to measure span (affecting the linguistic processes deployed, N. Martin, 1999; N. Martin & Ayala, 2003). These variables together determine the activation available to support maintenance of linguistic information in STM.

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